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Sustainable sanitation-how can we improve sanitation systems in the global south?

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Sustainable sanitation- how can we improve sanitation systems in the global south?

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Monitoring Progress in Citywide Sanitation

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For over 10 years, citywide sanitation plans have been developed, and now, citywide inclusive sanitation is being piloted globally, yet no tools exist to monitor changes in sanitation at a citywide level. This paper explores the use of Shit Flow Diagram Graphics (SFDGs) and City Service Delivery Assessments (CSDAs) to monitor changes in sanitation at a citywide level. This was done by documenting the changes in sanitation from 2015 to 2019 in Tiruchirappalli, India, and developing SFDGs and CSDAs for those years. The changes in the SFDGs and CSDAs were then compared with the documented changes. The SFDGs captured all changes in service delivery that affected >1% of the population, and all of the interventions in the enabling environment change in terms of appropriateness, acknowledgment, or implementation were captured by the CSDAs. Therefore, units of both tools were assessed to be appropriate for monitoring purposes. Using these tools to monitor change was complex and tedious, and this was improved by the development of Trend Graphs and Citywide CSDAs. This paper highlights the potential of Trend Graphs and Citywide CSDAs to monitor sanitation at a citywide level. Additionally, this is the first paper to attempt to monitor changes in sanitation holistically at a citywide level.

Keywords: enabling environment, India, sanitation tools, urban sanitation, Tiruchirappalli

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INTRODUCTION

The world is rapidly urbanizing. For the first time over 50% of the world population live in urban areas and this will rise to 68% by 2050 (UN DESA, 2018). In 2017 it was estimated that 75% of those living in urban areas live in low - and middle-income countries (Ritchie et al., 2018). Furthermore, one-third of the people living in urban areas live in slum conditions (Ritchie et al., 2018), defined as housing that lacks one or more of the following: access to improved sanitation or water, sufficient living area, durability of housing and security of tenure (UN Habitat, 2018). Rapid and ongoing urban growth puts pressure on existing urban services such as sanitation.

Additionally, the international community has raised the service level for sanitation. The focus of the Millennium Development Goals (MDGs) was to increase the percentage of a country's population with access to a certain standard of toilet, but the Sustainable Development Goals (SDGs) considers the whole sanitation service chain (SSC) (**Figure 1**). The SSC contains a series of steps from the capture of human excreta in the toilet through to treatment and finally disposal or end use (**Figure 1**). There are two categories of sanitation systems: offsite (also referred to as sewered or networked) and onsite (also referred to as non-sewered or non-networked). Offsite sanitation systems are defined as systems where excreta and wastewater are collected and transported away

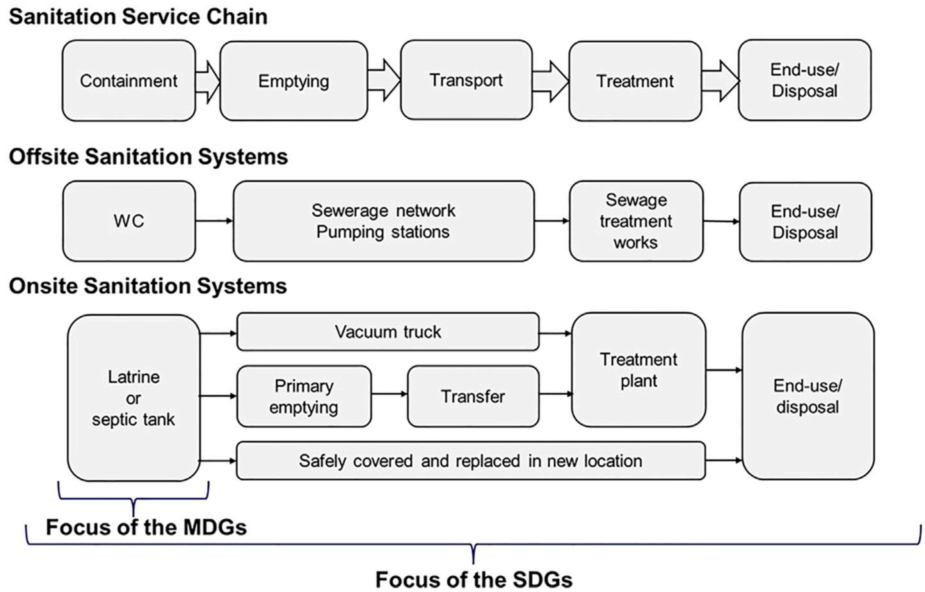

FIGURE 1 | The steps of the sanitation service chain (SSC) chain and examples of these steps in offsite and onsite sanitation systems in relation to the Millennium Development Goals (MDGs) and Sustainable Development Goals (SDGs).

from where they are generated and use sewers for transport (Tilley et al., 2014). While onsite sanitation systems are defined as systems where excreta and wastewater are collected and stored or treated where they are generated (Tilley et al., 2014), then emptied and the contents are transported for treatment or buried onsite (**Figure 1**). In urban areas in low- and middle-income countries 56% of the population has offsite sanitation, while 38% have septic tanks or pit latrines (forms of onsite sanitation), and the remainder of the urban population use other forms of sanitation or practice open defecation (JMP, 2021). Within low- and middle-income cities, sanitation is complex as normally both types of sanitation systems are simultaneously implemented. In a study with data from 39 cities in low- and middle-income countries 72% had a combination of onsite and offsite sanitation, while the remaining cities had onsite sanitation only (Peal et al., 2020).

Traditional approaches to urban sanitation are focused on investments in offsite infrastructure, which normally serve only a part of the city (Evans et al., 2006), meaning that onsite infrastructure and the enabling environment (as defined by Lüthi et al., 2011—aspects of policies, legislations, financing, etc. that facilitate service delivery) are neglected. To meet the target for urban sanitation of the SDGs, more innovative approaches are required (Gambrill et al., 2020). The citywide sanitation approach (CSA) emerged as a response to the traditional infrastructure-focused approach (Evans et al., 2006). This approach advocates sanitation development across a city, as well as strategies and tools for a stage-wise implementation of contextually appropriate sanitation solutions (BORDA, 2016; Walther, 2016). It aims to ensure that sanitation services are equitable, and institutionally and environmentally sustainable (BORDA, 2016). CSA has been adopted in India at the national level. To date, over 165 cities have developed a citywide sanitation plan (MoUD, 2008; MoUD, 2013). CSA has developed into Citywide Inclusive Sanitation (CWIS), which has a greater focus on equity along the SSC (Narayan and Lüthi, 2020). CWIS focuses on inclusion within service provision, by prioritizing the most vulnerable in the city (Schrecongost et al., 2020). Currently, CWIS is being implemented in over 40 cities globally (Narayan and Lüthi 2019; Gambrill et al., 2020). CWIS differs from CSA as it is an overarching framework formed from seven principles (Schrecongost et al., 2020), whereas CSA is a planning tool or method. A planning framework for CWIS has been proposed by Narayan et al. (2021), but this is yet to be trialled. Within the proposed CIWS planning framework, the importance of situational analysis is highlighted, which could include the use of the tools piloted in this paper. As actions and strategies implemented in both CSA and CWIS, so there is a need to go beyond an initial situational analysis and monitor sanitation progress at the citywide level.

Although there are several tools that can be used to aid the analysis of the initial context (Schertenleib et al., 2021), limited tools and frameworks exist to monitoring urban sanitation. Key Performance Indicator Tool (a part of FSM Toolbox and no longer available) provides an overview of onsite sanitation and monitors performance using a set of service targets (FSM Toolbox, 2017). As this tool does not cover offsite sanitation, it cannot be used to monitor cities that have a combination of sanitation systems. Additionally, it does not cover the enabling environment. The Performance Assessment Tool was developed to monitor water supply and offsite sanitation in Indian cities (CEPT University, 2011). This tool again does not cover the enabling environment nor onsite sanitation, so it is also inappropriate. The authors believe that currently, no tools nor frameworks have been developed to monitor citywide sanitation.

Scott and Cotton (2020) have suggested that Shit Flow Diagram Graphics (SFDGs) and CSDAs (City Service Delivery Assessments) could be used for assessing service delivery and enabling environment aspects of CWIS. SFDGs were designed as an advocacy and decision support tool and are used to highlight existing challenges in service delivery along the SSC (SFD-PI, 2018a). To date, more than 120 SFDGs have been developed for cities globally (SFD-PI, 2018b). Whereas the CSDA is used to assess the enabling environment across the SSC in a city, it has been used less widely than the SDFGs. The original CSDA only covered onsite sanitation (Ross et al., 2016), but it has been expanded for citywide use (Safi, 2019; Blackett and Hawkins, 2020). SFDGs and CSDAs have been used together to gain an understanding of the current sanitation situation in urban areas (Peal et al., 2014a; Peal et al., 2014b). SFDGs have also been used to model future sanitation scenarios and to assess how these scenarios impact sanitation coverage across a city (Martinez, 2016). It should be noted that the outputs of these tools are intrinsically linked, as the enabling environment captured in the CSDA facilitates the service delivery captured in the SFD (Scott and Cotton, 2020). It is hypothesized that these tools, which have previously been used for situational analysis have the potential to monitor changes in sanitation service delivery and the enabling environment across the SSC of a city.

This paper, therefore, aims to pilot and evaluate the use of SFDGs and CSDAs for monitoring citywide sanitation approaches (CSA and CWIS) which are being implemented in Tiruchirappalli (Trichy), India. Trichy was chosen as a baseline SDFG exist for 2015 (Rohilla et al., 2015), a citywide sanitation plan was available (TCC, 2018) and it has adopted a CWIS approach (Safi, 2019). Therefore, it was expected that significant changes in sanitation had occurred in the city since 2015 in terms of service delivery and the enabling environment.

METHODS

Case study area

Trichy is in the South of India on the banks of the Cauvery River in Tamil Nadu State (Rohilla et al., 2015). The city covers an area of 167.23 km^2 and is subdivided into 65 wards, in four zones. It has a tropical climate and has no major change in temperature between summer and winter (Rohilla et al., 2015). The population of the city was calculated to be 1,104,710 with an estimated household size of four (Safi, 2019).

Recording Changes in the Sanitation Service Chain

The changes in the SSC both in the service delivery and the enabling environment from 2015 to 2019 were analyzed through reviews of secondary data, interviews of key informants with the city stakeholders, and observations (Safi, 2019). The data collection was guided by the SFD manual (SFD-PI, 2018a). It took approximately 2 months to collect the data, with the aid of a local organization that acted as a gatekeeper to the sanitation community.

Shit flow diagram graphics

The 2019 SFDG for the city was developed based on the data collected (SFD-PI, 2018a). A new SFDG for 2015 was developed as the design of the SFDG had changed; this was to enable easier visual comparison. The original SFDG (Rohilla et al., 2015) was updated in collaboration with the authors as it was known that it did not capture all the onsite sanitation systems in Trichy. Trend Graphs were also developed from the SFDG data, to assess their use when comparing data visually (Martinez, 2016).

Development of City Service Delivery Assessments scorecards

The CSDAs of 2015 and 2019 for Trichy were developed as per the CWIS CSDA Guideline (Blackett and Hawkins, 2020). The CSDA for 2015 was developed using the SFD Report data (Rohilla et al., 2015) and key informant interviews (Safi, 2019). For the 2019 CSDA, data collection was guided by the SDF Manual (SFD-PI, 2018a). Details of the data collected can be found in Safi (2019). The initial CSDAs were developed by the researcher. These were then validated in consultation with sanitation stakeholders and experts in Trichy, as documented in Safi (2019). Citywide CSDAs were developed for each year to assess their use when comparing the data visually (Safi, 2019).

Sensitivity of the tools

The SFDG shows the status of service delivery in the form of percentage population (SFD-PI, 2018a). The sensitivity of the SFDG is 1% of the population (SFD-PI, 2018a). The CSDA is more complex as each pillar is divided into three indicators (**Figure 3**), and then each indicator is subdivided into one to four sub-indicators which are scored 0, 0.5, or 1 (Blackett and Hawkins, 2020). Scoring is based on the existence, appropriateness, acknowledgment and implementation of each sub-indicator, e.g., 0 = not available/inappropriate, 0.5 = appropriate but not widely known, 1.0 = widely known and acknowledged, available and fully implemented (Blackett and Hawkins, 2020). The sub-indicator scores are then averaged to give the indicator score (Blackett and Hawkins, 2020). The indicator scores are then classified as either poor (red) 0–0.4, improving (yellow) 0.5–0.7, or satisfactory (green) 0.8–1.0 (**Figure 3**). The sensitivity of the tools is related to their original aim, so the ability of each tool to capture change needs to be assessed.

RESULT AND DISCUSSION

Table 1 highlights the sanitation interventions in Trichy that occurred between 2015 and 2019, including changes in service

TABLE 1 | Sanitation interventions in Trichy from 2015 to 2019.

No	Intervention	Type of sanitation system	Step of SSC	Data source
Service delivery				
1	7,218 new individual HH toilets were constructed under Swachh Bharat Mission (SBM); 60% of these toilets were connected to the sewer line and the rest (40%) to the onsite sanitation systems (OSS)	Offsite and onsite	User interface and containment	Safi (2019)
2	7,050 unsanitary household latrines were converted to sanitary latrines under SBM. Out of those, 81% are connected to the sewer line and 19% to OSS	Offsite and onsite	User interface and containment	Safi (2019)
3	The number of public toilets and community toilets (PTs/CTs) has increased from 381 to 427; 70% of these toilets are connected to the sewer line, and the remaining 30% are connected to the OSS	Offsite and onsite	User interface and containment	Safi, (2019)
4	In the year 2016, a sewerage project was completed in Srirangam area that covered 3,080 connections to the sewer	Offsite	Emptying and transport	Safi (2019)
5	The number of fecal sludge (FS) emptying and transportation vacuum tankers in the city have increased from 30 to 50	Onsite	Emptying and transport	Safi, (2019)
6	One new decanting station was opened in the Vasudevan Street, Srirangam zone of the city for fecal sludge disposal	Onsite	Transport	Safi, (2019)
7	The increase in the load of wastewater and fecal sludge for treatment from the baseline year (2015) is properly handled by the sewage treatment plant	Offsite and onsite	Treatment	Safi (2019)
8	A 37 million-liters per day sewage treatment plant (rehabilitation of the old system) was under renovation	Offsite and onsite	Treatment	Safi (2019)
9	A Fecal Sludge Treatment Plant (32,000 L per day) was also planned to be constructed in the North West of the city	Onsite	Treatment	Safi (2019)
Enabling environment				
10	Numerous information, education, and communication (IEC) activities on hygienic sanitation were organized as 32 animators and two supervisors were engaged (the data on the exact number of the IEC activities was not available). This was undertaken by the SBM and was effective in the reduction of open defection in the city	Offsite and onsite	User interface and containment	Safi (2019)
11	A National Fecal Sludge and Septage Management Policy (2017) was issued	Onsite	Entire SSC	MoUD (2017)
12	The National Urban Sanitation Policy (2008) and Tamil Nadu Urban Sanitation Policy (2012) were acknowledged at the local level	Offsite and onsite	Entire SSC	Safi (2019)
13	The Operative Guidelines for Septage Management (2014) in the Tamil Nadu State including Trichy city was implemented	Onsite	Entire SSC	Safi (2019)
14	A city sanitation plan for Trichy was developed	Offsite and onsite	Entire SSC	TCC (2018)
15	An investment plan for FSM in Tamil Nadu State was developed and approved	Onsite	Entire SSC	MAWSD, (2018)
16	A Combined Development and Building Rules (2019) was issued for Tamil Nadu State	Offsite and onsite	User interface and containment	Safi (2019)
17	The following were the ongoing investment programs related to the sanitation sector in the city: i. Swachh Bharat Mission (SBM) (since 2014) was constructing toilets and containment units, and connecting households and community toilets to sewer where the sewer network exists. ii. Atal Mission for Rejuvenation and Urban Transformation (AMRUT) were constructing and extending sewerage systems in the city	Offsite and onsite	User interface and containment (onsite and offsite) for SBM. Entire chain (Offsite) for AMRUT	TNUSSP (2017)

Note. FSM, fecal sludge management; SSC, sanitation service chain.

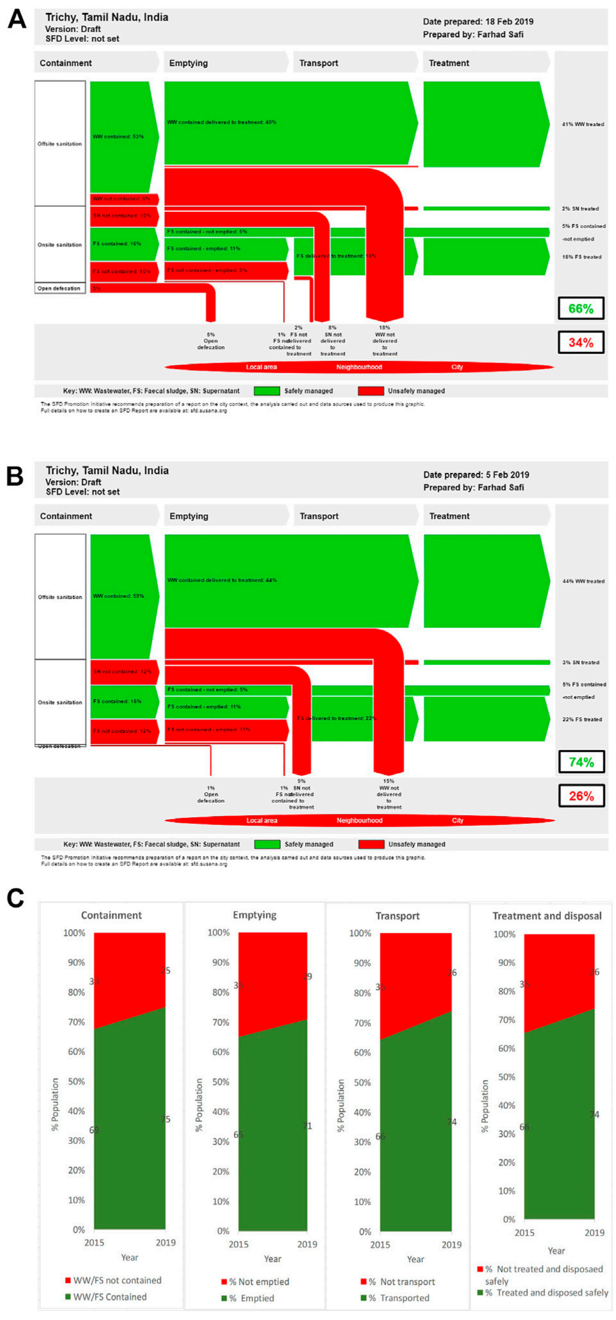

FIGURE 2 | (A) New Shit Flow Diagram (SFD) for 2015, **(B)** SFD for 2019, **(C)** Trend Graphs 2015–2019.

delivery and enabling environment. The impact of the interventions (**Table 1**) on SFDGs and CSDA for 2019 was validated in stakeholder meetings.

Citywide Service Delivery Monitoring Shit Flow Diagram Graphics

The SFDGs for 2015 and 2019 can be found in **Figures 2A,B**. In **Figure 2A**, it can be seen that 41% of the population were using onsite sanitation and 59% offsite sanitation (Rohilla, et al., 2015), and this remained the same in 2019 (**Figure 2B**).

The most noticeable change when comparing **Figures 2A,B** was the 8% increase (from 66% to 74%) in safely managed excreta across the city, caused mainly by the elimination of direct discharge to open drains and reduction in open defecation. This can be attributed to the following changes across the SSC:

1) Containment (6%): This improvement was due to the construction of new individual and community/public toilets, upgrading of existing unsanitary toilets, conducting information, education, and communication activities (**Table 1**, Interventions 1, 3, 2, and 10).
2) Emptying (6%) and transport (8%): Twenty new private vacuum tankers and a new decanting station came into operation, which increased the fecal sludge emptying and transport service (**Table 1**, Interventions 5 and 6). The sewer network was also extended as 3,080 new connections were made.
3) Treatment (8%): The existing sewage treatment plant was used for the treatment of the increased load of wastewater and fecal sludge transported to it (**Table 1**, Intervention 7). As the plant was underloaded in 2015, the increased treatment was due to improvement in the previous step of the SSC, e.g., fecal sludge and wastewater being transported to the treatment site. A small proportion of wastewater was managed onsite by septic tanks with soak pits. It is assumed that the wastewater in the septic tanks was safely managed as defined by SFD Manual (SFD-PI 2018a).

Only Interventions 8 and 9 in **Table 1** were not captured in the SFDGs, as they had not been fully implemented. The visual comparison of the two SFDGs (**Figures 2A,B**) took skill, time, and was tedious, as some changes were not easily seen. Therefore, Trend Graphs were developed as in Martinez (2016) (**Figure 2C**). These graphs captured the individual impact of interventions of the service delivery as in the original SFDGs. Trend Graphs (**Figure 2C**) more clearly show the overall change in each of the components of the sanitation service chain. The data are not disaggregated between onsite and offsite, but as the tools are being explored to monitor citywide sanitation, this level of detail is not required.

The SFDGs and Trend Graphs only captured change at the level of ±1% population, for Trichy in 2019. This equates to 11,047 population or 2,761 households. The magnitude of the change is dependent on the scale of the intervention in relation to the population of the city, e.g., in Trichy an additional 3,080 new sewer connections, serving an approximate population of 12,320, (**Table 1**, Intervention 4), is approximately a 1% improvement in the safe containment in 2019. Therefore, the magnitude of any interventions needed to keep pace with population growth. The effect of population growth was noted to be a major factor when using these tools to model future sanitation scenarios, as little impact was seen with many of the proposed interventions (Martinez, 2016). These units are thought to be appropriate

A

Offsite CSDA 2015	WC, house connection	Sewerage	Sewage treatment & reuse
Enabling			
Policy, legislation	0.7	0.8	1.0
Planning, budgeting	0.3	0.5	0.5
Inclusion	0.5	0.5	
Delivering			
Funding	0.3	0.5	0.5
Capacity, outreach	0.7	0.7	0.7
Inclusion	0.5	0.5	
Sustaining			
Regulation, cost recovery	0.7	0.7	0.7
Institutions, service providers	0.5	0.5	0.5
Inclusion	0.5	0.5	

Onsite CSDA 2015	Toilet, pit or septic tank	Emptying & transport	Sludge treatment & reuse
Enabling			
Policy, legislation	0.7	0.3	1.0
Planning, budgeting	0.3	0.3	0.3
Inclusion	0.5	0.5	
Delivering			
Funding	0.5	0.2	0.3
Capacity, outreach	0.3	0.3	0.7
Inclusion	0.5	0.5	
Sustaining			
Regulation, cost recovery	0.5	0.7	0.7
Institutions, service providers	0.4	0.4	0.4
Inclusion	0.5	0.5	

B

Offsite Sanitation 2019	WC, house connection	Sewerage	Sewage treatment & reuse
Enabling			
Policy, legislation	1.0	1.0	1.0
Planning, budgeting	0.8	0.8	0.8
Inclusion	0.5	0.5	
Delivering			
Funding	0.7	0.7	0.7
Capacity, outreach	0.8	0.8	0.8
Inclusion	0.5	0.5	
Sustaining			
Regulation, cost recovery	0.7	0.7	0.7
Institutions, service providers	0.5	0.5	0.5
Inclusion	0.5	0.5	

Onsite Sanitation 2019	Toilet, pit or septic tank	Emptying & transport	Sludge treatment & reuse
Enabling			
Policy, legislation	0.8	0.7	1.0
Planning, budgeting	1.0	0.8	0.8
Inclusion	0.5	0.5	
Delivering			
Funding	1.0	0.3	0.8
Capacity, outreach	0.5	0.5	0.8
Inclusion	0.5	0.5	
Sustaining			
Regulation, cost recovery	0.5	0.7	0.7
Institutions, service providers	0.4	0.4	0.4
Inclusion	0.5	0.5	

C

Citywide (Offsite and Onsite) CSDA 2015			
Offsite: 59%	WC, house connection	Sewerage	Sewage treatment & reuse
Onsite: 41%	Toilet, pit or septic tank	Emptying & transport	Sludge treatment & reuse
Enabling			
Policy, legislation	0.7	0.6	1.0
Planning, budgeting	0.3	0.4	0.4
Inclusion	0.5	0.5	
Delivering			
Funding	0.4	0.4	0.4
Capacity, outreach	0.5	0.5	0.7
Inclusion	0.5	0.5	
Sustaining			
Regulation, cost recovery	0.6	0.7	0.7
Institutions, service providers	0.5	0.5	0.5
Inclusion	0.5	0.5	

Citywide (Offsite and Onsite) CSDA 2019			
Offsite:59%	WC, house connection	Sewerage	Sewage treatment & reuse
Onsite: 41%	Toilet, pit or septic tank	Emptying & transport	Sludge treatment & reuse
Enabling			
Policy, legislation	1.0	0.9	1.0
Planning, budgeting	0.9	0.8	0.8
Inclusion	0.5	0.5	
Delivering			
Funding	0.8	0.5	0.7
Capacity, outreach	0.7	0.7	0.8
Inclusion	0.5	0.5	
Sustaining			
Regulation, cost recovery	0.6	0.7	0.7
Institutions, service providers	0.5	0.5	0.5
Inclusion	0.5	0.5	

FIGURE 3 | (A) City Service Delivery Assessments (CSDAs) for Trichy, offsite (blue) and onsite (green) sanitation 2015, **(B)** offsite (blue) and onsite (green) 2019, and **(C)** citywide 2015 and 2019.

for citywide monitoring as it ensures services are keeping pace with population growth.

Citywide Enabling Environment Monitoring City Service Delivery Assessments

The offsite and onsite CSDAs were developed for the years 2015 and 2019 (**Figures 3A,B**) and were compared separately with the documented changes (**Table 1**).

Enabling Pillar-Policy and Legislation Indicators

Containment changed from 0.7 (improving) to 1.0 (satisfactory) in offsite sanitation (WC, house connection), whereas it changed from 0.7 (improving) to 0.8 (satisfactory) for onsite sanitation (toilet, pit, or septic tank) (**Figures 3A,B**). Emptying and transport in offsite sanitation (sewerage) changed from 0.8 to 1.0 (remained satisfactory), while in onsite, they changed from 0.3 (poor) to 0.7 (improving). For treatment and reuse, in onsite and offsite sanitation, the rating did not change as it gained the highest rating, 1.0 (satisfactory) in 2015, and it remained at this level. For onsite sanitation, these changes were linked to Interventions 11 and 13 (**Table 1**) and general improvement in sanitation can be attributed to the implementation of Intervention 12, **Table 1**.

Enabling Pillar-Planning and Budgeting Indicators

For containment, offsite sanitation changed from 0.3 (poor) to 0.8 (satisfactory) and, for onsite sanitation, from 0.3 (poor) to 1.0 (**Figures 3A,B**). The remaining two steps of the SSC in both systems changed to 0.8 (satisfactory) from 0.5 (improving) in offsite and 0.3 (poor) in onsite. These changes are linked to Interventions 14 and 15, but mainly 17, as this included the budget, (**Table 1**).

Enabling Pillar-Inclusion Indicators

This indicator remained at 0.5 (improving) for both offsite and onsite for containment, and emptying and transport (**Figures 3A,B**). The policy, planning, and budgetary arrangements before 2015 include some aspects of inclusion; hence, the initial scores were 0.5. Although CWIS was being implemented in Trichy in 2019, it was only at the planning stage and had not yet been implemented, so no change was captured in the CSDA for this indicator as no changes had occurred.

Delivery Pillar-Funding Indicators

For all parts of the offsite, SSC changed to 0.7 (satisfactory), from 0.5 (improving) or 0.3 (poor) (**Figures 3A,B**). For onsite sanitation, containment changed from 0.5 (improving) to 1.0 (satisfactory), emptying and transport changed from 0.2 to 0.3 (remaining poor), while treatment and reuse changed from 0.3 (poor) to 0.8 (satisfactory). These changes were linked to Interventions 15 and 17 (**Table 1**). As no significant public funds were assigned for transport and emptying in these interventions, these scores increased only slightly. The CSDAs only capture public funding, so although 20 new vacuum tankers were purchased by private operators, this was not captured.

Delivery Pillar-Capacity and Outreach Indicators

The score increased in all parts of the offsite SSC from 0.7 (improving) to 0.8 (satisfactory) (**Figures 3A,B**). While in onsite sanitation, the scores for containment, and emptying and transport increased from 0.3 (poor) to 0.5 (improving), and for treatment and reuse, the scores changed from 0.7 (improving) to 0.8 (satisfactory). These slight improvements were linked to the implementation of outreach activities (Intervention 10, **Table 1**).

Delivery Pillar-Inclusion Indicators

Remained at 0.5 (improving) from 2015 to 2019 in both the offsite and onsite for containment, and emptying and transport (**Figures 3A,B**). Delivery before 2015 includes some aspects of inclusion; hence, the initial score was 0.5. Although CWIS was being implemented in Trichy in 2019, it was only at the planning stage and had not yet been implemented, so no change was captured in the CSDA for this indicator as it has not occurred.

Sustaining Pillar-Regulation and Cost Recovery Indicators

For offsite sanitation, the score remained the same: 0.7 (improving) across the SSC (**Figures 3A,B**). This is the same for onsite sanitation for emptying and transport, treatment, and reuse, except the score for containment, remained 0.5. Although Intervention 13 (**Table 1**) was implemented by the municipality, it was not fully enforced, so no improvement was shown on the CSDA for onsite sanitation. As the new guidelines and rules for containment (Intervention 16, **Table 1**) were reiterations of previous rules and guidelines, no improvement was shown on the CSDA.

Sustaining Pillar-Institutions and Service Providers Indicators

The scores remained the same: 0.5 (improving) for offsite sanitation and 0.4 (poor) for onsite from 2015 to 2019 (**Figures 3A,B**). No new interventions relating to these sub-indicators could be found; the scores remained the same.

Sustaining Pillar-Inclusion Indicators

The scores remained 0.5 (improving) for containment, and emptying and transport in both onsite and offsite (**Figures 3A,B**). Sustaining before 2015 includes some aspects of inclusion; hence, the initial score was 0.5. Although CWIS was being implemented in Trichy in 2019, it was only at the planning stage and had not yet been implemented, so no change was captured in the CSDA for this indicator as it has not occurred.

Not all interventions on **Table 1** were captured in the CSDA, due to the scoring of the sub-indicators being related to the appropriateness, level of acknowledgment, or implementation, rather than the existence of an intervention. The scoring system and its sensitivity were deemed appropriate for monitoring changes at a citywide level, as it was able to capture changes that occurred over the 4 years. Increasing the levels in scoring criteria would add additional complexity to the tool and make it harder to score, as differences between the categories would be reduced. As the CSDA only covers the public sector, this means any improvement due to the private sector such as investments were not captured. This may lead to sections of SSC on the CSDA being rated lower than they are in reality. As there is no indication of the percentage population using each type of sanitation system, the most dominant type of sanitation within the city cannot be identified. Therefore, they must be used in conjunction with an SFDG (**Figures 2A,B**), which contains these data. Another option is to develop a Citywide CSDA for each year by weighting the CSDA indicator scores for offsite and onsite sanitation by the percentage of the population using each type of sanitation (Safi, 2019). This CSDA then reflects the enabling environment at a citywide level for a given year (**Figure 3C**) and makes the comparison of the changes easier to analyze.

In general, onsite sanitation scored lower than offsite sanitation across all pillars in both 2015 and 2019 (**Figures 3A,B**), and 41% of the population used this type of sanitation system in both years. This is reflected in the lowering of the Citywide CSDA indicator scores (**Figure 3C**) compared with the score for offsite sanitation in each year. The sanitation situation in Trichy was unusual, as the percentage of the population using onsite and offsite was almost equally split (**Figures 2A,B**). In a study of sanitation in 39 low- and middle-income cities, similar sanitation was only found in five cities (Peal et al., 2020). Although this situation seems to be more common in India, 27% of the cities in India in this study had similar sanitation situations (Peal et al., 2020). If there was a more dominant sanitation type, the Citywide CSDA would reflect this and may hide the sanitation needs of the marginalized as they may be using a different sanitation system compared with the majority of the population. As all three pillars in the CSDAs (**Figures 3A–C**) have an inclusion indicator, this should capture inequalities in the sanitation focus of a city, but this needs to be evaluated further. As CSDAs and Citywide CSDAs have not been widely used, the authors recommend further piloting of these tools for monitoring purposes, paying special attention to their ability to capture inclusion. A further development would be to trial change CSDAs (Safi, 2019), which capture the change in the enabling environment on one CSDA.

Although piloting of these tools to monitor changes in citywide sanitation was deemed to be successful, several limitations or challenges were noted. Extensive data is required for both the development of the SFDGs and CSDAs. Trichy was purposively chosen for this study as data on sanitation were readily available and accessible [an initial SFDG already existed (Rohilla et al., 2015), a citywide sanitation plan was available (TCC, 2018), and it has adopted a CWIS approach (Safi, 2019)], this may not be the case in other cities. Even with these data being available, the data collection period took 2 months; in cities where less data are available, it may take longer, although it should be noted that the researcher was not from the sanitation sector in Trichy, so the data collection period stated could be an overestimation of the time required. In most cities, there is a general lack of data on sanitation, which means that some assumptions will need to be made. Guidance on these assumptions is given in the manuals of the tools (SFD-PI, 2018a; Blackett and Hawkins, 2020). All assumptions made were validated in consultation with sanitation stakeholders and experts in Trichy before the final CSDAs and SFDGs were developed (Safi, 2019). The biases of the sanitation stakeholders and experts need to be considered in this process, as there may be political reasons for them wanting the current sanitation situation to be seen as being worse or better than it is. These biases can be and were minimized by consulting with a broad range of sanitation experts and stakeholders from different organizations within a city. The final outputs of these tools could be seen as being subjective, due to the methods and assumptions that are required. This is because both tools were designed for advocacy and therefore not designed to be accurate or precise (SFD-PI, 2018a; Blackett and Hawkins, 2020). This subjectivity is and was minimized by validating the outputs of these tools with a wide range of sanitation stakeholders and experts. The analysis and comparison of the output of the tools were done by visual comparisons without guidance, and it was noted to be time consuming and tedious. Additionally, this could be seen as being subjective. Guidance for these comparisons could be developed, or software could be produced to aid this process. This software could generate a short report or graphic noting the positive and negative changes in sanitation at a citywide level. Although some of these data were in the public domain, some of the data required could be seen as being sensitive, e.g., performance of sewage treatment plant; hence, the results could also be deemed as being sensitive, as cities may not want to highlight slippages in sanitation coverage, which could be linked to the units used, e.g., the city may be increasing sanitation coverage in terms of numbers, but not keeping up with population growth. Most of the limitations in terms of subjectivity and biases discussed can be overcome or minimized by consulting and working with a wider range of sanitation stakeholders and experts, meaning that this is not a standalone process, and it should be done in conjunction with the sanitation community. This can be difficult to do if there is a lack of political buy-in or an undeveloped sanitation sector in a city. In these cities, the tools could be used to monitor changes in sanitation, but the lack of data, assumptions, and potential biases should be acknowledged. Undertaking this process may even stimulate political buy-in and the development of the sanitation sector in these cities.

CONCLUSION

All the service delivery changes that were fully implemented and that affected 1% of the population or more were captured on the SFDGs, but it is difficult to see these changes. Trend Graphs were then developed, which clearly showed all changes at each step of the SSC. The data in the Trend Graphs were not disaggregated, but this is not required when applying a citywide approach. The units of the SFDGs and the Trend Graphs (percentage of the population) and the sensitivity of these tools were judged to be appropriate for citywide monitoring. An advantage of these units is that interventions need to keep pace with population growth for any improvements to be recorded. All of the interventions related to the enabling environment were captured by the CSDAs if they had brought about an increase in appropriateness, level of acknowledgment, or implementation in a certain part of the SSC. It was noted that the CSDAs only capture public sector activities, and the sensitivity was assessed to be good enough to monitor change. Comparing four CSDAs to review these changes was complex and tedious. This was improved by developing citywide CSDA. As CSDAs have been used less than SFDGs, further piloting of this tool is required to assess their suitability for monitoring. The main challenges in using these tools for citywide monitoring were linked to the amount and availability of data, subjectivity, and potential biases, which were overcome by consulting with a wider range of sanitation stakeholders and experts, who were used to validate assumptions and outputs of the tools. This paper highlights the potential of Trend Graphs and Citywide CSDAs to monitor sanitation at a citywide level. Additionally, it is thought to be the first paper to attempt to monitor changes in sanitation at a citywide level.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. These data can be found here: https://cdm21063.contentdm.oclc.org/digital/collection/masters2/id/83759.

ETHICS STATEMENT

Ethical review and approval were not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

CF and FS contributed to the conception and design of the study, performed the analysis of data, and wrote the first draft of the manuscript. FS, CF, and BL were in charge of the development of tools and data collection. All authors contributed to manuscript revision, and read and approved the submitted version.

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REFERENCES

Blackett, I., and Hawkins, P. (2020). *City Service Delivery Assessment for Citywide Inclusive Sanitation -User Guide*. UK: Inclusive Sanitation in Practice.

BORDA (2016). *Body of Knowledge City Sanitation Planning*. Bremen, Germany: BORDA.

CEPT University (2011). *Performance Measurement for Urban Water Supply and Sanitation-List and Definition of KPIs and Local Action Indicators*. Gujarat, India: CEPT University.

Evans, B. E., and Saywell, D.Sanitation 21 task force (2006). *Sanitation 21: Simple Approaches to Complex Sanitation - A Draft Framework for Analysis*. London, UK: Report. International Water Association.

FSM Toolbox (2017). *Monitor the Performance of the Project with Set Indicators*. Available at: http://www.fsmtoolbox.com/fsm-workflow/07-operation-maintenance/7-2-monitor-the-performance-of-the-project-with-set-indicators/ (accessed November 10, 2018).

Gambrill, M., Gilsdorf, R. J., and Kotwal, N. (2020). Citywide Inclusive Sanitation-Business as Unusual: Shifting the Paradigm by Shifting Minds. *Front. Environ. Sci.* 7, 201. doi:10.3389/fenvs.2019.00201JMP2021

JMP (2021). WashData. Available at: https://washdata.org/data (accessed May 22, 2021).

Martinez, L. F. (2016). *Using the SFD Methodology for Modelling Future Scenarios in Kumasi, Ghana*. Loughborough, UK: MSc Dissertation, WEDC.

MAWSD (2018). *FSM Investment Plan*. Chennai, India: Municipal Administration and Water Supply Department (MAWSD), Government of Tamil Nadu.

MoUD (2013). *Advisory Note on Septage Management in Urban India*. New Delhi, India: Ministry of Urban Development (MoUD) Government of India.

MoUD (2017). *National Policy on Faecal Sludge Management (FSSM)*. New Delhi, India: Ministry of Urban Development (MoUD) Government of India.

MoUD (2008). *National Urban Sanitation Policy*. New Delhi, India: Ministry of Urban Development (MoUD) Government of India.

Narayan, A., and Lüthi, C. (2020). *Solving Urban Sanitation - Sustainably and Equitably*, 43. Alexandria, VA: World Water, 18–21.

Narayan, A. S., and Lüthi, C. (2019). Citywide Inclusive Sanitation–Old Wine in New Bottle. *Sandec News* 20, 21–22.

Narayan, A. S., Maurer, M., and Lüthi, C. (2021). The Clean Plan: Analysing Sanitation Planning in India Using the CWIS Planning Framework. *J. Water Sanitation Hy giene Develop.* 11 (6), 1036–1047. doi:10.2166/washdev.2021.130

Peal, A., Evans, B., Ahilan, S., Ban, R., Blackett, I., Hawkins, P., et al. (2020). Estimating Safely Managed Sanitation in Urban Areas; Lessons Learned from a Global Implementation of Excreta-Flow Diagrams. *Front. Environ. Sci.* 8, 1. doi:10.3389/fenvs.2020.00001

Peal, A., Evans, B., Blackett, I., Hawkins, P., and Heymans, C. (2014a). Fecal Sludge Management (FSM): Analytical Tools for Assessing FSM in Cities. *J. Water* 4, 371–383. doi:10.2166/washdev.2014.139

Peal, A., Evans, B., Blackett, I., Hawkins, P., and Heymans, C. (2014b). Fecal Sludge Management (FSM): Analytical Tools for Assessing FSM in Cities. *J. Water* 4, 563–575. doi:10.2166/washdev.2014.026

Ritchie, R., Mispyand Ortiz-Ospina (2018). *Measuring Progress toward Sustainable Development Goals*. https://sdg-tracker.org/(accessed April 24, 2020).

Rohilla, S. K., Luthra, B., Varma, R. S., and Padhi, S. K. (2015). *Tiruchirappalli, India SFD Report, Centre for Science and Environment (CSE), SFD Promotion Initiative*. Tiruchirappalli: SFD-PI.

Ross, I., Scott, R., Mujica, A., White, Z., and Smith, M. (2016). *Fecal Sludge Management : Diagnostics for Service Delivery in Urban Areas- Tools and Guidelines (English). Water and Sanitation Program Technical Paper, Water and Sanitation Program (WSP)*. Washington DC: World Bank Group.

Safi, F. (2019). *Monitoring Changes in Citywide Sanitation: An Assessment of Two Tools*. Delft, Netherlands: MSc Dissertation, IHE Delft Insititute for Water Education. https://cdm21063.contentdm.oclc.org/digital/collection/masters2/id/83854.

Schertenleib, R., Lüthi, C., Panesar, A., Büürma, M., Kapur, D., Narayan, A. S., et al. (2021). *A Sanitation Journey - Principles, Approaches* & *Tools for Urban Sanitation*. Bonn: Sustainable Sanitation Alliance.

Schrecongost, A., Pedi, D., Jan, W., Shrestha, R., and Ban, R. (2020). Citywide Inclusive Sanitation: A Public Service Approach for Reaching the Urban Sanitation SDGs. *Front. Environ. Sci.* 8, 19. doi:10.3389/fenvs.2020.00019

Scott, P., and Cotton, A. P. (2020). The Sanitation Cityscape - toward a Conceptual Framework for Integrated and Citywide Urban Sanitation. *Front. Environ. Sci.* 8, 70. doi:10.3389/fenvs.2020.00070

SFD-PI (2018b). About SFD, SFD Promotion Initiative. Available at: https://sfd.susana.org (accessed October 20, 2019).

SFD-PI (2018a). *SFD Manual – Volume 1 and 2, SFD Promotion Initiative*. SFD-PI.

TCC (2018). *Tiruchirappalli City Sanitation Plan, Tiruchirappalli City Corporation (TCC)*. Tiruchirappalli, India: TCC.

Tilley, E., Ulrich, L., Lüthi, C., Reymond, Ph., and Zurbrügg, C. (2014). *Compendium of Sanitation Systems and Technologies*. 2nd Revised Edition. Dübendorf, Switzerland: Swiss Federal Institute of Aquatic Science and Technology (Eawag).

Tnussp (2017). *Legal and Institutional Review, Tamil Nadu Urban Sanitation Support Program (TNUSSP)*. Chennai, India.

UN DESA (2018). *World Urbanization Prospects: The 2018 Revision*. New York, U.S: UN.

UN (2017). SDG Goal 6: Ensure Access to Water and Sanitation for All. Available at: https://www.un.org/sustainabledevelopment/water-and-sanitation/(accessed September 14, 2019).

Un-Habitat (2018). *SDG Indicator 11.1.1 Training Module: Adequate Housing and Slum Upgrading*. United Nations Human Settlement Programme (UN-Habitat).

Walther, D. (2016). *Introducing City Sanitation Plan - SNUSP II - Practitioner's Manual*. New Delhi, India: GIZ.

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frontiers in Environmental Science

ORIGINAL RESEARCH
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Container-Based Sanitation Services and Attrition: An Examination of Drivers and Implications

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Haiti is far from achieving the UN goal of sanitation access for all; 20% of the population has no sanitation access, and less than 0.1% of the country's excreta is safely managed. Container-Based Sanitation (CBS) may be key to achieving timely and equitable sanitation coverage in Haiti's cities. CBS can provide immediate sanitation access without preexisting infrastructure, and where permanent infrastructure is impractical. Investor caution and policy barriers, however, presently limit the growth of CBS solutions. Globally, most CBS services are provided by private organizations like EkoLakay, which provides a portable toilet and weekly excreta collection for a monthly fee. While the EkoLakay service is popular, attrition is high. This study examines the relationship between users and the service, and its role in improved sanitation accessibility. For this study, 633 active and former EkoLakay subscribers in Cap Haïtien were interviewed to reveal causes and implications of attrition. Households with active EkoLakay subscriptions are more likely than former subscribers to live in unauthorized informal residences and to lack energy or water infrastructure. A quarter of users unsubscribe voluntarily, after investing in permanent sanitation infrastructure. Over 30% of former users, however, reported unsubscribing due to economic challenges. Many involuntary terminations resulted in households losing access to private improved sanitation or reverting to open defecation, reducing progress toward global sustainability goals. Insights obtained contextualize the relationship between users and CBS services to inform public strategies for mitigating barriers to achieving universal safe sanitation.

Keywords: container-based sanitation, urban sanitation, non-sewered sanitation, citywide inclusive sanitation, safely managed sanitation, SDG6, sustainable sanitation, on-site sanitation

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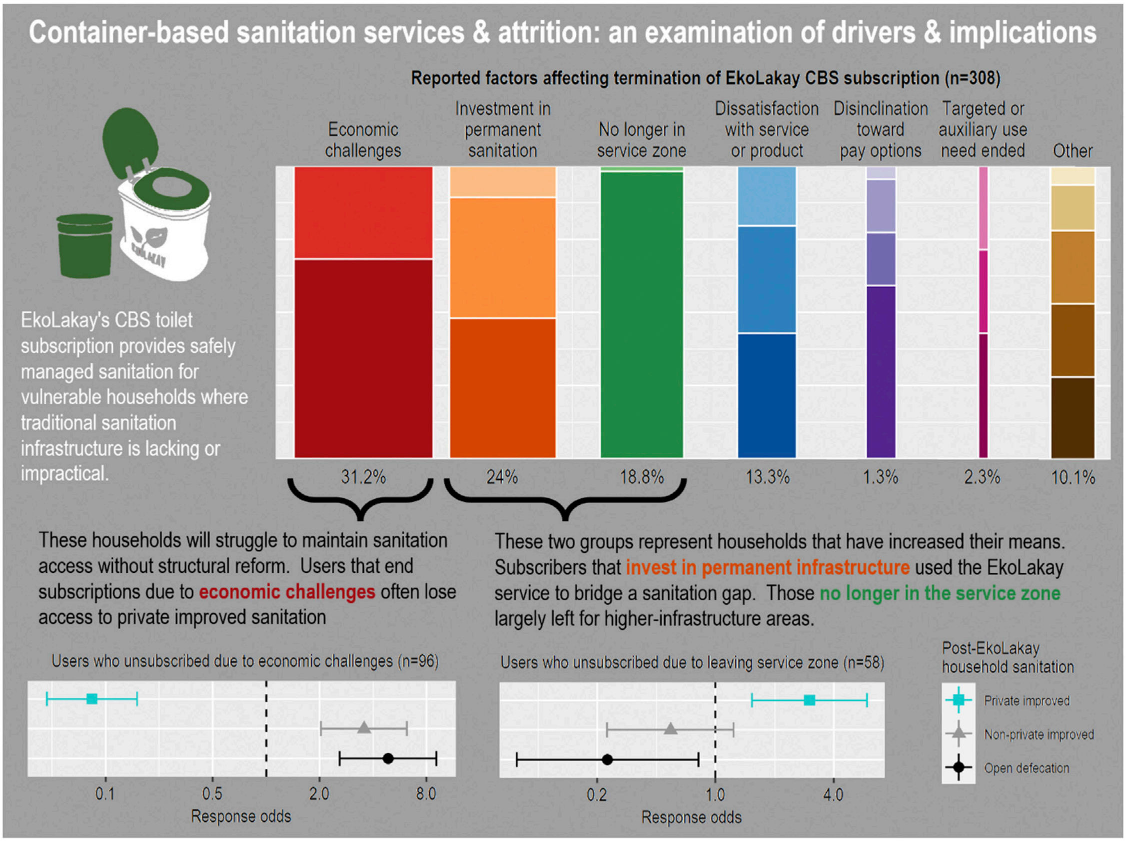
1 INTRODUCTION

In 2015, 10.4% of global citizens lacked access to basic sanitation, a daunting number given the United Nations' Sustainable Development Goal 6 (SDG 6) strives to eliminate open defecation and halve untreated wastewater by 2030 (WHO/UNICEF, 2017). The picture is especially grim in Haiti, where open defecation rates stood at 19.8% (World Bank, World Development Indicators, 2018a), and over 99% of the country's wastewater remained untreated as of 2017 (WHO Joint Monitoring Programme, 2017). A potential solution for making rapid progress on these goals exists in Container-Based Sanitation (CBS). CBS is a non-sewered sanitation strategy, through which excreta is captured



GRAPHICAL ABSTRACT |

in sealable containers and transported to semi-centralized[1] facilities for treatment, requiring limited in-home infrastructure. Since 2017, CBS technology has been recognized by the Joint Monitoring Programme as "improved sanitation" (WHO/UNICEF, 2017). To assess its future viability in Haiti and potentially other regions of the world facing similar sanitation needs, and to optimize service delivery, it is vital to better understand the factors affecting use of CBS services, the relationship between users and the service, and its role in improved sanitation accessibility. To address this critical need, this study utilizes interviews with 633 active and former CBS service users in Haiti.

As of 2018, two-thirds of Haiti's urban population lived in impoverished unplanned communities (World Bank, World Development Indicators, 2018b). Haiti ranks among the lowest twenty countries globally for urban sanitation coverage; except for a small number of local projects, all other forms of improved sanitation in the country only meet "basic" standards; from latrines to piped, water-based sanitation, excreta is ultimately released untreated into the environment (World Bank, World Development Indicators, 2012). In 2017, diarrhoeal disease was the fifth leading contributor to loss of life in Haiti, at a rate of 20.5 years of life lost (YLL) for every 1,000 people in the country (Fene et al., 2020). About half of the diarrhoeal disease burden in Haiti is attributable to inadequate excreta management (WHO, 2018).

One of Haiti's only safely managed sanitation options is EkoLakay, a privately run CBS service (Russel et al., 2019). The CBS model is uniquely suited to provide sanitation access in rapidly urbanizing informal settlements like those found in Haiti. In such environments, disputed land rights, low-income levels, inadequate infrastructure, and/or vulnerable environmental conditions combine to make forms of sanitation such as traditional sewage or latrines unattainable and risky, from environmental and economic perspectives (Tilmans et al., 2015). CBS allows users to seal excreta in containers during flooding; it is waterless, and the toilet itself is space-efficient and portable (Russel et al., 2019). CBS can be quickly deployed as an immediate intervention to the sanitation crisis, and can serve as either a transitional or long-term solution for urban households.

While CBS has identifiable advantages over traditional sanitation systems, it also has unique vulnerabilities. CBS service delivery can be interrupted by disruptions in transportation infrastructure, worker strikes, or pandemics (Saul and Gebauer, 2018; Mackinnon et al., 2019; Russel et al.,

[1]Semi-centralized facilities treat the products of sub-city populations; they are defined by scale, and definitions vary from tens to thousands of households.

2019; World Bank, 2019; Ferguson et al., 2021). CBS technologies also require greater user engagement than more traditional sanitation technologies. Perhaps the most significant barrier to CBS expansion, however, is policy and/or regulatory environments established without consideration of the characteristics, abilities, and needs of this unique sanitation service model (Mara, 2018; UNICEF and WHO, 2020). Examples range from direct obstacles to excreta reuse, to ambiguity caused by policy language based on the assumption of centralized infrastructure. Furthermore, while CBS has lower life-cycle costs than traditional sanitation infrastructure (EY, 2020), it does not yet benefit from public subsidization (Remington et al., 2018).

The EkoLakay CBS service, operated by Haitian non-governmental organization SOIL (Sustainable Organic Integrated Livelihoods), provides subscribers with a urine-diverting toilet and weekly container collection. The monthly service fee is 200–300 HTG (Haitian gourdes); the equivalent of 2.11–3.15 USD as of August 2019 (details of pricing structure in **Supplementary Table S1**). The EkoLakay toilet (**Supplementary Figure S1**) houses a sealable five-gallon container that receives solid excreta and a one-gallon jug that receives liquid waste through a urine diverter. During the weekly exchange of full excreta containers for sanitized containers, EkoLakay provides dry carbon-based cover material for covering the fecal matter after each defecation. Users manually dispose of urine (which has a minimal pathogen load in comparison to feces) (Bischel et al., 2019) primarily through infiltration into the ground, reducing the volume and weight of excreta to be transported and treated. EkoLakay transports the sealed excreta containers to a treatment site where trained staff, equipped with personal protective equipment, thermophilically compost the material for local sale (Preneta et al., 2013).

Despite their many advantages, CBS services can be subject to high attrition rates. Such patterns can lead to hesitantancy among decision-makers to subsidize or fund widespread adoption of CBS services. EkoLakay provides CBS service to twelve neighborhoods around Cap Haïtien, all of which are flood-prone, dense, urban or peri-urban, and generally have comparably low sanitation coverage and income levels. Between August 2014 and August 2019, EkoLakay customers in this service area opened 2,331 contracts, 1,323 of which were eventually closed. Subscription durations ranged from 1 week to 5 years[2]. For the economically vulnerable households[3] that represent the bulk of the EkoLakay subscriber base (Russel et al., 2019), financial shocks, resource constraints, and housing instability may disrupt continuity of subscription (Alwang et al., 2001; Briguglio et al., 2009).

CBS is likely one of, if not the lowest-cost, most readily deployable means of extending sanitation coverage to resource-insecure and low-infrastructure communities (Sklar and Faustin, 2017; EY, 2020; Delaire et al., 2021), but among such households, even the subsidized cost of service may be prohibitive. The newly emerging Citywide Inclusive Sanitation (CWIS) framework is a response to such a challenge. CWIS posits that *all* urban residents suffer when *some* lack sanitation access; therefore, this framework prioritizes sanitation coverage for vulnerable residents as a tool for protecting community health. Through the lens of CWIS, urban sanitation coverage is best achieved through adaptive approaches, employing varied and context-appropriate technologies, incremental infrastructure development, and responsive pricing models. This framework proposes that the public health objectives of urban sanitation can only be achieved through a public service approach to the sanitation delivery (Schrecongost et al., 2020).

Analyzing the challenges and opportunities in achieving sustainable sanitation access requires a system-wide approach. In this study, problems are viewed in the context of a large, complex system involving multiple interconnected subsystems (Clayton and Radcliffe, 1996). For this research, we identify how household-level factors affect the ability of CBS to close the sanitation gap an urban Haitian community, allowing for the emergence of systemic-level variables to describe the larger context. .

Building on the study of a 2012 pilot project (Russel et al., 2015) and subsequent expansion of SOIL into Northern Haiti, this study seeks to gain insight into the causes of attrition from the EkoLakay CBS service and the implications of attrition for reaching 100% safely managed sanitation coverage. Toward this end, we ask four key research questions:

- What characteristics differentiate active and former EkoLakay subscriber households?
- Why do subscribers terminate their EkoLakay subscription?
- What household characteristics are associated with various reasons for terminating an EkoLakay subscription?
- Do household-level responses reflect larger systemic-level relationships, (e.g.,relationships between economic, social, ecological, governance, and technical systems)?
- How do former subscribers feel about their EkoLakay CBS experience?

The answers to these questions will provide insight into the challenge of access to safe and reliable sanitation in low-income urban contexts, and generate important knowledge for decisionmakers in the public sector. By contextualizing the relationship between users and CBS services, as well as potential systemic-level relationships, including those affected by the systems listed above, we can expand our understanding of the potential role of CBS as a component of an urban sanitation portfolio, as low-income countries strive for universal safe sanitation access.

2 METHODOLOGY

This study used a mixed methodology approach (Greene, 2007), deriving qualitative and quantitative data from EkoLakay subscriber records and structured interviews with active and

[2]Subscriptions were terminated either by the subscriber voluntarily, or by the service provider after incurring 3 months of cumulative debt.

[3]The concept of economic vulnerability takes into account more than the static concept of poverty level by also looking forward at potential economic shocks and risks that could plunge a household into poverty.

TABLE 1 | Reported sanitation options available in metro Cap Haïtien, and correlative study response categorizations.

WHO Joint Monitoring Programme Categories			Options available in Cap Haïtien, Haiti	Study categories and responses
Improved sanitation	**Private improved sanitation**	Safely managed facilities	• EkoLakay CBS service	• Private flush toilet • Private latrine • Private dry toilet
		Basic facilities	• Private latrine, flush, or dry toilet (no treatment after discharge)	
	Non-private improved sanitation	Limited facilities	• Shared or public latrine, flush, or dry toilet (no treatment after discharge)	• Public or shared flush toilet, latrine, or dry toilet • Improved sanitation at home of neighbor or family member • Improved sanitation at church, school, or work
Unimproved sanitation		Unimproved facilities	• Shallow pit • Pit with no slab	• No access to a toilet • "In a hole" • "In a bag" • "By the river"
Open defecation		No facilities	• In a bag • In a field • By the river	

Detailed WHO sanitation category definitions provided in ***Supplementary Table S2.***

former subscribers of the EkoLakay CBS service in Cap Haïtien, Haiti. Interview questions addressed respondents' experiences with EkoLakay, motivations for terminating their subscription, and post-EkoLakay household sanitation, where relevant. In addition, self-reported data on household demographics, household income, infrastructure, expenses, and property were collected (details in supplemental materials).

2.1 Research Team and Research Instrument Development

Fourteen field team staff were hired from the Cap Haïtien region, reflecting a range of neighborhoods and socioeconomic backgrounds. The field team participated in an intensive 4-week training period facilitated by an investigator, project manager, and local translator/guide. The field team trained in research ethics and survey/interview best-practices while collaboratively refining and validating the survey instrument. Interview questions were structured around self-reported results whether by telephone or in-person, to ensure consistency regardless of interview format. Field team members then recruited respondents and served as interviewers. The result of this process was an optimized research tool, deeply informed by local cultural expertise, as well as skilled interviewers with an intimate understanding of the response coding protocols for our interview guide. All training and tool-development was conducted in Haitian Kreyol.

2.2 Sample Selection, Response Rate, Confidence

SOIL provided lists of former and active EkoLakay subscribers for whom telephone contact information was available. To ensure that active subscribers would have sufficient experience with EkoLakay to describe their satisfaction (i.e., three financial transactions and twelve collection events), we filtered out newly enrolled subscribers with less than 3 months' exposure to the service. Households of SOIL employees were also eliminated. The total number of potential participants meeting the criteria was 1,199 former and 733 active subscriber households.

We anonymized and randomized the lists of households. Research team staff recruited participants by phone, requesting an in-person appointment for an interview. Respondents who had moved away from the Cap Haïtien area, or were unwilling to meet in-person, were offered the opportunity to be interviewed by phone. We recruited one respondent to represent each household who had decision-making input and was 18 years or older.[4]

Due to high rates of inactive phone numbers, it was necessary to attempt contact with all active and former subscribers to achieve an adequate sample size. Recruiters attempted to reach respondents up to five times.[5] Of 733 potential active subscriber households, we contacted 383; nine declined to participate, 49 failed to schedule an interview, and we were unable to reach 358. We achieved an active-subscriber completion rate of 84.5%, for a sample of 44.3% (n = 325), a 95% confidence level and 4% margin of error. Of 1,199 potential former subscribers, we successfully contacted 407; 30 declined to participate, and 68 failed to schedule or complete an interview. We achieved a former-subscriber completion rate of 75.9%, for a sample of 25.8% (n = 309), a 95% confidence level and 5% margin of error. Sample sizes vary by analysis because respondents could decline to answer any prompt.

2.3 Data Collection and Analysis

Interviewers visited households and collected survey responses using Qualtrics® (XM, 2019) on a handheld smartphone. For the first month, 347 household interviews were completed both in-person and

[4]SOIL's experience in these communities has found household structures rarely recognize a single "head of household"; they are more likely to have multiple adult members engage in financial decision-making.

[5]As answering services are uncommon, telephone numbers are often reassigned to new users, and returning calls would place the expense burden on the recipient, recruiters did not leave messages for respondents who did not answer the phone.

TABLE 2 | Subscriber status, by household characteristics.

	Sample odds ratio (95% CI); *p*-value	
By count of selected amenities in home (*n* = 626)		
	Former subscribers (*n* = 303)	Active subscribers (*n* = 323)
0 amenities (*n* = 333)	0.51 (0.37–0.70)‡ p = 3.85e-05***	1.97 (1.43–2.71)‡ p = 3.85e-05***
1 amenity (*n* = 155)	1.27 (0.88–1.83)‡ p = 0.230	0.79 (0.55–1.13)‡ p = 0.230
2 + amenities (*n* = 138)	2.07 (1.40–3.04)‡ p = 3.08e-04***	0.48 (0.33–0.71)‡ p = 3.08e-04***
By presence of children under 5 years in home (*n* = 624)		
	Former subscribers (*n* = 302)	Active subscribers (*n* = 322)
No children under 5 years in home (*n* = 170)	0.69 (0.48–0.99)‡ p = 0.053	1.44 (1.01–2.06)‡ p = 0.053
Children under 5 years in home (*n* = 454)	1.44 (1.01–2.06)‡ p = 0.053	0.69 (0.48–0.99)‡ p = 0.053

Dark gray field indicates a response occurring more frequently than would occur in a random distribution.
Light gray field indicates a response occurring less frequently than would occur in a random distribution.
**= significant at 0.05 level.*
***= significant at 0.01 level.*
****= significant at 0.001 level.*
‡p-value is the result of Pearson's chi-square test between the sample and all other respondent-response combinations (1 df).
Selected amenities were self-reported by respondent, from list including: Drilled or Hand-dug well; Generator; Indoor shower; Inverter; Solar panels; Water cistern on house.

over the phone. Due to significant transportation and energy disruption countrywide, the second month of surveys was administered exclusively by telephone for a total of 633 interviews.[6] Interviews consisted of closed-ended questions regarding household demographics, home infrastructure, and subscription payment method; and open-ended questions regarding present household sanitation, perceptions of the EkoLakay service, and factors affecting subscription termination. These open ended questions focused on household-level factors, but allowed for potential systemic-level concerns to arise.

Former subscriber respondents were asked *What were your main reasons for leaving EkoLakay*? They were not prompted or offered potential responses or categories. Interviewers limited participant responses to three "reasons". Many respondents described more than one reason; therefore, total responses exceed total respondent count. Responses to open-ended questions were categorized in the field by the interviewer, using predefined codes. Interviewers summarized responses that did not fit the available codes, and investigators later categorized these summaries. In some cases, new categories were necessary to house these responses.

Interviewers coded respondents' descriptions of their household sanitation, using a detailed list. After all data had been collected, investigators further aggregated codes into qualitative categories. Reports of household sanitation were organized into categories associated with the WHO Sanitation Ladder (**Table 1**), and through an iterative process of team-based coding (Tolley et al., 2016), investigators created thematic categories to describe reported factors affecting an EkoLakay subscription termination (these themes are fully explored in **section 3.2**).

Additional closed-ended questions used a Likert-style scale to ascertain subscriber perspectives on the EkoLakay experience. These included, *Would you want to subscribe to the EkoLakay service again?*, and *Would you recommend EkoLakay to a friend or neighbor?*

Characteristics of active and former subscriber households were compared to identify parameters associated with retention or attrition. Household characteristics were also analyzed for associations with reported attrition factor themes. Comparisons were based on odds ratio analysis, performed using chi-square and Fisher's exact tests. Relevant contextual factors associated with systemic-level variables were identified through emergent themes in open-ended responses (**Supplementary Table S3**).

3 RESULTS

3.1 Household Characteristics Associated With Attrition and Retention

We examined multiple household variables for potential association with attrition and retention of the EkoLakay service and found associations between subscriber status (active vs. former) and two household characteristics: household amenities count, and presence of children under the age of five in the home.[7] Selected amenities were self-reported by the respondent from list including: Drilled well; Hand-dug well; Generator; Indoor shower; Inverter; Solar

[6]After data collection, responses to one open- and three closed-ended questions were analyzed to ensure that this transition did not skew the results (analyses available in supplemental materials). Results did not yield significant differences between groups; therefore, all data were included in analyses.

[7]Non-inferential findings are available in supplemental materials.

TABLE 3 | Reported factors affecting decision to terminate EkoLakay subscription (*n* = 308).

Themes; specific reasons	Respondent count	% within theme	% of all respondents
Economic challenges	**96**	—	**31.2**
Negative external factors	35	36.5	11.4
Affordability/economic accessibility	75	78.1	24.4
Investment in permanent infrastructure	**74**	—	**24.0**
Repaired existing sanitation option	8	10.8	2.6
Dug a latrine	31	41.9	10.1
Installed flush toilet	36	48.6	11.7
Access to service zone	**58**	—	**18.8**
EkoLakay left the neighborhood	1	1.7	0.3
Subscriber no longer in EkoLakay service zone	57	98.3	18.5
Dissatisfaction with aspects of service or product	**34**	—	**11.0**
Dissatisfaction with aspects of cover material	10	29.4	3.2
Dissatisfaction with aspects of service provision	11	32.4	3.6
Dissatisfaction with aspects of toilet	21	61.8	6.8
Disinclination toward/accessibility of payment options	**21**	—	**6.8**
Don't want to use mobile payment	1	4.8	0.3
Payment options	4	19.0	1.3
Unable to reach payment collector	4	19.0	1.3
Difficulty with monthly payment schedule	13	61.9	4.2
Targeted or auxiliary use need ended	**7**	—	**2.3**
Renters left	2	28.6	0.6
Semipublic use location (church, school, or business) moved or closed	2	28.6	0.6
Illness abated or accessibility need ended	3	42.9	1.0
Other	**31**	—	**10.1**
Negative sentiments about CBS or excreta reuse	2	6.5	0.6
Irresponsible users or inability to control other users	5	16.1	1.6
Moved to new location	8	25.8	2.6
Economic means changed positively	8	25.8	2.6
Traveling or rarely at home	9	29.0	2.9
All respondents	**308**	—	—

Cumulative column sums may exceed total respondent count, as respondents could offer up to three 'reasons' for terminating subscription.

panels; and Water cistern on house. Active subscribers were more likely to report none of the selected household amenities in their home (OR = 0.51, CI = 0.37–0.70, $p < 0.001$) and less likely to report two or more amenities (OR = 2.07, CI = 1.40-3.04, $p < 0.001$) (**Table 2**). Active subscriber households are more likely to have children under the age of five in the home (OR = 1.44, CI = 1.01–2.06, $p = 0.05$) [8] Household and respondent characteristics with no relationship to attrition or retention are listed in **Supplementary Table S4**.

3.2 Self-Reported Factors Affecting Termination of EkoLakay Subscriptions; Major Themes

From respondents' self-described reasons, seven major themes emerged to describe factors affecting the termination of an EkoLakay subscription. The two prevailing themes include *economic challenges* (*n* = 96; 31.2% of former-subscriber respondents), and *investments in permanent sanitation infrastructure* (*n* = 74; 24.0%). These are followed by: loss of *access to the service zone* (moving away from an EkoLakay service zone or EkoLakay ceasing service in the area[9]) (*n* = 58; 18.8%), *dissatisfaction with aspects of the EkoLakay service or technology* (*n* = 34; 11.0%), *disinclination toward or accessibility of payment options* (*n* = 21; 6.8%), *cessation of a targeted or auxiliary purpose for the toilet* (*n* = 7; 2.3%), and other factors (*n* = 31; 10.1%) (**Table 3**). Further breakdown of specific responses within each category is provided in **Supplementary Table S5**.

3.2.1 Economic Challenges

Within the dominant theme of economic challenges as a reason for terminating a household EkoLakay subscription, responses fell into two sub-themes: general affordability or

[8]Note that the number of children in each household was reported as of the time of interview; it is likely that former subscribers reporting no children under five did have young children in their household at the time of their subscription to EkoLakay.

[9]EkoLakay ceased service to one neighborhood (Milo), which was located far from the processing facility and had insufficient subscriber numbers.

TABLE 4 | Reported factors affecting termination of EkoLakay subscription, by selected household characteristics.

	Odds ratio (95% CI); *p*-value		
By count of selected amenities in home at time of interview (*n* = 248)			
	0 amenities (*n* = 117)	1 amenity (*n* = 66)	2 + amenities (*n* = 65)
Economic challenges (*n* = 77)	2.65 (1.52–4.62)[‡] *p* = 8.18e-04***	0.57 (0.30–1.09)[‡] *p* = 0.121	0.46 (0.24–0.92)[‡] *p* = 0.037*
Investment in permanent infrastructure (*n* = 66)	0.77 (0.44–1.36)[‡] *p* = 0.448	0.84 (0.44–1.62)[‡] *p* = 0.729	1.62 (0.87–2.99)[‡] *p* = 0.170
No longer in EkoLakay service zone (*n* = 40)	0.48 (0.24–0.98)[‡] *p* = 0.063	1.06 (0.49–2.25)[‡] *p* = 1.000	2.16 (1.06–2.16)[‡] *p* = 0.049*
Dissatisfaction with aspects of service or product (*n* = 31)	0.78 (0.37–1.68)[‡] *p* = 0.665	1.37 (0.61–3.08)[‡] *p* = 0.587	0.98 (0.41–2.31)[§] *p* = 1.000
Disinclination toward/accessibility of payment options (*n* = 20)	0.35 (0.12–0.98)[§] *p* = 0.059	2.45 (0.97–6.22)[§] *p* = 0.065	1.23 (0.45–3.34)[§] *p* = 0.791
Targeted or auxiliary use need ended (*n* = 6)	1.12 (0.22–5.67)[§] *p* = 1.000	0.54 (0.06–4.75)[§] *p* = 1.000	1.42 (0.25–7.95)[§] *p* = 0.654

Samples include only respondents reporting characteristics of the home associated with their EkoLakay subscription
Amenities considered for this analysis include: generator, indoor shower, inverter, solar panels, water cistern on house, well

By presence of household member(s) with a disability or chronic illness (*n* = 301)		
	No disability or chronic illness in home (*n* = 186)	1 + members with disability or chronic illness in home (*n* = 115)
Economic challenges (*n* = 95)	0.90 (0.54–1.47)[‡] *p* = 0.759	1.12 (0.68–1.84)[‡] *p* = 0.759
Investment in permanent infrastructure (*n* = 74)	1.94 (1.09–3.46)[‡] *p* = 0.032*	0.51 (0.29–0.92)[‡] *p* = 0.032*
No longer in EkoLakay service zone (*n* = 55)	0.83 (0.46–0.83)[‡] *p* = 0.648	1.20 (0.66–2.18)[‡] *p* = 0.648
Favorable comparison to existing/other options (*n* = 34)	1.56 (0.71–3.38)[‡] *p* = 0.351	0.64 (0.30–1.40)[‡] *p* = 0.351
Disinclination toward/accessibility of payment options (*n* = 21)	0.28 (0.11–0.72)[§] *p* = 0.009**	3.54 (1.39–9.07)[§] *p* = 0.009**
Targeted or auxiliary use need ended (*n* = 7)	0.45 (0.10–2.07)[§] *p* = 0.434	2.20 (0.48–10.00)[§] *p* = 0.434

Disabilities reported for this analysis include: Arthritis, Bad back, Blindness or visual impairment, Chronic medical condition, Cognitive or mental health issues, Deaf, Missing a leg or foot, Mobility issues, Mute

By reported payment method (*n* = 302)			
	Cash only (*n* = 219)	Mobile payment (*n* = 100)	Subsidy (*n* = 3)
Economic challenges (*n* = 93)	1.72 (0.96–3.08)[‡] *p* = 0.091	1.01 (0.60–1.70)[‡] *p* = 1.000	16.20 (0.83–316.94)[§] *p* = 0.009**
Investment in permanent infrastructure (*n* = 74)	0.86 (0.48–1.54)[‡] *p* = 0.728	1.04 (0.60–1.82)[‡] *p* = 0.999	0.43 (0.02–8.47)[§] *p* = 0.575
No longer in EkoLakay service zone (*n* = 57)	0.44 (0.24–0.44)[‡] *p* = 0.010**	1.55 (0.85–2.82)[‡] *p* = 0.201	0.60 (0.03–11.83)[§] *p* = 1.000
Dissatisfaction with aspects of service or product (*n* = 34)	4.40 (1.31–14.80)[§] *p* = 0.008**	0.81 (0.37–1.76)[‡] *p* = 0.726	1.10 (0.06–21.74)[b] *p* = 1.000
Disinclination toward/accessibility of payment options (*n* = 21)	0.94 (0.35–2.52)[§] *p* = 1.000	2.32 (0.95–5.67)[§] *p* = 0.091	1.85 (0.09–37.00)[§] *p* = 1.000
Targeted or auxiliary use need ended (*n* = 7)	2.31 (0.27–19.48)[§] *p* = 0.678	0.79 (0.15–4.13)[§] *p* = 1.000	5.57 (0.26–117.71)[§] *p* = 1.000

Dark gray indicates response occurring significantly more frequently than would occur in a random distribution.
Light gray indicates response occurring significantly less frequently than would occur in a random distribution.
**= significant at 0.05 level.*
***= significant at 0.01 level.*
****= significant at 0.001 level.*
‡p-value is the result of Pearson's chi-square test between the sample and all other respondent-response combinations (1 df).
§p-value is the result of Fisher's exact test between the sample and all other respondent-response combinations (1 df).

economic accessibility (*n* = 75; 24.4% of former-subscriber respondents) and negative outside factors (*n* = 35; 11.4%) (**Table 3**).

Within the *affordability* sub-theme, common explanations included difficulty avoiding debt in the service (*n* = 37, 12.3%) or affording the cost (*n* = 35, 11.6%). Some respondents

TABLE 5 | Former subscribers' household sanitation upon leaving, by reported factors affecting subscription termination (n = 309).

	Odds ratio (95% CI); p-value		
	Open defecation (n = 56)	**Non-private improved sanitation (n = 75)**	**Private improved sanitation (n = 169)**
Economic challenges (n = 96)	4.66 (2.53–8.59)‡ p = 4.86e-07***	3.56 (2.06–6.15)‡ p = 6.00e-06***	0.11 (0.06–0.19)‡ p = 7.71e-16***
Investment in permanent infrastructure (n = 74)	0.26 (0.01–4.79)§ p = 0.343	0.09 (0.03–0.29)§ p = 1.42e-07***	46.76 (11.19–195.36)‡ p = 1.69e-15***
No longer in EkoLakay service zone (n = 61)	0.36 (0.14–0.36)§ p = 0.037*	0.57 (0.27–1.20)‡ p = 0.187	2.78 (1.44–5.35)‡ p = 0.003**
Dissatisfaction with aspects of service or product (n = 35)	1.65 (0.73–3.77)§ p = 0.245	2.32 (1.11–4.86)‡ p = 0.039*	0.32 (0.15–0.68)‡ p = 0.004**
Disinclination toward/accessibility of payment options (n = 22)	1.69 (0.63–4.53)§ p = 0.271	0.64 (0.21–1.95)§ p = 0.611	0.90 (0.38–2.16)‡ p = 0.993
Targeted or auxiliary use need ended (n = 7)	0.38 (0.02–6.98)§ p = 0.598	0.26 (0.01–4.79)§ p = 0.343	8.59 (0.47–156.83)§ p = 0.039*

Dark gray indicates response occurring significantly more frequently than would occur in a random distribution.
Light gray indicates response occurring significantly less frequently than would occur in a random distribution.
**= significant at 0.05 level.*
***= significant at 0.01 level.*
****= significant at 0.001 level.*
‡p-value is the result of Pearson's chi-square test between the sample and all other respondent-response combinations (1 df).
§p-value is the result of Fisher's exact test between the sample and all other respondent-response combinations (1 df).

TABLE 6 | Former subscriber responses to "Would you want to join the EkoLakay service again?", by household sanitation status at time of interview (n = 299).

	Sample odds ratio (95% CI); p-value		
	Open defecation (n = 47)	**Non-private improved sanitation (n = 72)**	**Private improved sanitation (n = 184)**
Yes (n = 117)	3.00 (1.58–5.71)‡ p = 9.98e-04***	1.80 (1.05–3.08)‡ p = 0.042*	0.36 (0.22–0.59)‡ p = 5.85e-05***
I don't know (n = 59)	1.30 (0.62–1.30)‡ p = 0.625	1.09 (0.57–2.11)‡ p = 0.921	0.75 (0.42–1.33)‡ p = 0.402
No (n = 123)	0.21 (0.09–0.21)‡ p = 1.33e-04***	0.50 (0.28–0.89)‡ p = 0.026*	3.56 (2.12–5.98)‡ p = 1.71e-06***

Dark gray field indicates a response occurring more frequently than would occur in a random distribution.
Light gray field indicates a response occurring less frequently than would occur in a random distribution.
**= significant at 0.05 level.*
***= significant at 0.01 level.*
****= significant at 0.001 level.*
‡p-values are the result of Pearson's chi-square test between the sample and all other respondent-response combinations (1 df).
Row and column counts may exceed respondent count, as respondents could report multiple household sanitation options.

expressed a perception that the service "costs too much" (n = 7; 2.3%).[10]

Negative outside factors described by respondents included a change in economic means; reports that cost of living had increased; and difficulty due to sudden or large expenses. Many respondents expressed multiple concerns within the "economic challenges" theme.

Respondents reporting none of the selected amenities in their home at the time of interview were more likely than the average household to report having terminated their subscription over economic challenges (OR = 2.65, CI = 1.52-4.62, p < 0.001), and those with two or more amenities were less likely to mention this theme (OR = 2.16, CI = 1.06–2.16, p = 0.049) (**Table 4**).

Respondents reporting that the cost of their EkoLakay subscription was covered by a subsidy were more likely than the average household to report ending their subscription due to economic challenges (OR = 16.20, CI = 0.83–316.94, p = 0.009) (**Table 4**). Every respondent representing a household formerly covered by subsidy indicated that withdrawal of the subsidy caused them to lose access to the EkoLakay CBS service.

Respondents who attributed their subscription termination to economic challenges were highly likely to transition to open defecation after losing access to EkoLakay (OR = 4.66, CI = 2.53–8.59, p < 0.001) (**Table 5**).

[10]Respondents were not asked to compare EkoLakay specifically to alternative services.

TABLE 7 | Interest in re-subscribing to EkoLakay, by factors affecting subscription termination.

	Odds ratio (95% CI); *p*-value		
	"Would you want to join the EkoLakay service again?"		
	Yes (*n* = 121)	I don't know (*n* = 59)	No (*n* = 182)
Economic challenges (*n* = 95)	2.44 (1.48–4.00)‡ *p* = 5.99e-04***	0.78 (0.41–1.46)‡ *p* = 0.532	0.41 (0.25–0.67)‡ *p* = 5.99e-04***
Investment in permanent infrastructure (*n* = 73)	0.33 (0.18–0.62)‡ *p* = 3.25e-04***	0.51 (0.24–1.09)‡ *p* = 0.090	2.99 (1.62–5.52)‡ *p* = 3.25e-04***
Access to service zone (*n* = 57)	0.64 (0.35–1.18)‡ *p* = 0.178	1.84 (0.95–3.58)‡ *p* = 0.093	1.56 (0.85–1.56)‡ *p* = 0.178
Dissatisfaction with aspects of service or product (*n* = 34)	1.06 (0.51–2.19)‡ *p* = 1.000	1.58 (0.69–3.59)e *p* = 0.260	0.94 (0.46–1.95)‡ *p* = 1.000
Disinclination toward/accessibility of payment options (*n* = 21)	1.40 (0.58–3.41)‡ *p* = 0.493	1.32 (0.46–3.76)e *p* = 0.573	0.71 (0.29–1.74)‡ *p* = 0.493
Targeted or auxiliary use need ended (*n* = 7)	3.88 (0.74–20.33)e *p* = 0.120	0.68 (0.08–5.79)e *p* = 1.000	0.26 (0.05–1.35)e *p* = 0.120

Dark gray indicates response occurring significantly more frequently than would occur in a random distribution.
Light gray indicates response occurring significantly less frequently than would occur in a random distribution.
**= significant at 0.05 level.*
***= significant at 0.01 level.*
****= significant at 0.001 level.*
‡*p-value is the result of Pearson's chi-square test between the sample and all other respondent-response combinations (1 df).*
[e]*p-value is the result of Fisher's exact test between the sample and all other respondent-response combinations (1 df).*

3.2.2 Investment in Permanent Sanitation Infrastructure

Among subscribers who reported that they left the EkoLakay service because they installed or repaired permanent sanitation infrastructure in their home, 36 (11.7%) reported installing a flush toilet, 31 (10.1%) installed a latrine, and 8 (2.6%) reported repairing or servicing their preexisting sanitation infrastructure (including emptying a full pit latrine) (**Table 3**).

3.2.3 No Longer in EkoLakay Service Zone

Most respondents who reported no longer living in an EkoLakay service zone reported having moved to a neighborhood outside of the EkoLakay service area ($n = 57$; 18.5%) (**Table 3**).

Respondents reporting two or more amenities in the home were more likely than the average respondent to mention losing access to an EkoLakay service zone (OR = 2.16, CI = 1.06-2.16, $p = 0.049$) (**Table 4**).

3.2.4 Dissatisfaction With Aspects of EkoLakay Service or Product

Former subscribers who cited dissatisfaction among their reasons for leaving EkoLakay offered critiques of the physical toilet technology ($n = 21$; 6.8%), customer service or service provision ($n = 11$; 3.6%), and characteristics of the cover material ($n = 10$; 3.2%) (**Table 3**). Some respondents expressed multiple themes within this category.

3.2.5 Disinclination Toward or Difficulty Accessing Payment Options

Among reports of disinclination toward or difficulty accessing payment options, most expressed difficulty with the monthly payment schedule ($n = 13$; 4.2%). Others reported difficulty reaching a payment collector, dissatisfaction with the payment options in general, and disinclination toward mobile payment specifically (**Table 3**).

Respondents indicating the presence of a household member with a disability or chronic illness were more likely than other household representatives to cite disinclination toward or accessibility of EkoLakay's payment options as a reason for leaving EkoLakay (OR = 3.54, CI = 1.39–9.07, $p = 0.009$) (**Table 4**).

3.2.6 Targeted or Auxiliary Use Need Ended

Six subscribers reported that they terminated their EkoLakay service because they had used it to meet a targeted or auxiliary purpose, and that need had ended. These reports included the abatement of an illness or cessation of an accessibility need (including the death of a mobility-challenged household member); departure of renters for whom they had supplied the EkoLakay toilet; and closing of a semipublic location (such as a church or business) at which they had used EkoLakay.

3.2.7 Other Reported Reasons for Terminating an EkoLakay Subscription

Other factors reported among respondents' reasons for leaving the service included travel or time away from the home; positive changes in economic means; moving to a home with preexisting sanitation infrastructure; inability to control other users of the toilet (from within and/or outside the home); and negative sentiments about transformation or treatment of excreta, or the use of CBS (**Table 3**).

3.2.8 Systemic-Level Contextual Factors

Consistent with the intent to consider relationships between interacting systems, we identified the presence of variables indicating the influence of systemic-level contextual factors on the accessibility and suitability of the EkoLakay CBS system for respondents. Responses included reference to economic, social, governance, technical, and ecological systems, with multiple overlapping responses (**Supplementary Table S3**).

3.3 Subscriber Retention

3.3.1 Interest in Re-subscribing

Nearly 40% of former subscribers ($n = 118$) indicated that they would be interested in subscribing to EkoLakay again. Respondents whose households practiced open defecation at the time of interview were more likely than the average respondent to express interest in re-subscribing to EkoLakay (OR = 3.00, CI = 1.58–5.71, $p = 0.001$), as were those using non-private sanitation (OR = 1.80, CI = 1.05–3.08, $p = 0.042$). Households with private improved sanitation at the time of interview were more likely to express disinterest in re-subscribing (OR = 3.56, CI = 2.12–5.98, $p < 0.001$) (**Table 6**).

Respondents who reported economic challenges among the reasons for terminating their EkoLakay subscription were highly likely to be interested in re-subscribing to the service (OR = 2.44, CI = 1.48–4.00, $p < 0.001$). Households that left due to having installed permanent sanitation infrastructure were likely to be uninterested in re-subscribing (OR = 2.99, CI = 1.62–5.52, $p < 0.001$) (**Table 7**).

3.3.2 Willingness to Recommend EkoLakay

Over 94% of respondents reported that they would recommend EkoLakay to a friend or neighbor (**Supplementary Table S6**). Willingness to recommend was even expressed by some of the 16% of respondents who mentioned dissatisfaction with aspects of the EkoLakay service or technology among factors affecting their subscription termination. Willingness to recommend was not related to subscriber status or interest in re-subscribing (**Supplementary Table S7**).

4 DISCUSSION

Using selected household amenities as a proxy for household economic capacity, it appears that odds of having ended a household EkoLakay subscription increase as economic capacity increases. This relationship illustrates the important role EkoLakay serves in providing sanitation access for households experiencing extreme resource-insecurity; i.e., lacking basic water and electrical infrastructure.

While resource scarcity is associated with subscription retention, we can also see that many resource-strained households struggle to afford even the lowest price of the service, or to keep up with the monthly payment schedule. Inconsistent employment incomes, unexpected expenses, or withdrawal of subsidy can tip this balance, causing a household to lose access to the CBS service. Though the EkoLakay service model includes a buffer period for missed payments, [11] service is eventually terminated when subscribers have not paid down their debt within 3 months. Whether a subscription was terminated by EkoLakay due to debt, or preemptively by a subscriber experiencing economic challenges, many of these departures can be inferred to be involuntary. This inference is corroborated by the finding in **section 3.3.1**, that interest in re-subscribing to EkoLakay is strongly associated with having cited economic challenges among reasons for subscription termination. Furthermore, reports of difficulty affording EkoLakay's monthly fee were significantly more common than statements indicating that the cost of the service is too high. This differentiation is meaningful: the former responses frame the economic barrier as a lack of household means, while the latter suggests that the perceived value of the service is insufficient to warrant its price tag. The distribution of these responses illustrates broad recognition of EkoLakay's value regardless of ability to afford the service.

Households reverting to open defecation after losing access to EkoLakay represent the most vulnerable group in terms of sanitation access. The role of economic barriers in involuntary attrition suggests that realizing the potential public health gains of CBS may require economic assistance for resource-strained households. Subsidization of sanitation access for economically insecure households is a strategic component of the CWIS approach. Recent research indicates that the cost of supporting households with subsidized access to the EkoLakay CBS service would be comparably low relative to alternative public sanitation infrastructure investments (EY, 2020), and therefore well warranted from a public health perspective.

Collectively, respondents who reported having invested in permanent sanitation infrastructure or no longer living an EkoLakay service zone represent a quarter of all former subscribers. The association between higher household amenities count and likelihood of moving out of an EkoLakay-serviced neighborhood imply that such movement is associated with advancement in means rather than poverty-related instability. For these users, EkoLakay's CBS service met immediate sanitation needs while the household amassed the resources to obtain or repair permanent sanitation infrastructure. Together with the subscribers who attributed their departure to an improvement in economic means (**section 3.2.7**), it appears that while one third of attrition is attributable to economic vulnerability, another third is associated with advancement.

Some complaints about the EkoLakay toilet technology give insight into vulnerabilities of a CBS system like EkoLakay. Traditional improved sanitation technologies require little familiarity or user effort to function effectively. Container-based systems, however, require application of cover material, exchange of collection receptacles, and in the case of EkoLakay model, regular emptying of a urine collection jug. Only one respondent cited dissatisfaction with this effort as a reason for leaving. Multiple respondents, however, were driven to leave the service because they could not control the behavior of other toilet users. While regular users of the CBS system can be trained in the basic maintenance of these components, non-household users, or users less committed to stewarding the system, may misuse it,

[11] At the time of the study, container exchange would be suspended after two missed payments, but the toilet would not be reclaimed.

causing malfunction. As CBS service providers have refined their product, this unique challenge has shaped service models. User responsibility is a key challenge for management of public and multifamily CBS toilets in Haiti, and this is a main reason that SOIL transitioned to the EkoLakay household-level service model from previously providing public toilets. Providing CBS services at the household level reduces challenges associated with untrained users, which can occur in public settings; in low-resource environments, however, household structure and lack of property barriers limit control over potential users of the toilet.

Along a similar vein, some respondents ended their subscription for lack of a reasonable place to keep the toilet. A CBS toilet has the advantage of being small and mobile, but EkoLakay does not provide a superstructure to protect it from weather if users prefer to place it outdoors. Subscriber households must provide some form of protection for the toilet if they want to use or store it outside of the home. Some EkoLakay users have a household density of up to 11 persons per room; for such households, indoor space is particularly limited. Such a challenge is likely to characterize many CBS services, and may be a topic of focus for future service model research and development.

Reports of difficulty with payment methods imply that aspects of a CBS business model, other than price alone, may affect accessibility of the service. EkoLakay ceased offering door-to-door payment collection to incoming subscribers in 2018 (and raised the price of door-to-door payment for existing subscribers to incentivise the shift to a more efficient system) (Saul and Gebauer, 2018), so for many users, cash payment now requires a visit to an EkoLakay depot or office. Households reporting disabled members were the only respondents to cite unwillingness to use mobile payment or difficulty reaching a payment collector among reasons for ending their subscription. The use of mobile payment apps requires one to deposit cash at a payment agent, and these facilities are sparser in low-income, low-infrastructure neighborhoods, making mobile payment less accessible to EkoLakay customers in such neighborhoods. Furthermore, use of mobile cash apps requires basic literacy, and therefore this money management tool is not accessible to some highly vulnerable members of a community. Our findings imply that pricing differences favoring mobile payment may place a burden on mobility-challenged subscribers and households in the distant peri-urban environment with a limited transportation budget. This burden could be ameliorated through a context-responive payment model, either through the service provider or as part of public sector-supported service delivery.

Reported interest in re-subscribing to EkoLakay, as related to post-subscription household sanitation, paints a picture of a bimodal user base; with progress from open defecation to private improved sanitation, former subscribers express reduced interest in re-subscribing to EkoLakay. It appears most subscribers either used EkoLakay to meet their household needs while saving to access desired permanent sanitation infrastructure, or they exist in a state of extreme resource scarcity, with marginal resources and scant access to sanitation alternatives. The latter group will require public support in order for Haiti to achieve sanitation coverage in urban communities.

The EkoLakay service is perceived positively by most users, whether it be for its inherent value or its usefulness at a specific stage in a household's development, which fits with a growing body of literature (O'Keefe et al., 2015; Nyoka et al., 2017; Tidwell et al., 2020). Respondents who report willingness to recommend EkoLakay include many who left the service voluntarily. Former subscribers with private improved sanitation in their home express high likelihood of recommending EkoLakay, despite low interest in re-subscribing. This indicates that, while some may favor permanent infrastructure, former EkoLakay users are satisfied with the role that CBS played in a past period of their household history.

5 CONCLUSION

Given the low national sanitation coverage (62% improved access in 2017), and rapid urban population growth (3% annual increase), the Haitian public health sector will likely need to prioritize interventions that can increase urban sanitation coverage rapidly (The World BankWorld Development Indicators, 2019). Considering urban Haiti's land tenure ambiguities, household poverty, high risk of flooding, and other geologic vulnerabilities, the traditional large-infrastructure approach to achieving citywide sanitation coverage is untenable in the near-term and perhaps even inappropriate in the long-term (Spuhler and Lüthi, 2020; Öberg et al., 2020).

This research has generated insights into the potential of CBS to close the sanitation gap among resource-insecure households in environments like that of northern Haiti. Former subscribers from the 7 years of EkoLakay service provision, fall largely into two groups; those for whom the service met household needs until they amassed the resources to invest in desired permanent sanitation infrastructure, and those who gained private sanitation through the service but struggled to maintain access due to extreme economic insecurity. Both groups indicate a 94% willingness to recommend the service to others.

Widespread desire to re-subscribe among vulnerable households, and high willingness to recommend the EkoLakay service to others provide evidence that household-level CBS is a tool with positive recognition and great potential for meeting SDG six within the Cap Haïtien population. Our findings indicate, however, that the potential public health gains of the CBS service model cannot be realized without financial subsidies for many economically vulnerable target users. Citywide Inclusive Sanitation provides a framework including context-dependent elements, such as responsive pricing and public subsidies for extending services to the most vulnerable. Our findings provide evidence that for CBS to reach those who need it most, a public service approach may be essential (Schrecongost et al., 2020). Public-private partnerhips, as have become common in water supply and distribution, could begin to bridge this gap. The measurable outcomes of CBS services also make them a suitable candidate for results-based financing models (Howard and White, 2020).

In addition to measurable household characteristics, it is evident that multiple interacting systemic-level factors affect continuity of access to sanitation in urban Haiti. Governance structures define access to sanitation infrastructure across locales.

Public policy also interacts with technical resources, including transportation and communication infrastructures, which affect the quality and accessibility of CBS service. Social support networks affect backup options and resilience; social awareness drives desire to maintain sanitation access. Ecological and geological characteristics endanger users of sanitation technologies that cannot contain excreta. Further research is warranted to go beyond household level analysis to specifically ascertain information regarding systemic-level opportunities and barriers to CBS adoption.

The abovementioned interconnected sytems impact the appropriateness and accessibility of CBS for households. Integrating CBS into community-wide sanitation delivery models may be key to ensuring that all aspects of the social, cultural, and technological systems can interact effectively, thus allowing the benefits of this innovation to reach those who need it most. Furthermore, increasing the CBS user base in Haiti could further contribute to cost-effectiveness; a recent study of resource-oriented CBS services including EkoLakay suggests that increasing the scale of such operations would optimize efficiency and reduce the cost of service delivery (Moya et al., 2019). Thus, the insights provided in this study may help to inform policy strategies for increasing safely managed sanitation coverage across vulnerable communities in Haiti and comparable environments.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Oregon State University (IRB-2019-0284) University of Oregon (IRB 07102019.010) Government of Haiti (Rèf 1819-58). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

FV: Conceptualization, Methodology, Validation, Formal analysis, Data Curation, Writing—Original Draft, Writing - Review and Editing, Visualization. KCR: Conceptualization, Methodology, Supervision, Writing—Review and Editing. LAC: Supervision, Writing—Review and Editing. DT: Methodology, Supervision, Writing—Review and Editing. JL: Methodology, Supervision, Project administration, Writing—Review and Editing. EL: Conceptualization, Project administration, Writing—Review and Editing. SK: Conceptualization, Writing—Review and Editing, Funding acquisition.

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SUPPLEMENTARY MATERIAL

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REFERENCES

Alwang, J., Siegel, P. B., and Jorgensen, S. L. (2001). *Vulnerability : A View from Different Disciplines*. Washington, D.C.: The World Bank. Available at: https://ideas.repec.org/p/wbk/hdnspu/23304.html (Accessed November 29, 2021).

Bischel, H. N., Caduff, L., Schindelholz, S., Kohn, T., and Julian, T. R. (2019). Health Risks for Sanitation Service Workers Along a Container-Based Urine Collection System and Resource Recovery Value Chain. *Environ. Sci. Technol.* 53, 7055–7067. doi:10.1021/acs.est.9b01092

Briguglio, L., Cordina, G., Farrugia, N., and Vella, S. (2009). Economic Vulnerability and Resilience: Concepts and Measurements. *Oxford Development Stud.* 37, 229–247. doi:10.1080/13600810903089893

Clayton, T., and Radcliffe, N. (1996). *Sustainability : A Systems Approach*. Boulder CO: Westview Press. doi:10.4324/9781315070711

Delaire, C., Peletz, R., Haji, S., Kones, J., Samuel, E., Easthope-Frazer, A., et al. (2021). How Much Will Safe Sanitation for All Cost? Evidence from Five Cities. *Environ. Sci. Technol.* 55, 767–777. doi:10.1021/acs.est.0c06348

EY (2020). *How Cost Analysis Dispels Myths about Container-Based Sanitation*. London, UK: EY. Available at: https://www.ey.com/en_gl/corporate-responsibility/how-cost-analysis-dispels-myths-about-container-based-sanitation (Accessed November 25, 2020).

Fene, F., Ríos-Blancas, M. J., Lachaud, J., Razo, C., Lamadrid-Figueroa, H., Liu, M., et al. (2020). Life Expectancy, Death, and Disability in Haiti, 1990-2017: a Systematic Analysis from the Global Burden of Disease Study 2017. *Rev. Panam Salud Publica.* 44, 1. doi:10.26633/RPSP.2020.136

Ferguson, C., Mallory, A., Hutchings, P., Remington, C., Lloyd, E., Kiogora, D., et al. (2021). An Evaluation of Different Provision Strategies for Scaled-Up Container-Based Sanitation. *H2Open J.* 4, 216–230. doi:10.2166/h2oj.2021.112

Greene, J. C. (2007). *Mixed Methods in Social Inquiry*. San Francisco: Jossey-Bass.

Howard, G., and White, Z. (2020). Does Payment by Results Work? Lessons from a Multi-Country WASH Programme. *J. Water Sanitation Hyg. Development.* 10, 716–723. doi:10.2166/washdev.2020.039

Mackinnon, E., Campos, L. C., Parikh, P., and Sawant, N. (2019). Classifying Occupational Exposure Risks and Recommendations for Their Control in

Container-Based Sanitation Systems. *Waterlines.* 38, 170–196. doi:10.3362/1756-3488.18-00025

Mara, D. (2018). 'Top-down' Planning for Scalable Sustainable Sanitation in High-Density Low-Income Urban Areas: Is it More Appropriate Than 'bottom-Up' Planning? *J. Water Sanitation Hyg. Development.* 8, 165–175. doi:10.2166/washdev.2018.101

Moya, B., Sakrabani, R., and Parker, A. (2019). Realizing the Circular Economy for Sanitation: Assessing Enabling Conditions and Barriers to the Commercialization of Human Excreta Derived Fertilizer in Haiti and Kenya. *Sustainability.* 11, 3154. doi:10.3390/su11113154

Nyoka, R., Foote, A. D., Woods, E., Lokey, H., O'Reilly, C. E., Magumba, F., et al. (2017). Sanitation Practices and Perceptions in Kakuma Refugee Camp, Kenya: Comparing the Status Quo with a Novel Service-Based Approach. *PLoS One.* 12, e0180864. doi:10.1371/journal.pone.0180864

Öberg, G., Metson, G. S., Kuwayama, Y., and A. Conrad, S. S. (2020). Conventional Sewer Systems Are Too Time-Consuming, Costly and Inflexible to Meet the Challenges of the 21st Century. *Sustainability.* 12, 6518. doi:10.3390/su12166518

O'Keefe, M., Lüthi, C., Tumwebaze, I. K., and Tobias, R. (2015). Opportunities and Limits to Market-Driven Sanitation Services: Evidence from Urban Informal Settlements in East Africa. *Environ. Urbanization* 27, 421–440. doi:10.1177/0956247815581758

Preneta, N., Kramer, S., Magloire, B., and Noel, J. M. (2013). Thermophilic Co-Composting of Human Wastes in Haiti. *J. Water Sanitation Hyg. Development.* 3, 649–654. doi:10.2166/washdev.2013.145

Remington, C., Jean, L., Kramer, S., Boys, J., and Dorea, C. (2018). "Process Cost Analysis for the Optimization of a Container- Based Sanitation Service in Haiti," in *Transformation Towards Sustainable and Resilient Wash Services* (Kenya: Nakuru), 6.

Russel, K. C., Hughes, K., Roach, M., Auerbach, D., Foote, A., Kramer, S., et al. (2019). Taking Container-Based Sanitation to Scale: Opportunities and Challenges. *Front. Environ. Sci.* 7, 190. doi:10.3389/fenvs.2019.00190

Russel, K., Tilmans, S., Kramer, S., Sklar, R., Tillias, D., and Davis, J. (2015). User Perceptions of and Willingness to Pay for Household Container-Based Sanitation Services: Experience from Cap Haitien, Haiti. *Environ. Urbanization.* 27, 525–540. doi:10.1177/0956247815596522

Saul, C., and Gebauer, H. (2018). Digital Transformation as an Enabler for Advanced Services in the Sanitation Sector. *Sustainability.* 10, 752. doi:10.3390/su10030752

Schrecongost, A., Pedi, D., Rosenboom, J. W., Shrestha, R., and Ban, R. (2020). Citywide Inclusive Sanitation: A Public Service Approach for Reaching the Urban Sanitation SDGs. *Front. Environ. Sci.* 8, 19. doi:10.3389/fenvs.2020.00019

Sklar, R., and Faustin, C. (2017). *Pit Latrines or Container Based Toilets? A Cost-Benefit Analysis Comparing Two Approaches to Improving Sanitation Access in Urban Areas of Haïti*. Washington, D.C.: Copenhagen Consensus Center. Available at: https://www.pseau.org/outils/ouvrages/copenhagen_consensus_center_pit_latrines_or_container_based_toilets_a_cost_benefit_analysis_comparing_two_approaches_to_improving_sanitation_access_in_urban_areas_of_haiti_2017.pdf.

Spuhler, D., and Lüthi, C. (2020). Review of Frameworks and Tools for Urban Strategic Sanitation Planning: Considering Technology Innovations and Sustainability. *J. Water Sanitation Hyg. Development.* 10, 768–785. doi:10.2166/washdev.2020.062

The World Bank, World Development Indicators (2019). Urban Population Growth (Annual %) [Dataset]. Available at: https://data.worldbank.org/indicator/SP.URB.GROW?locations=HT (Accessed September 17, 2020).

Tidwell, J. B., Nyarko, K. B., Ross, I., Dwumfour-Asare, B., and Scott, P. (2020). *Evaluation of User Experiences for the Clean Team Ghana Container-Based Sanitation Service in Kumasi*. Ghana: medRxiv. doi:10.1101/2020.10.23.20218578

Tilmans, S., Russel, K., Sklar, R., Page, L., Kramer, S., and Davis, J. (2015). Container-based Sanitation: Assessing Costs and Effectiveness of Excreta Management in Cap Haitien, Haiti. *Environ. Urbanization.* 27, 89–104. doi:10.1177/0956247815572746

Tolley, E. E., Ulin, P. R., Mack, N., Robinson, E. T., and Succop, S. M. (2016). *Qualitative Methods in Public Health: A Field Guide for Applied Research*. Hoboken, United States: John Wiley & Sons. Incorporated Available at: http://ebookcentral.proquest.com/lib/principiacollege/detail.action?docID=4461564 (Accessed February 9, 2021).

UNICEF and WHO (2020). *State of the World's Sanitation: An Urgent Call to Transform Sanitation for Better Health, Environments, Economies and Societies*. New York, NY: United Nations Children's Fund (UNICEF) and the World Health Organization. Available at: https://www.unicef.org/reports/state-worlds-sanitation-2020 (Accessed May 17, 2021).

WHO (2018). Burden of Disease from Inadequate Sanitation in Low- and Middle-Income Countries [Dataset]. Available at: https://www.who.int/data/gho/data/themes/topics/indicator-groups/indicator-group-details/GHO/burden-of-disease-from-inadequate-sanitation-in-low–and-middle-income-countries (Accessed January 5, 2021).

WHO Joint Monitoring Programme (2017). Sanitation Service Levels [Dataset]. Available at: https://washdata.org/data/household#!/dashboard/new (Accessed March 30, 2020).

WHO/UNICEF (2017). *Progress on Drinking Water, Sanitation and Hygiene: 2017 Update and SDG Baselines*. Geneva: World Health Organization (WHO) and the United Nations Children's Fund (UNICEF): Available at: https://www.unicef.org/publications/index_96611.html (Accessed June 3, 2018).

World Bank (2019). *Evaluating the Potential of Container-Based Sanitation*. Washington DC: World Bank Group. Available at: https://openknowledge.worldbank.org/handle/10986/31292.

World Bank, World Development Indicators (2012). Poverty Headcount Ratio at $1.90 a Day (2011 PPP) (% of Population) [Dataset]. Available at: https://data.worldbank.org/topic/poverty?locations=HT (Accessed June 1, 2020).

World Bank, World Development Indicators (2018a). People Practicing Open Defecation (% of Population) [Dataset]. Available at: https://data.worldbank.org/indicator/SH.STA.ODFC.ZS (Accessed September 16, 2020).

World Bank, World Development Indicators (2018b). Population Living in Slums (% of Urban Population) [Dataset]. Available at: https://data.worldbank.org/topic/poverty?locations=HT (Accessed June 1, 2020).

XM (2019). *Qualtrics*. Provo, UT: Qualtrics. Available at: https://www.qualtrics.com.

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Assessment of Environmental and Social Effects of Rural Toilet Retrofitting on a Regional Scale in China

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In China, more than 47 million toilets in rural areas have been upgraded since the nationwide sanitation program, popularly referred to as the “toilet revolution,” was launched in 2015. However, little is currently known about the environmental risks of manure, or rural residents’ satisfaction. Here, we have selected 50 rural residents from 10 provinces and focused on two types of toilets to evaluate the environmental and social impacts of improving toilets in rural areas. The monitoring results showed that human excrement was mainly alkaline, and the concentrations of total nitrogen and phosphorus in the composting toilets ranged from 259.21 to 330.46 mg/kg and from 2.71 to 3.71 mg/kg, respectively, while their contents in septic tank effluents were generally 381.31–2040.84 mg/L and 10.41–80.46 mg/L, respectively. The pH and EC values exceeded the soil background value in individual regions, and the harmless effect of the two types of toilets did not fully meet the standard requirements, indicating that toilet manure, albeit possessed certain resource utilization potential, guard against the risk of pollution. Additionally, based on a fuzzy comprehensive evaluation model, it was found that the comprehensive evaluation score of Jiangsu Province is the highest, that of Gansu Province is the lowest, and the overall score is “high in the southeast and low in the northwest.” This study provides basic data and references for establishing a scientific and feasible evaluation system of rural toilet retrofitting and strengthens government guidance and training related to toilet retrofitting.

Keywords: toilet reform, harmless effect, manure utilization, comprehensive evaluation, physicochemical

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1 INTRODUCTION

In the process of rapid economic development and the continuous advancement of rural urbanization, the huge population and remote geographical location of rural areas have meant that they have long-term disadvantages in terms of infrastructure, science and technology, and development awareness, especially with regard to rural toilets, which are considered to be the most difficult to manage, and there is a lack of rural infrastructure in developing countries (Cheng et al., 2018; Li et al., 2021). Non-hygienic toilets, such as open toilets, in which feces cannot be safely stored quickly enough, can cause intestinal infectious diseases such as dysentery and typhoid fever, thereby increasing the risk of death from infectious diseases (Chen and Kallawicha, 2021; Gao et al., 2021). Some studies have also indicated that the contributions of total nitrogen and total phosphorus from toilet sewage accounted for 84% of the total pollutant load of rural domestic sewage (Angelakis et al., 2015). Recently, the Chinese government has launched a series of special actions toward the retrofitting of toilets in rural areas and formulated a number of policies, such as the *Three-year Action Plan for Rural Living Environment Improvement Guiding Suggestions* related to promoting the special action of the "Toilet Revolution" in rural areas, aiming to improve the prevalence of sanitary toilets and the utilization rate of toilet excreta as a resource. Chinese statistics have shown that as of 2020, the usage rate of rural sanitary toilets in China has greatly improved, from 7.5% (1993) to 68% (2020), with an increase of about 5% per year, and more than 40 million rural household toilets have been renovated in total. China has a long history of using human excreta in agriculture, with farmers generally viewing latrine waste as a "valuable fertilizer" (Ferguson, 2014). Solid feces' composition encompasses a large amount of organic matter, which makes it possible to turn it into biofuel (Abomohra et al., 2020). However, feces that are not effectively treated can cause the spread of diseases through fecal–oral routes, especially in children and immunocompromised pregnant women (Majorin et al., 2017). Therefore, the focus has generally shifted toward increasing people's access to toilets and ensuring that the handling of human excreta complies with public health standards.

China lacks a comprehensive means of evaluation of the effectiveness of toilet retrofitting in rural areas, and the environmental and social benefits of toilet retrofitting remain ill-defined (Ma et al., 2021). Most studies have focused on social surveys, including those on the penetration rate of sanitary toilets and the perceptions of rural households (Angelakis et al., 2015). For example, a recent survey of 980 rural households from 22 provinces across China reported on farmer households' satisfaction with toilet retrofitting (Zhou et al., 2022). In addition, based on interviews with 414 residents from 13 villages across three provinces in the west of China, a study analyzed the current situation and attitudes related to possible changes in the rural sanitation service chain (Guo et al., 2021). Recently, sporadic studies evaluating the effects of toilet retrofitting have gradually emerged, but most of these are limited to small areas or evaluation methodology. Li et al. (2021) used system dynamics to assess the effect of toilet improvements in Jiaozhou, China. Zhu et al. (2021) assessed indicators and ranked their weights in relation to the innovation of toilet technologies *via* the analytic hierarchy process and life cycle assessment methods. These studies do not reflect the overall effectiveness of rural toilet retrofitting in China. The pollution load of feces after toilet retrofitting, whether the feces can be harmless, whether the sanitary environment meets the requirements of national standards, whether toilet operation, and maintenance can be long-lasting, etc., remain unknown (Zhang et al., 2020).

According to the China Health and Family Planning Statistical Yearbook, the number of three-compartment septic tanks exceeded 80 million by the end of 2017, accounting for 37.6% of the total of number of rural sanitary household toilets in China. In water-scarce and cold areas, composting toilets were regarded as the most popular toilet model. Therefore, here, we evaluated the effects of retrofitting three-compartment septic tanks and composting toilets in rural China from the two aspects of the environment and society, to improve the effects of the current rural toilet retrofitting approach. These results provide basic data and references for establishing a scientific and appropriate evaluation index system for rural toilet retrofitting and provide a scientific basis as well as policy advice related to optimizing rural toilets and improving the quality of rural toilet retrofitting.

2 METHODS AND MATERIALS

2.1 Sample Collection

In this study, composting toilet samples were collected from Heilongjiang Province (HLJ), Jilin Province (JL), Gansu Province (GS), and Inner Mongolia Autonomous Region (Inner Mongolia: NM), which belong to the northwest region, 5 in each province, with a total of 20 samples. A total of 30 samples of three-compartment septic tank effluent in the southeastern region were collected from Shandong Province (SD), Ningxia Hui Autonomous Region (Ningxia: NX), Jiangsu Province (JS), Shaanxi Province (SX), Hunan Province (HN), and Hubei Province (HB) were collected, which also corresponded to five samples per province (**Figure 1**).

2.2 Questionnaire

To ensure that the questionnaire was scientific, authentic, and representative, this survey adopted a random survey. For some rural residents who were unable to accurately express the contents of the questionnaire, we invited people with higher education (high school degree or above) to retell it with their consent. In addition, we assured the participants that their answers were private, anonymous, and confidential to encourage them to express their opinions freely. The surveyed households in each province had the same toilet mode and had similar usage time. Fifty questionnaires were valid. The contents of the questionnaire included the total population, population structure, existing toilet patterns, toilet sewage treatment methods, septic tank cleaning frequency, toilet use time, etc.

2.3 Sample Monitoring

Measurements of total nitrogen (TN), total phosphorus (TP), organic matter (OM), and pH for composting toilet samples were obtained using organic fertilizers (NY/T 525-2021) (Wei et al., 2021). After the septic tank water sample was filtered through a 0.45 μm membrane, the total nitrogen (TN), total phosphorus (TP), ammonium nitrogen (NH_4^+-N), and nitrous nitrogen (NO_3^--N) in the water sample were detected using a continuous flow analyzer (Skalar SAN+, the Netherlands) according to the method described (Martínez Salgado et al., 2019). The number of fecal coliforms and the mortality rate of aphid eggs and *Salmonella* were measured in accordance with the standard hygienic requirements for harmless disposal of night soil (GB7959-2012) (Pathma and Sakthivel, 2012).

2.4 Data Analysis

SPSS 20.0 was used to analyze the intra-group samples by one-way variance (ANOVA), and the least significant difference (LSD) test was used for statistical comparison. In addition, the reliability of the recovered questionnaire was tested using SPSS 20.0 software. The

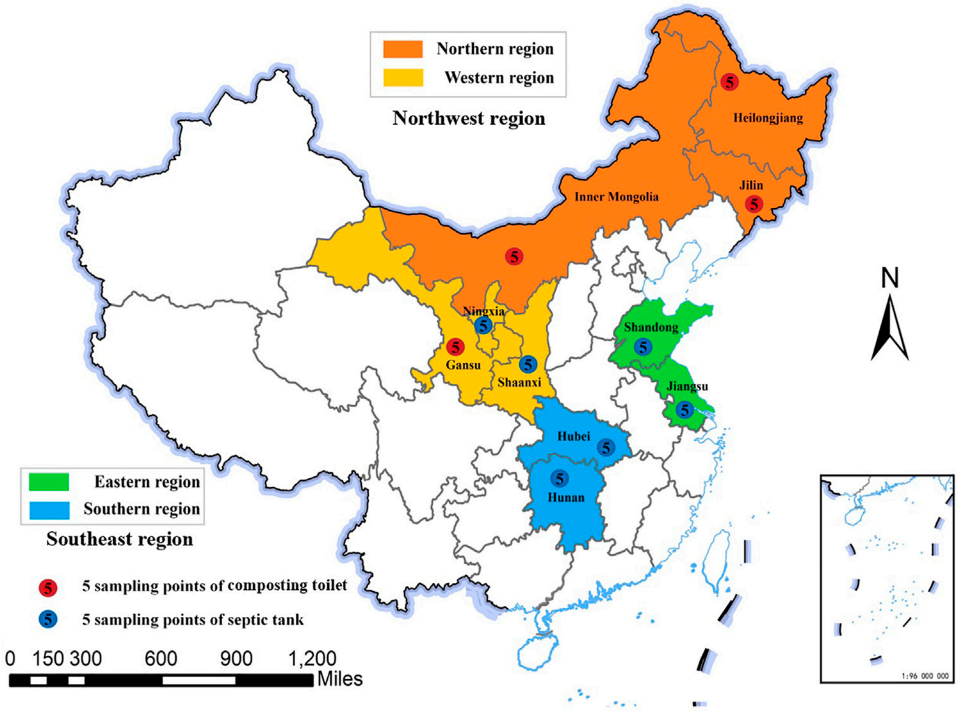

FIGURE 1 | Map of the samples of excrement from 50 rural household toilets.

physical and chemical indicators of the samples were plotted using ggbetweenstats in ggstatsplot (R 4.0.3).

2.5 Fuzzy Evaluation Method

Here, we chose the fuzzy synthetic evaluation method, which mainly converts qualitative evaluation into quantitative according to the membership theory of fuzzy mathematics; that is, we used fuzzy mathematics to make an overall evaluation of objects or objects restricted by multiple factors, and it can better solve vague and difficult to quantify problems, which is suitable for evaluation involving subjective indicators in this study. The basic processes of fuzzy synthetic evaluation were shown as follows:

1) determine a set of evaluation objects;
2) structural evaluation grade;
3) fuzzy synthetic evaluation is used to determine the subordination degree of a single factor;
4) building a fuzzy evaluation matrix; and
5) the overall evaluation results were calculated.

3 RESULTS AND DISCUSSION

3.1 Environmental Effect of Feces After Toilet Retrofitting

3.1.1 Physiochemical Characteristics

Figure 2 shows the contents of physical and chemical indicators in all samples. It was observed that the TN and TP contents in composting toilet samples ranged from 259.21 to 330.46 mg/kg and 2.71 to 3.71 mg/kg, respectively, and the samples in Jilin Province were found to have the highest TN content, while Inner Mongolian samples had the lowest TN content. Gansu Province's composting toilet samples had the highest TP content at 3.71 mg/kg, whereas the lowest level was detected at 2.71 mg/kg in Jilin Province. In addition, the contents of NH_4^+-N and NO_3^--N in composting toilet samples in four provinces ranged from 15.6 to 50.16 mg/kg and 8.51–24.45 mg/kg, respectively. The organic content (OM) of feces was 110.78–274.10 g/kg (Gansu > Heilongjiang > Jilin > Inner Mongolia). The nutritional levels of the treatment products of composting toilets (259.21–330.46 mg/kg) in this study were lower than in previous studies (720–950 mg/kg), probably due to the use of different bulking materials (Kelova et al., 2021). However, it should not be overlooked that this concentration can still fulfill the nutrient needs of crops and can thus replace the use of chemical fertilizers and help close the nutrient cycle loop. Anand and Apul (2014) estimated that 4.9–6.4% of annual commercial fertilizers used in Australia could be replaced with human feces. Mature compost can also be used as an amendment, substituting other materials used for soil remediation (Vinnerås et al., 2003). Therefore, as a type of toilet with no flush, composting toilets can offer a sustainable solution to the problem of water and resource reuse.

In septic tank effluent, the concentrations of TN, TP, and organic carbon were observed at 381.31–2040.84 mg/L, 10.41–80.46 mg/L, and 66.32–1,003.01 mg/L, respectively, and showed no significant differences between provinces ($p > 0.05$)

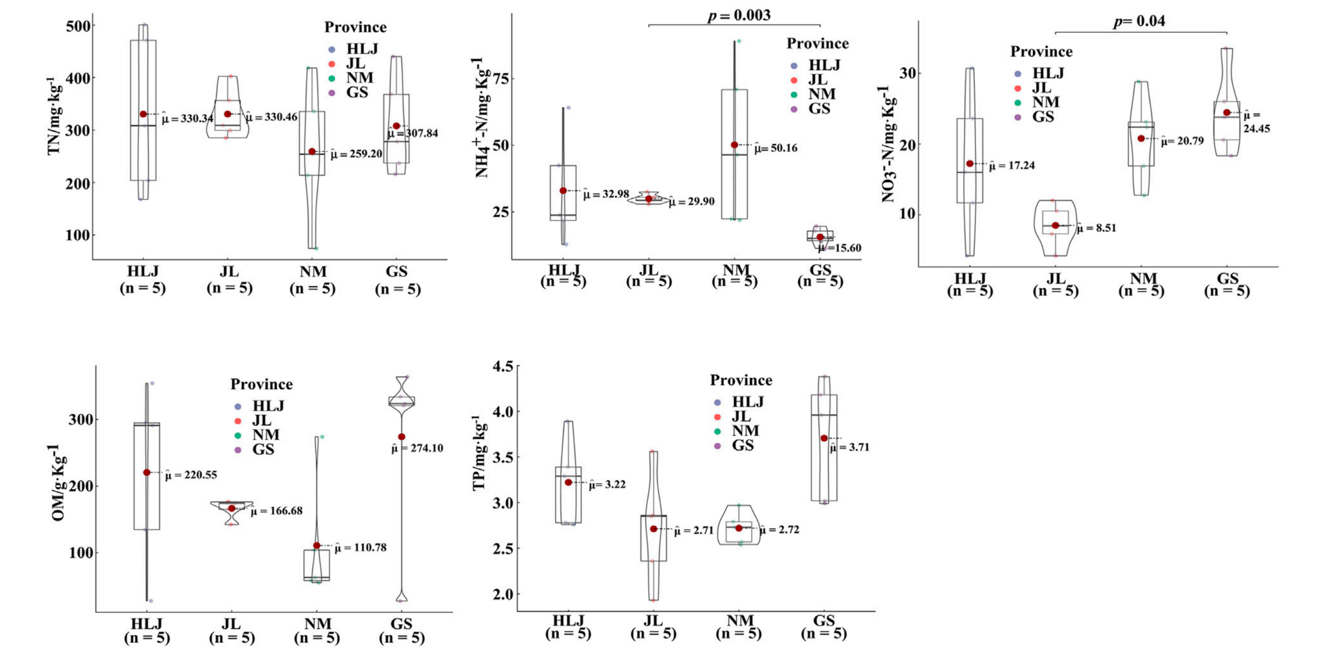

FIGURE 2 | The physiochemical indicators of composting toilet samples. The figure shows box plots, dot plots and violin plots of TN, TP, NH_4^+-N, NO_3-N and OM in different provinces, in which û represents the mean of 5 samples and n represents the number of samples. HLJ, JL, NM and GS represent Heilongjiang Province, Jilin province, Inner Mongolia Autonomous Region (Inner Mongolia) and Gansu province; annotate the pairwise comparisons using p-values.

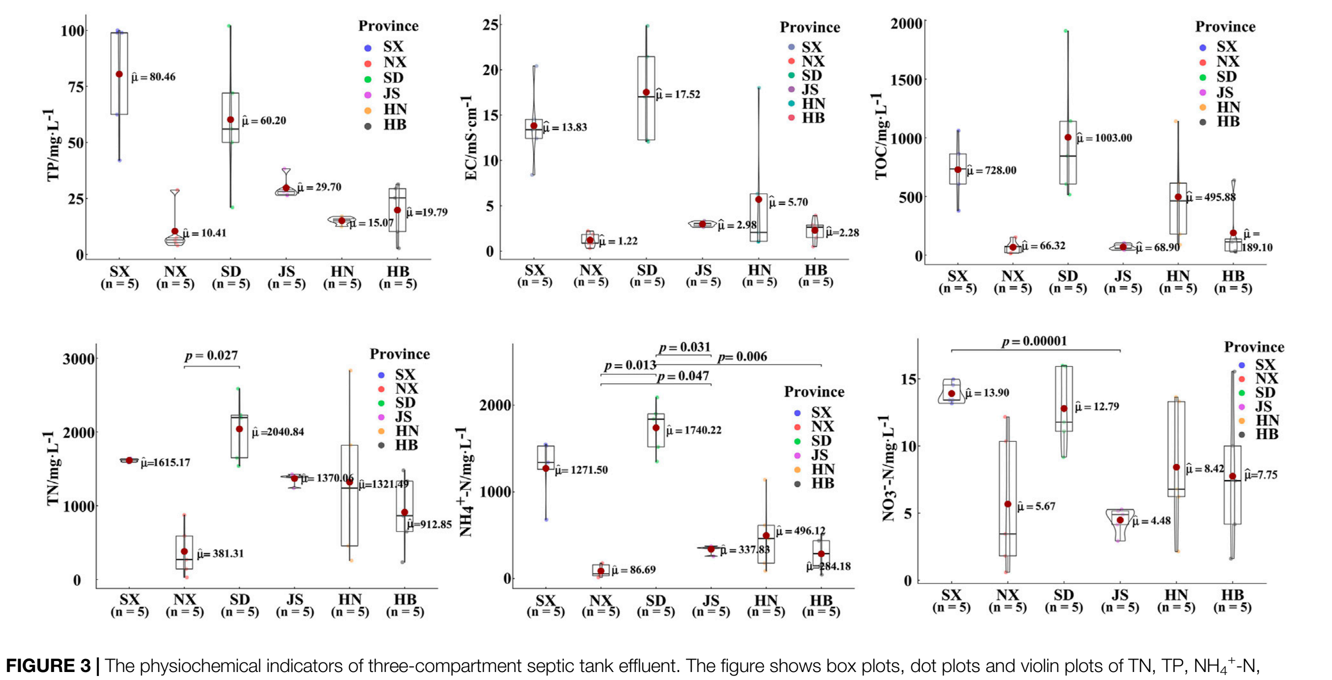

FIGURE 3 | The physiochemical indicators of three-compartment septic tank effluent. The figure shows box plots, dot plots and violin plots of TN, TP, NH_4^+-N, NO_3-N, TOC and EC in different provinces, in which û represents the mean of 5 samples and n represents the number of samples. SX, NX, SD, JS, HN and HB represent Shaanxi province, Ningxia Hui Autonomous Region (Ningxia), Shandong province, Jiangsu province, Hunan province and Hubei province.

(**Figure 3**). The results were higher than those in previous studies, which showed TN and NH_4^+-N concentrations at 194.8–411.16 mg/L and 160.4–322.76 mg/L, respectively, based on 57 septic tanks in six provinces of China (Wang et al., 2021). Combined with on-site sampling, it was found that the collected effluent was relatively turbid, especially in Shaanxi, Shandong, and Hunan provinces. According to the feedback of the surveyed rural residents, since these were newly rebuilt septic tanks, the use time was between 2 and 3 months, thus the feces remained for a relatively short period in the septic tank to ferment, compared with the findings of the study of Wang et al. This explains why the physiochemical indicators of the effluent in this study were higher than those in other studies (Tan et al., 2021; Cui et al., 2006). In addition, our investigation found that the rural residents in Ningxia, Jiangsu, and Hunan provinces have the habit of discharging domestic water into septic tanks. The dilution effect of the domestic water may cause the chemical indicators of the septic tank effluent in this area to be lower than those in the province. In particular, due to the shortage of local water resources in the Ningxia region, domestic water was temporarily stored to flush the toilets; however, the mixing of domestic wastewater into septic tanks meant that the residence time of the manure failed to meet the standard requirements. The direct use of agriculture not only pollutes the soil environment but also increases the risk to human health. When feces is left in the open, there is a higher risk that humans, especially children, may come into direct contact with fecal pathogens (Majorin et al., 2017). The children are at a higher risk of exposure to fecal–oral pathogens because they play on the ground, and place their hands near their faces and in their mouths (Bawankule et al., 2017; Islam et al., 2018). Fecal–oral pathogens can cause diarrheal illnesses, which can lead to stunting, a condition that affects 162 million children worldwide (Beardsley et al., 2021).

In addition, the results show that the electrical conductivity of the septic tank effluent in Shaanxi and Shandong provinces was relatively high, far exceeding the total salt control limitation given by the Standard for Irrigation Water Quality (GB 5084-2021). Salinity is abiotic stress that harms agriculture by decreasing productivity. High electrical conductivity has a negative impact on the morphological and biochemical functions of plants, which can inhibit seed germination, plant growth, development, and yield (Arif et al., 2020). Moreover, high electrical conductivity hampers photosynthetic machinery, transpiration, and gaseous exchange by decreasing the content of chlorophyll and carotenoids and distorting the chloroplast ultrastructure and PSII system (Pan et al., 2021). High electrical conductivity lowers the soil water potential and leaf water potential, thus disturbing plant–water relations and reducing the turgor of the plant, which ultimately leads to osmotic stress (Navada et al., 2020). Plants take up salt from the soil *via* transporters that create ion toxicity and disturb mineral uptake and ion homeostasis. Salinity leads to the extensive accumulation of ions (Na^+ and Cl^-) and inhibits K^+ and Ca^{2+} uptake, thus resulting in ionic imbalance (Isayenkov and Maathuis, 2019). Therefore, septic tank effluent resources in this area should be diluted first and then returned to the field. This could prevent the soil salinization caused by high salt accumulation. In the future, more long-term positioning studies should focus on the effects of manure return on crop absorption and soil salt accumulation.

The pH values of composting toilet samples and septic tank effluent were found to be alkaline, with an average value between 7.32 and 8.37 (**Figure 4**), suggesting that some of the effluents from the septic tank cannot be used directly for the irrigation of

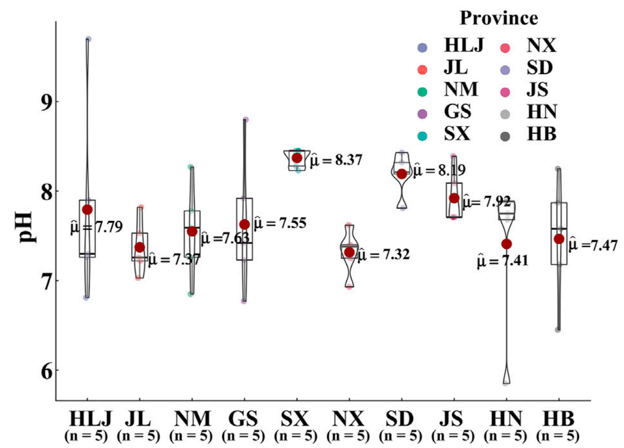

FIGURE 4 | The pH of toilet feces surveyed in 10 provinces (regions). The figure shows box plots, dot plots and violin plots of fecal distribution in different provinces, in which û represents the mean of 5 samples and n represents the number of samples.

farmlands as high pH conditions could cause the exchangeable moiety to combine with other anions and increase the heavy metal content in the soil (Ouyang et al., 2020). Furthermore, high pH levels lead to low soil organic matter content; strong acid leaching; poor texture; poor structure; soil consolidation; poor ventilation; water permeability; the incoordination of soil water, air, and heat; easy erosion; soil erosion; and soil fertility, which are all disadvantageous for tillage and plant growth (Köninger et al., 2021).

3.1.2 Harmlessness of Toilet Excreta

Fecal coliform, *Salmonella*, and Ascaris eggs are regarded as important indices of harmlessness. With reference to the Hygienic Standard for the Harmlessness of Feces (GB 7959-2012), we have here defined qualified samples as those with a mean level of fecal coliforms between 10^{-1} and 10^{-2}, a mortality rate of Ascaris eggs >95%, and no *Salmonella* was detected. Among the 50 toilet fecal samples, the total rate of qualified fecal coliform bacteria was 84%, the total mortality of Ascaris eggs reached 90%, and *Salmonella* was not detected in any samples (**Table 1**). Specifically, the average qualified rates of fecal coliform bacteria and Ascaris eggs in the compost toilet samples were 70 and 80%, respectively, while the two qualified rates of septic tank effluent were 93.3 and 96.7%, respectively, indicating that the harmlessness of the feces treated in the three-compartment septic tank was significantly higher than that in composting toilets ($p < 0.01$). Among them, the composting toilets adopted in the northwest were generally unable to achieve harmlessness, especially in the Inner Mongolia region, as the conditions affecting the process of composting were not sufficient. As previously stated, the key to composting treatment is fermentation, and many external factors including water content and temperature restrict the degradation effect, and it is thus here proposed to optimize composting toilet technology and thus improve the level of harmlessness (Hill and Baldwin, 2012). As for three-compartment septic tanks, although the effect

TABLE 1 | The qualified rate of harmless treatment of feces after toilet modification.

Provinces (autonomous regions)	Sample types	Qualified rate of fecal coliform group value	Qualified rate of mortality of Ascaris lumbricoides eggs	Qualified rate of salmonella value
Heilongjiang	Composting toilets	80%	80%	100%
Jilin		80%	100%	100%
Gansu		60%	80%	100%
Inner Mongolia		60%	60%	100%
Shaanxi	The effluent of three compartment septic tank	80%	100%	100%
Ningxia		80%	80%	100%
Shandong		100%	100%	100%
Jiangsu		100%	100%	100%
Hunan		100%	100%	100%
Hubei		100%	100%	100%

of treatment on pathogenic factors was better than that in the composting toilet, it was still lower than that required by the public health body, which is in line with the findings of the study by Lusk et al. (2017). The report of Tollestrup et al. (2014) also raised the fact that the dispersal of septic tank effluents can contribute to increasing the incidence of infectious diseases.

Fortunately, compared with previously used rural toilets, the degree of harmlessness of feces after toilet retrofitting increases to a certain extent (Gao et al., 2017). This can act as a reference for promoting new sanitation practices that enhance the availability and sustainability of water and sanitation services in other low- to middle-income countries worldwide, which will ultimately contribute to achieving Sustainable Development Goal 6: ensure availability and sustainable management of water and sanitation for all.

3.2 Social Effect of Toilet Retrofitting

The indicators of the effects of toilet retrofitting were determined with reference to the standards and policy documents regarding rural areas in China, and the quantitative values of the influencing factors were provided by means of expert consultation and scoring. The 24 participants in the consultation and scoring process included government officials and scientific researchers in related academic fields. Additionally, it was determined that the manure utilization index had the highest weight among the other first-level indicators, in terms of the national demand orientation, the focus of grassroots work, and public feedback. The weight of each indicator was obtained based on the opinions of experts, as shown in **Table 2**.

3.2.1 Determine the Index Weight

1) Determine a set of evaluation objects

Total object set: A (effect of rural toilet retrofitting) = {E1,E2,E3,E4} = {Toilet construction, Mass satisfaction, Manure utilization, Later management, and maintenance}; various levels of index set: B1 (toilet construction) = {C1 (toilet house construction), C2 (underground construction), C3 (toilet product quality)}; B2 (mass satisfaction) = {C4 (easy operation), C5 (cost expenditure), C6 (toilet environment)}; B3 (manure utilization) =

TABLE 2 | Evaluation index system of toilet improvement in rural areas.

First-level index	Index weight	Secondary index	Index weight	Assessment factors
Toilet construction	0.25	Toilet house construction	0.1/0.4	Whether the construction of toilet houses meets the requirements of national standards, and whether the location of toilets is reasonable,
		Underground part construction	0.1/0.4	Whether the construction, construction and use of water and aqua privies meet the requirements of national standards
		Toilet product quality	0.05/0.2	The appearance and structural proportion of toilet products meet the national design requirements.
Mass satisfaction	0.2	Easy to use	0.05/0.25	Whether the old toilet will be demolished after the new toilet is built, and whether the new toilet will be abandoned.
		Cost expenditure	0.05/0.25	Toilet reconstruction expenses, daily use expenses and later operation and maintenance expenses
		Toilet environment	0.1/0.5	The toilet house is odorless, free of mosquitoes and flies, and ventilated.
Fecal utilization	0.3	Harmless treatment	0.1/ (1/3)	Whether the type of toilet is harmless sanitary toilet
		Resource utilization	0.1/ (1/3)	Whether to carry out unified treatment after returning to the field, composting or clearing
		Environmental risk of faeces	0.1/ (1/3)	There is no leakage in the septic storage tank, and the feces are not dumped at random.
Later stage management and protection	0.25	Regular maintenance of toilet products	0.1/0.4	Professional operation and maintenance team
		Establish a management and protection mechanism	0.1/0.4	Whether the local government has established the dung removal and transfer mechanism and whether the mechanism is normal.
		Incorporate into the village rules and regulations	0.05/0.2	Raise villagers' awareness of hygiene

{C7 (harmless treatment), C8 (utilization of resources), C9 (environmental risk of feces)}; B4 (later management and maintenance) = {C10 (regular maintenance of toilet products), C11 (establishment of management and maintenance mechanism), C12 (incorporated into village regulations)}.

2) Structural evaluation grade

We constructed an evaluation level set to score each indicator and thus obtain relative scores. This study established five relatively fair evaluation level matrices. The percentile system is easy to operate and widely used. In order to avoid the problems of the percentile system being dominated by subjectivity and poor objectivity, here, we have used "very satisfied, relatively satisfied, general, dissatisfied, and extremely dissatisfied" grades, which help to effectively overcome the differences in the professional knowledge of the evaluators. Hence, S = {very satisfied, relatively satisfied, general, dissatisfied, extremely dissatisfied} = {100, 80, 60, 40, 20} (Lu and Xu, 2011).

3) The fuzzy evaluation method was used to determine the subordination degree of a single factor in the effective evaluation of rural toilet retrofitting.

Taking the Inner Mongolia region as an example, the single-factor membership degree of the rural toilet renovation effect is presented in **Table 3**.

4) Building a fuzzy evaluation matrix

Based on the statistics related to the obtained data and combined with the use of the fuzzy comprehensive evaluation method, the first-level fuzzy evaluation matrix of the rural toilet retrofitting effect was determined to be E1, E2, E3, and E4, respectively.

$$E_1 = \begin{bmatrix} \frac{1}{5} & \frac{2}{5} & \frac{1}{5} & \frac{1}{5} & \frac{0}{5} \\ \frac{2}{5} & \frac{2}{5} & \frac{1}{5} & \frac{0}{5} & \frac{0}{5} \\ \frac{1}{5} & \frac{1}{5} & \frac{2}{5} & \frac{1}{5} & \frac{0}{5} \end{bmatrix} E_2 = \begin{bmatrix} \frac{4}{5} & \frac{1}{5} & \frac{0}{5} & \frac{0}{5} & \frac{0}{5} \\ \frac{1}{5} & \frac{1}{5} & \frac{2}{5} & \frac{0}{5} & \frac{1}{5} \\ \frac{0}{5} & \frac{1}{5} & \frac{3}{5} & \frac{1}{5} & \frac{0}{5} \end{bmatrix}$$

$$E_3 = \begin{bmatrix} \frac{1}{5} & \frac{2}{5} & \frac{2}{5} & \frac{0}{5} & \frac{0}{5} \\ \frac{3}{5} & \frac{1}{5} & \frac{1}{5} & \frac{0}{5} & \frac{0}{5} \\ \frac{0}{5} & \frac{1}{5} & \frac{2}{5} & \frac{2}{5} & \frac{0}{5} \end{bmatrix} E_4 = \begin{bmatrix} \frac{0}{5} & \frac{1}{5} & \frac{1}{5} & \frac{2}{5} & \frac{1}{5} \\ \frac{0}{5} & \frac{1}{5} & \frac{1}{5} & \frac{2}{5} & \frac{1}{5} \\ \frac{5}{5} & \frac{0}{5} & \frac{0}{5} & \frac{0}{5} & \frac{0}{5} \end{bmatrix}.$$

3.2.2 Effect Evaluation

According to formula F=Wi*E, where Wi represents a collection of indicator weights for individual layers, a fuzzy evaluation calculation is performed on indicators B1, B2, B3, and B4. E1 is the first level of the toilet construction indicator fuzzy comprehensive evaluation:

$$F_1 = w_1 * E_1 = (0.4, 0.4, 0.2) * \begin{bmatrix} \frac{1}{5} & \frac{2}{5} & \frac{1}{5} & \frac{1}{5} & \frac{0}{5} \\ \frac{2}{5} & \frac{2}{5} & \frac{1}{5} & \frac{0}{5} & \frac{0}{5} \\ \frac{1}{5} & \frac{1}{5} & \frac{2}{5} & \frac{1}{5} & \frac{0}{5} \end{bmatrix} = (0.28, 0.36, 0.24, 0.12, 0). \quad (1)$$

Similarly, the fuzzy ratings for E2, E3, and E4 are F2 = W2*E2= (0.25, 0.2, 0.4, 0.1, 0.05), F3 = W3*E3= (0.27,0.27,0.33,0.13,0), and F4 = W4*E4= (0.2,0.16,0.16,0.32,0.16).

According to the second-level evaluation formula,

$$F = W * E = (0.25, 0.2, 0.3, 0.25) * \begin{bmatrix} 0.28 & 0.36 & 0.24 & 0.12 & 0 \\ 0.25 & 0.2 & 0.4 & 0.1 & 0.05 \\ 0.27 & 0.27 & 0.33 & 0.13 & 0 \\ 0.2 & 0.16 & 0.16 & 0.32 & 0.16 \end{bmatrix} = (0.251, 0.251, 0.279, 0.169, 0.05).$$

The weighted average method was used to calculate the comprehensive evaluation score of the rural toilet retrofitting effect in Inner Mongolia (Y = 70.67). Similarly, the comprehensive evaluation scores of the secondary indices were as follows: Y1 = 76, Y2 = 70, Y3 = 73.6, and Y4 = 58.4.

TABLE 3 | Single factor membership degree of toilet improvement effect in rural areas of Inner Mongolia.

Evaluation index	Very satisfied	More satisfied	General	Not satisfied	Extremely unsatisfied
Toilet house construction C1	1	2	1	1	0
Underground part construction C2	2	2	1	0	0
Toilet product quality	1	1	2	1	0
Easy to use C3	4	1	0	0	0
Cost expenditure C4	1	1	2	0	1
Toilet environment C5	0	1	3	1	0
Harmless treatment C6	1	2	2	0	0
Resource utilization C7	3	1	1	0	0
Environmental risk of faeces C8	0	1	2	2	0
Regular maintenance of toilet products C9	0	1	1	2	1
Establish a management and protection mechanism C10	0	1	1	2	1
Incorporate into the village rules and regulations C11	5	0	0	0	0

TABLE 4 | Comprehensive score and second-level index score of changing rural toilets into toilets in 10 provinces (autonomous regions).

Provinces (autonomous regions)	Comprehensive evaluation score (Y)	Toilet construction (Y1)	Mass satisfaction (Y2)	Fecal utilization (Y3)	Later stage management and protection (Y4)
Heilongjiang	64.2	66.4	67	65.3	58.4
Jilin	72.6	85.6	79	62.7	66.4
Gansu	64.6	71.2	63	62.7	61.6
Heilongjiang	63.6	70.4	61	62.7	60
Shaanxi	72.6	83.2	80	64	66.4
Ningxia	82	81.6	93	77.3	79.2
Shandong	92.4	95.5	98	82.7	96.8
Jiangsu	91.8	94.4	95	88	91.2
Hunan	91.8	95.2	91	86.7	95.2
Inner Mongolia	70.67	76	70	73.6	58.4

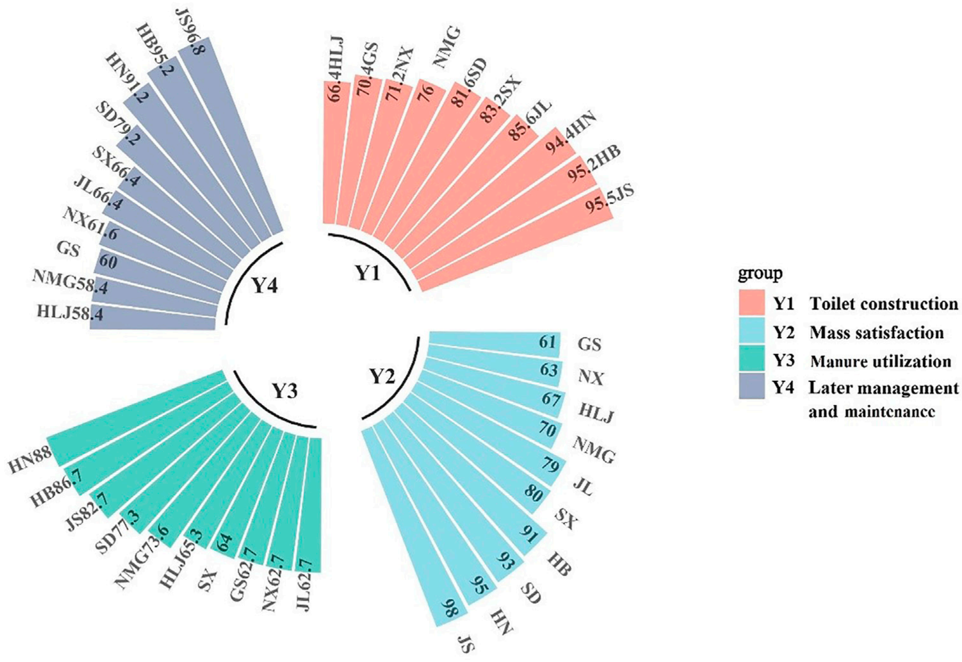

FIGURE 5 | Comprehensive scores of fuzzy evaluations of the second-level indicators of 10 provinces (regions).

The comprehensive evaluation scores of rural toilet retrofitting in other provinces were in line with those of Inner Mongolia. The comprehensive and secondary index scores of the ten provinces are shown in **Table 4**. The results show that Jiangsu Province had the highest comprehensive evaluation score of 92.4 followed by Hunan and Hubei provinces, both with 91.8, whereas Gansu Province had the lowest score of 63.6. Overall, the scores showed a "high southeast, low northwest" trend. In the toilet construction indicator layer, Hunan, Hubei, and Jilin provinces had scores higher than 85, whereas the northwest region's scores were generally low, with Heilongjiang Province achieving the lowest score of 66.4 (**Figure 5**). In the mass satisfaction indicator layer, the scores of the four provinces in the southeastern region were all above 90. The scores of the six provinces in the northwest region ranged from 60 to 80, showing a polarization trend and the scores of the manure utilization index layer generally exhibited a trend of southern > eastern > northwestern. In the later management and maintenance index layer, the scores of Jiangsu, Hunan, and Hubei provinces were much higher than those of other provinces; Jiangsu Province had the highest score of 96.8, whereas Ningxia and Jilin provinces had the lowest scores of only 62.7. Overall, composting toilets are less acceptable in the rural areas than three-compartment septic tank toilets. Rural residents are reluctant to accept the technology because of perceived odor and maintenance issues. Composting toilets require the user to be more active in managing their waste compared to the flush model used in the developed areas. Maintenance requirements such as the turning of the compost, the addition of bulking agents, emptying the chamber, and cleaning the toilet without using much water are unacceptable to the rural residents. In addition, the composting toilets may be perceived as second-class, inconvenient, and burdensome, all of which perceptions would limit the adoption of the technology (Anand and Apul, 2014). However, our results differ from those of Gao et al. (2017), who believed that the composting toilets should be given more attention due to their suitability, as they can be used in water shortage and cold conditions.

Consequently, the comprehensive evaluation scores of toilets retrofitting in Shandong, Jiangsu, Hunan, and Hubei provinces were found to be "relatively satisfied" and "very satisfied." The scores in Heilongjiang, Jilin, Ningxia Hui, Gansu, Shaanxi, and Inner Mongolia were between average and relatively satisfactory. These results indicate that the rural residents were satisfied with the improvements to rural toilets, but the evaluation *via* secondary indicators shows that some problems remain. Heilongjiang Province achieved the lowest score for toilet construction mainly because the five households surveyed stated low satisfaction with the construction of toilet houses, most of which have leakage problems. The satisfaction levels of the surveyed rural residents in Ningxia and Gansu provinces were relatively low mainly because they were dissatisfied with the convenience of using composting toilets. According to rural residents' feedback, compost toilets are only suitable for two to three people. When there are a large number of users, the efficiency of the toilet is greatly reduced, and it may even stop functioning. With regard to manure utilization, the scores in the provinces (regions) were higher, reflecting the significant development trend in the utilization of manure resources in China's rural environment. However, the low scores pertaining to the harmlessness treatment and environmental risk indicators of fecal contamination indicate that the provinces (regions) were not yet fully equipped with technologies and facilities for fecal treatment and recycling, and they need to be further strengthened. It is worth noting that the scores may not reflect the actual situation, due to the small number of samples, and certain errors may arise during the sampling and investigation that mean our results cannot be used as a guiding document.

4 CONCLUSION AND OUTLOOK

Based on the monitoring of the physiochemical properties and degree of harmlessness of toilet sewage, as well as the comprehensive evaluation of the mass satisfaction, manure utilization, and consequential management and maintenance following toilet retrofitting, in relation to 50 rural residents in 10 provinces (regions) of China, it can be concluded that the effectiveness of rural toilets after retrofitting was remarkable. The comprehensive evaluations of the ten provinces (regions) gave results that were between average and very satisfied, but the construction of toilet houses, the utilization of manure resources, and the consequential management and maintenance still need to be strengthened by government investment and technical guidance. In accordance with our evaluation results, we make the following four suggestions for the improvement of toilets in rural areas in the future:

1) The development of suitable technical models for toilet retrofitting in Northwest China. The existing composting toilets are generally unable to make feces harmless, and the satisfaction of the masses is low due to disadvantages such as strong odors and low fermentation efficiency. We should thus aim to make developments in technologies such as antifreeze, water preservation, and efficient fermentation in the future.
2) In areas with abundant water resources and strong economic conditions, it is recommended to popularize flushing toilets, which allow for better fecal treatment, but we need to be on guard against the potential risk of diseases related to the flushing treatment.
3) A standard system of toilet retrofitting in rural areas should be established and perfected, and the quality, construction, and acceptance level of toilets should be strictly controlled to avoid the environmental pollution and irregular operation caused by poor toilet quality.
4) Improving the utilization rate of manure resources and strengthening the research on subsequent manure utilization technology will be the next priority to limit the environmental health risks caused by manure applications.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

YG and LT designed and conducted the experiments, collected samples, and analyzed data. XZ and YX directed the experimental design and overall concept and provided guidance to YG. CZ, QL, and XW: investigation. BY and PC: methodology.

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REFERENCES

Abomohra, A. E.-F., Elsayed, M., Esakkimuthu, S., El-Sheekh, M., and Hanelt, D. (2020). Potential of Fat, Oil and Grease (FOG) for Biodiesel Production: A Critical Review on the Recent Progress and Future Perspectives. *Prog. Energ. Combustion Sci.* 81, 100868. doi:10.1016/j.pecs.2020.100868

Anand, C. K., and Apul, D. S. (2014). Composting Toilets as a Sustainable Alternative to Urban Sanitation - A Review. *Waste Manag.* 34 (2), 329–343. doi:10.1016/j.wasman.2013.10.006

Angelakis, A., and Snyder, S. (2015). Wastewater Treatment and Reuse: Past, Present, and Future. *Water* 7 (12), 4887–4895. doi:10.3390/w7094887

Arif, Y., Singh, P., Siddiqui, H., Bajguz, A., and Hayat, S. (2020). Salinity Induced Physiological and Biochemical Changes in Plants: An Omic Approach towards Salt

Stress Tolerance. *Plant Physiol. Biochem.* 156, 64–77. doi:10.1016/j.plaphy.2020.08.042

Bawankule, R., Singh, A., Kumar, K., and Pedgaonkar, S. (2017). Disposal of Children's Stools and its Association with Childhood Diarrhea in India. *BMC Public Health* 17 (1), 12. doi:10.1186/s12889-016-3948-2

Beardsley, R., Cronk, R., Tracy, W., Fleming, L., Ng'ambi, M., Tidwell, J. B., et al. (2021). Factors Associated with Safe Child Feces Disposal in Ethiopia, India, and Zambia. *Int. J. Hyg. Environ. Health* 237, 113832. doi:10.1016/j.ijheh.2021.113832

Chen, T., and Kallawicha, K. (2021). Association between Sanitary Toilet Coverage Rate and Intestinal Infectious Disease in Jiangsu Province, China. *Sci. Rep.* 11 (1), 12805. doi:10.1038/s41598-021-92291-z

Cheng, S., Li, Z., Uddin, S. M. N., Mang, H.-P., Zhou, X., Zhang, J., et al. (2018). Toilet Revolution in China. *J. Environ. Manage.* 216, 347–356. doi:10.1016/j.jenvman.2017.09.043

Cui, L. H., Liu, W., Zhu, X. Z., Ma, M., Huang, X. H., and Xia, Y. Y. (2006). Performance of Hybrid Constructed Wetland Systems for Treating Septic Tank Effluent. *J. Environ. Sci. (China)* 18 (4), 665–669. doi:10.3321/j.issn:1001-0742.2006.04.009

Ferguson, D. T. (2014). Nightsoil and the 'Great Divergence': Human Waste, the Urban Economy, and Economic Productivity, 1500-1900. *J. Glob. Hist.* 9 (3), 379–402. doi:10.1017/s1740022814000175

Gao, H., Zhou, C., Li, F., Han, B., and Li, X. (2017). Economic and Environmental Analysis of Five Chinese Rural Toilet Technologies Based on the Economic Input-Output Life Cycle Assessment. *J. Clean. Prod.* 163, S379–S391. doi:10.1016/j.jclepro.2015.12.089

Gao, Y., Li, H., Yang, B., Wei, X., Zhang, C., Xu, Y., et al. (2021). The Preliminary Evaluation of Differential Characteristics and Factor Evaluation of the Microbial Structure of Rural Household Toilet Excrement in China. *Environ. Sci. Pollut. Res.* 28 (32), 43842–43852. doi:10.1007/s11356-021-13779-9

Guo, S., Zhou, X., Simha, P., Mercado, L. F. P., Lv, Y., and Li, Z. (2021). Poor Awareness and Attitudes to Sanitation Servicing Can Impede China's Rural Toilet Revolution: Evidence from Western China. *Sci. Total Environ.* 794, 148660. doi:10.1016/j.scitotenv.2021.148660

Hill, G. B., and Baldwin, S. A. (2012). Vermicomposting Toilets, an Alternative to Latrine Style Microbial Composting Toilets, Prove Far superior in Mass Reduction, Pathogen Destruction, Compost Quality, and Operational Cost. *Waste Manag.* 32 (10), 1811–1820. doi:10.1016/j.wasman.2012.04.023

Isayenkov, S. V., and Maathuis, F. J. M. (2019). Plant Salinity Stress: Many Unanswered Questions Remain. *Front. Plant Sci.* 10, 80. doi:10.3389/fpls.2019.00080

Islam, M., Ercumen, A., Ashraf, S., Rahman, M., Shoab, A. K., Luby, S. P., et al. (2018). Unsafe Disposal of Feces of Children. *PLoS One* 13 (4), e0195218. doi:10.1371/journal.pone.0195218

Kelova, M. E., Eich-Greatorex, S., and Krogstad, T. (2021). Human Excreta as a Resource in Agriculture - Evaluating the Fertilizer Potential of Different Composting and Fermentation-Derived Products. *Resour. Conservation Recycling* 175, 105748. doi:10.1016/j.resconrec.2021.105748

Köninger, J., Lugato, E., Panagos, P., Kochupillai, M., Orgiazzi, A., and Briones, M. J. I. (2021). Manure Management and Soil Biodiversity: Towards More Sustainable Food Systems in the EU. *Agric. Syst.* 194, 103251. doi:10.1016/j.agsy.2021.103251

Li, Y., Cheng, S., Li, Z., Song, H., Guo, M., Li, Z., et al. (2021). Using System Dynamics to Assess the Complexity of Rural Toilet Retrofitting: Case Study in Eastern China. *J. Environ. Manage.* 280, 111655. doi:10.1016/j.jenvman.2020.111655

Lu, J., and Xu, J. (2011). Application of Fuzzy Comprehensive Evaluation Model Based on Analytic Hierarchy Process for Rural Drinking Water, Proceeding of the 2011 5th International Conference on Bioinformatics and Biomedical Engineering, May 2011, Wuhan, China. IEEE, 1–5. doi:10.1109/icbbe.2011.5780843

Lusk, M. G., Toor, G. S., Yang, Y.-Y., Mechtensimer, S., De, M., and Obreza, T. A. (2017). A Review of the Fate and Transport of Nitrogen, Phosphorus, Pathogens, and Trace Organic Chemicals in Septic Systems. *Crit. Rev. Environ. Sci. Technol.* 47 (7), 455–541. doi:10.1080/10643389.2017.1327787

Majorin, F., Torondel, B., Routray, P., Rout, M., and Clasen, T. (2017). Identifying Potential Sources of Exposure along the Child Feces Management Pathway: A Cross-Sectional Study Among Urban Slums in Odisha, India. *Am. J. Trop. Med. Hyg.* 97 (3), 861–869. doi:10.4269/ajtmh.16-0688

Martínez Salgado, M. M., Ortega Blu, R., Janssens, M., and Fincheira, P. (2019). Grape Pomace Compost as a Source of Organic Matter: Evolution of Quality Parameters to Evaluate Maturity and Stability. *J. Clean. Prod.* 216, 56–63. doi:10.1016/j.jclepro.2019.01.156

Navada, S., Vadstein, O., Gaumet, F., Tveten, A.-K., Spanu, C., Mikkelsen, Ø., et al. (2020). Biofilms Remember: Osmotic Stress Priming as a Microbial Management Strategy for Improving Salinity Acclimation in Nitrifying Biofilms. *Water Res.* 176, 115732. doi:10.1016/j.watres.2020.115732

Ouyang, J., Liu, Z., Zhang, L., Wang, Y., and Zhou, L. (2020). Analysis of Influencing Factors of Heavy Metals Pollution in farmland-rice System Around a Uranium Tailings Dam. *Process Saf. Environ. Prot.* 139, 124–132. doi:10.1016/j.psep.2020.04.003

Pan, T., Liu, M., Kreslavski, V. D., Zharmukhamedov, S. K., Nie, C., Yu, M., et al. (2021). Non-stomatal Limitation of Photosynthesis by Soil Salinity. *Crit. Rev. Environ. Sci. Technol.* 51 (8), 791–825. doi:10.1080/10643389.2020.1735231

Pathma, J., and Sakthivel, N. (2012). Microbial Diversity of Vermicompost Bacteria that Exhibit Useful Agricultural Traits and Waste Management Potential. *SpringerPlus* 1 (1), 1–19. doi:10.1186/2193-1801-1-26

Tan, L., Zhang, C., Liu, F., Chen, P., Wei, X., Li, H., et al. (2021). Three-compartment Septic Tanks as Sustainable On-Site Treatment Facilities? Watch Out for the Potential Dissemination of Human-Associated Pathogens and Antibiotic Resistance. *J. Environ. Manage.* 300, 113709. doi:10.1016/j.jenvman.2021.113709

Tollestrup, K., Frost, F. J., Kunde, T. R., Yates, M. V., and Jackson, S. (2014). Cryptosporidium Infection, Onsite Wastewater Systems and Private wells in the Arid Southwest. *J. Water Health* 12 (1), 161–172. doi:10.2166/wh.2013.049

Vinnerås, B., Bjorklund, A., and Jonsson, H. (2003). Thermal Composting of Faecal Matter as Treatment and Possible Disinfection Method-Laboratory-Scale and Pilot-Scale Studies. *Bioresour. Technol.* 88, 47–54. doi:10.1016/S0960-8524(02)00268-7

Wang, H., Wang, J., Chen, Y., Zheng, W., Guo, Q., Chen, S., et al. (2021). Pollutant-removal Performance of Rural Septic Tank and its Influencing Factors. *Chin. J. Environ. Eng.* 15 (2), 727–736. (in Chinese). doi:10.12030/j.cjee.202008129

Wei, Y., Wang, N., Lin, Y., Zhan, Y., Ding, X., Liu, Y., et al. (2021). Recycling of Nutrients from Organic Waste by Advanced Compost Technology- A Case Study. *Bioresour. Technol.* 337, 125411. doi:10.1016/j.biortech.2021.125411

Xiaolei, M., zhenyu, Y., Yaoping, D., yanlong, Z., yutong, W., and liangbing, H. (2021). Construction and Implementation of Standard System for Rural Household Toilets in China. *E3s Web Conf.* 248, 03016. doi:10.1051/e3sconf/202124803016

Zhang, S., Li, Y., Zhang, Y., Lu, Z.-N., and Hao, Y. (2020). Does Sanitation Infrastructure in Rural Areas Affect Migrant Workers' Health? Empirical Evidence from China. *Environ. Geochem. Health* 42 (2), 625–646. doi:10.1007/s10653-019-00396-2

Zhou, X., Prithvi, P. S., Perez-Mercado, L. F., Barton, M. A., Lyu, Y., Guo, S., et al. (2022). China Should Focus beyond Access to Toilets to Tap into the Full Potential of its Rural Toilet Revolution. *Resour. Conservation Recycling* 178, 106100. doi:10.1016/j.resconrec.2021.106100

Zhu, L., Zhao, Z., Wang, Y., Huang, Q., Sun, Y., and Bi, D. (2021). Weighting of Toilet Assessment Scheme in China Implementing Analytic Hierarchy Process. *J. Environ. Manage.* 283, 111992. doi:10.1016/j.jenvman.2021.111992

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Mining of the Association Rules Between Socio-Economic Development Indicators and Rural Harmless Sanitary Toilet Penetration Rate to Inform Sanitation Improvement in China

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The imbalance of socioeconomic development (SED) in different regions of China has resulted in the variability of rural infrastructure penetration. This study aims to improve the SED of each region in China to increase the penetration rate of rural harmless sanitary toilets (RHST). For this purpose, we used association rule mining to analyze the relationship between SED indicators and the penetration rate of RHST for proposing differentiated improvement strategies. Population urbanization rate, tertiary vs. secondary industry output ratio, nonagricultural output value ratio, nonagricultural employment ratio, per capita gross domestic product, and the proportion of added value of industry in the total added value of commodity were used to measure the SED level of 30 regions in China from 2007 to 2017. Results showed that the SED of each region has been improving, and the proportion of added value of industry in the total added value of commodity accounted for the highest proportion of SED. The penetration rate of RHST in each region increased continuously but with significant variability from 2007 to 2017. The range of six SED indicators corresponding to high and low penetration rates of RHST was determined by association rule mining analysis. On the basis of the degree of RHST penetration rate by region in China in 2017 as a reference, differentiated measures were proposed to improve the penetration of RHST in different regions.

Keywords: socioeconomic development, rural harmless sanitary toilet, association rule, differentiated development, rural toilet retrofitting

INTRODUCTION

More than half (55%) of the global population lacked access to safely managed sanitation services in 2017 (WHO, 2020b). Developing countries (compared with developed countries) face more serious challenges in achieving the Sustainable Development Goal target of universal sanitation coverage by 2030, which is mainly due to high population growth and low coverage of existing sanitation facilities

(United Nations (2017) World Population Prospects, 2017; Trimmer et al., 2020; WHO, 2020b). Moreover, in a recent survey, only 4% of countries were reported to have sufficient financial resources to achieve national sanitation targets (WHO, 2020a). Household sanitation expenditures (compared with government expenditures) account for a higher proportion of all household water, sanitation, and hygiene expenditures (WHO, 2020a). Rural areas in developing countries also face high sanitation failure rates, which is often due to most rural areas not having well-established operation and maintenance systems (Roubík et al., 2020).

Successful sanitation change not only depends on the supply of sanitation infrastructure but also requires changes in the political, economic, social, cultural, and environmental underpinnings of sanitation, as well as systemic behavior change at the individual, household, and societal levels (Gasana et al., 2002; Novotný et al., 2018b; Guo et al., 2021). Rapid socioeconomic development (SED) is a major driving force for the continuous improvement in rural sanitation facilities in China. In 2017, rural residents of 12.519 million (compared with 6.914 million in 2007) new rural households in China had access to sanitary toilets (Ministry of Health of the People's Republic of China, 2008; China National Health Commission, 2018). However, the imbalance of SED across China's regions resulted in inconsistent penetration rate of rural harmless sanitary toilets (RHST) (China National Health Commission, 2018; Tian and Wang, 2019; Wei et al., 2020). Therefore, the high-quality SED of each region is the key to achieving rapid penetration rate of RHST in China.

The study of SED has been developed for multiple decades. The per capita income of a country's inhabitants can be an indicator that reflects SED (Chenery, 1960). According to the classical industrialization theory, the level of SED of a country or region can generally be measured in terms of economic development level, industrial structure, agricultural structure, employment structure, and spatial structure (Chen et al., 2006). According to Engel's law, the proportion of income spent on food consumption will gradually decrease as a household's income increases (Kaus, 2013), which means that the more a household will be able to improve household sanitation facilities. With the collection of various statistics becoming more detailed, the total value of the country's primary, secondary, and tertiary industries is also used to describe the country's SED (Wolfe, 1955). Chen et al. analyzed the distribution characteristics of China's regional industrialization process by introducing per capita gross domestic product (GDP), the ratio of the output value of primary, secondary, and tertiary industries, the proportion of added value of industry in the total added value of commodity, the urbanization rate of the population, and the proportion of employment in the primary industry as basic indicators to provide baseline references for the regional economic development (Chen et al., 2006). In this study, we followed Chen's methodology and collected a multi-indicator of SED to measure the SED levels of 30 regions in China from 2007 to 2017. The indicators include population urbanization rate (as spatial structure), tertiary vs. secondary industry output ratio (as industrial structure), nonagricultural output value ratio (as agricultural structure), nonagricultural employment ratio (as employment structure), per capita GDP (as economic development level), and the proportion of added value of industry in the total added value of commodity (as industrial structure) (Li et al., 2019). In addition, we collected data on the penetration rate of RHST in China from 2007 to 2017.

Many efforts have been made to reveal the relationship between socioeconomic and sanitation facilities (Ghosh and Cairncross, 2013; Novotný et al., 2018a). Researchers have discovered a pattern visible in data at the national level, in which access to sanitation facilities is strongly associated with the socioeconomic status of households (Ghosh and Cairncross, 2013; Chandana and Rao, 2022). Other researchers have also confirmed that taking advantage of economic opportunities, incorporating specialized technology, and follows-up with behavior change could help ensure not only access but also sustainable use, operation, and maintenance of sanitation (Tilley et al., 2014). However, in low- and middle-income countries, precision interventions (e.g., financial subsidies) implemented by governments and nongovernmental organizations in addition to improving regional SED can achieve higher access to sanitation (Deshpande et al., 2020). China is the largest developing country, with a rural population of 714.96 million and 556.68 million in 2007 and 2017, respectively. However, many of these rural people choose to shift from primary to secondary and tertiary industry employment each year to increase their household economic income, which undoubtedly improves household sanitation facilities (Zhang et al., 2020). At the same time, the rural toilet revolution is being implemented in various regions of China to increase rural sanitation penetration rate based on existing SED, which could increase the possibility of achieving some of the Millennium Development Goals and Sustainable Development Goals (Cheng et al., 2018). In this study, we examined the relationship between six selected categories of SED indicators and RHST penetration rates from 2007 to 2017.

We used the frequent pattern growth algorithm of the association rule mining method for data analysis to reveal the association relationships among items in a given dataset (Li et al., 2019; Liu et al., 2020). The association rule mining problem was initially studied to discover regularities in the shopping behavior of supermarket customers, which has created many commercial opportunities for stores (Agrawal et al., 1993). In the past decade, the technique has been widely used in evaluating medical datasets and accident investigation analysis, which is attributed to frequent patterns enabling the prediction of one item based on the emergence of others (Ahmed and Nath, 2021; Çakır et al., 2021). Here, we used association rule mining to investigate which SED indicators correspond to high RHST penetration rate and what other levels are associated with low RHST penetration rate. Moreover, we identified indicators of SED associated with influencing the current RHST penetration rate and summarized differentiated strategies for coordinating SED for regions to further enhance RHST penetration rate.

TABLE 1 | Discretization of the socio-economic development (SED) indicators and rural harmless sanitary toilets (RHST) penetration rate for association rule mining.

P	T	V	E	G	I	R
P1 (28.24, 38.16)	T1 (0.53, 0.80)	V1 (71.69, 78.73)	E1 (25.88, 47.05)	G1 (7,878, 29,963)	I1 (26.02, 38.38)	R1 (4.70, 23.90)
P2 (33.50, 45.2)	T2 (0.80, 1.08)	V2 (79.35, 83.71)	E2 (47.36, 58.05)	G2 (30,873, 53,868)	I2 (47.43, 65.22)	R2 (24.40, 42.30)
P3 (45.6, 52.01)	T3 (1.09, 1.59)	V3 (83.95, 86.83)	E3 (58.20, 68.12)	G3 (54838, 85,213)	I3 (65.78, 76.97)	R3 (42.60, 60.90)
P4 (52.43, 60.05)	T4 (1.72, 2.51)	V4 (86.99, 89.71)	E4 (68.28, 82.30)	G4 (86,969, 128,994)	I4 (77.21, 89.58)	R4 (62.00, 81.20)
P5 (60.30, 69.85)	T5 (2.94, 4.24)	V5 (89.75, 92.89)	E5 (83.20, 96.91)			R5 (83.20, 99.80)
P6 (76.31, 89.60)		V6 (93.09, 96.26)				
		V7 (97.90, 99.64)				

Note: P, population urbanization rate; T, tertiary vs. secondary industry output ratio; V, nonagricultural output value ratio; E, nonagricultural employment ratio; G, per capita GDP; I, the proportion of added value of industry in the total added value of commodity; R, rural harmless sanitary toilet penetration rate.

MATERIALS AND METHODS

Study Area and Data Sources

A total of 30 regions in mainland China were used as the research objects (the data on the penetration rate of RHST in Tibet, Hong Kong, Macao, and Taiwan are lacking; thus, they were excluded in this study). On the basis of the data provided by the China Statistical Yearbook (National Bureau of Statistics of China, 2018), China Health Statistical Yearbook (Ministry of Health of the People's Republic of China, 2008), and China Health and Family Planning Statistical Yearbook (National Health and Family Planning Commission of the People's Republic of China, 2013), data on SED from 2007 to 2017 were collected, including population urbanization rate, tertiary vs. secondary industry output ratio, nonagricultural output value ratio (secondary industry output value + tertiary industry output value)/(primary industry output value + secondary industry output value + tertiary industry output value), nonagricultural employment ratio (number of employees in the secondary industry + number of employees in the tertiary industry)/(number of employees in the primary industry + number of employees in the secondary industry + number of employees in the tertiary industry), per capita GDP, the proportion of added value of industry in the total added value of commodity, and RHST penetration rate.

Socio-Economic Development Level Quantification Using a Multi-Indicator System

Each SED indicator was divided by a reference value to remove units of measurement to obtain a dimensionless percentage (**Supplementary Table S1A**). The weights from the hierarchical analysis process of Chen et al. and the weights from the factor analysis of Li et al. were cited (**Supplementary Table S2A**), and the weights from the hierarchical analysis and the factor analysis were averaged to obtain the final weights for each indicator (Chen et al., 2006; Li et al., 2019). Finally, the indicator values were weighted and summed to obtain a quantitative measure of SED.

Association Rule Mining

We discretized six SED indicators and RHST penetration rate into different categories using k-means clustering for association rule mining (**Table 1**). We used the frequent pattern growth algorithm for association rule mining (Agarwal et al., 2000; Han et al., 2004). The problem of association rule mining is to find relationships between the items in a database (Assis et al., 2021). Frequent patterns are patterns that repeatedly appear in a dataset. These patterns carry relevant dataset relationships or correlations (Assis et al., 2021).

Let I be the database of frequent item sets, which is obtained through frequent pattern growth algorithm. Transaction set (T) is a collection of each event. An association rule is an expression shaped as X→Y, which indicates that the conditions in X lead to Y. In the study, we use X to represent different SED indicators, and Y to represent the penetration rate of RHST. The support indicates the frequency of the item set in the dataset (Assis et al., 2021). If the "support" of an item set is greater than a given minimum support threshold, then the item set is frequent (Li et al., 2019). The support of X is defined as the probability of event X occurring in dataset I, support (X) = P (X) (Agarwal, 2013). The support of the rule (X→Y) is the number of tuples in X and Y, as described in **Eq. 1** (Agarwal, 2013; Heng et al., 2017; Assis et al., 2021).

$$support\ (X \rightarrow Y) = support\,(X \cup Y) = P(X \cup Y) \quad (1)$$

The "confidence" is a measure of the accuracy of association rules. Confidence of rule X→Y is defined as the conditional probability of the Y event occurring given that the event X has occurred and is expressed by **Eq. 2** (Aggarwal et al., 2014; Assis et al., 2021).

$$confidence\ (X \rightarrow Y) = P(Y|X) = \frac{support\,(X \rightarrow Y)}{support\,(X)} \quad (2)$$

Support and confidence constitute the threshold for establishing association rules. However, these measures are still insufficient to filter out worthless association rules (Aggarwal, 2014). Lift can solve this weakness in association rules.

Lift can measure the correlation of association rules, and it is used to evaluate whether the item sets X and Y are independent, positively correlated, or negatively correlated. If the lift is equal to 1, then the item set is independent; if the lift is less than 1, then the item set is negatively correlated; if the lift is greater than 1, then the item set is positively correlated (Heng et al., 2017). The expression of lift is shown in **Eq. 3** (Assis et al., 2021).

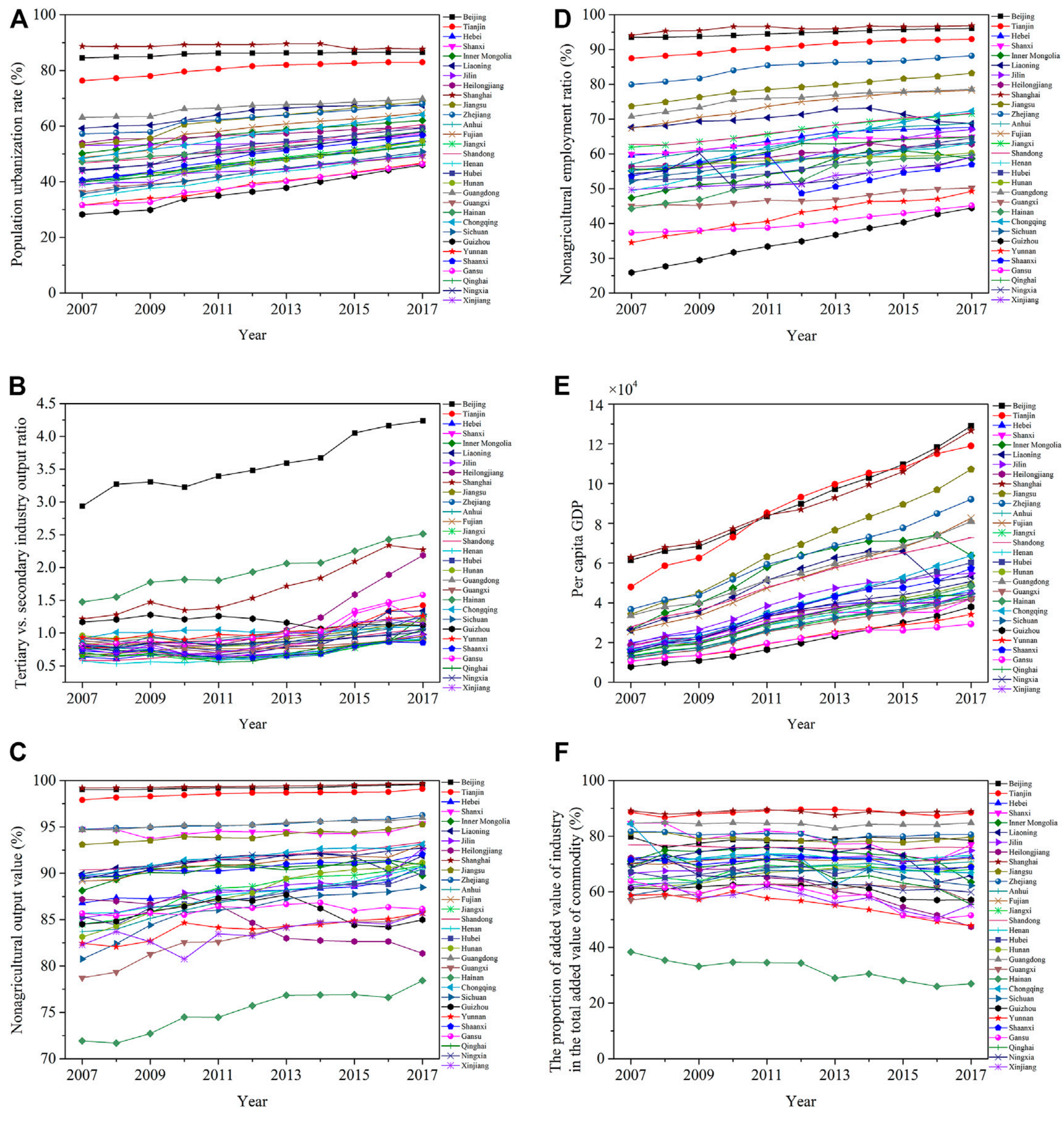

FIGURE 1 | Trends of different socioeconomic development (SED) indicators in 30 regions of China from 2007 to 2017.

$$lift\ (X \rightarrow Y) = \frac{confidence\,(X \rightarrow Y)}{support\,(Y)} \tag{3}$$

We set the goal of association rule mining to find the set of all items that have support greater than the minimum support (i.e., 3%) and confidence greater than the minimum confidence (i.e., 20%) and to make comprehensive decisions based on the lift (Li et al., 2019; Shabtay et al., 2021).

RESULTS AND DISCUSSION

Progress of Socio-Economic Development From 2007 to 2017 in China

In general, the population urbanization rate in China's regions showed a continuous upward trend from 2007 to 2017, except for Shanghai, which declined after 2014 (**Figure 1A**). Shanghai, Beijing, Tianjin, Guangdong, Jiangsu, and Zhejiang were ranked in the top six of China's population urbanization rates, which are all located in the coastal regions of China, except for Beijing, the capital of China. Henan, Xinjiang, Guangxi, Yunnan, Gansu, and Guizhou were the six regions with the lowest population urbanization rates in 2017. Guizhou, Shaanxi, Fujian, Henan, Chongqing, and Jiangsu were the six regions with the fastest population urbanization rates between 2007 and 2017.

We analyzed the tertiary vs. secondary industry output ratio for each region in China from 2007 to 2017 and found a continuous upward trend overall (**Figure 1B**). Beijing, Hainan, Shanghai, Heilongjiang, Gansu, and Tianjin ranked among the top six regions in terms of the tertiary vs. secondary industry output ratio in 2017, while Hebei, Henan, Anhui, Jiangxi, Guangxi, and Shaanxi were the six regions with the lowest tertiary vs. secondary industry output ratio in 2017. Beijing's tertiary vs. secondary industry output ratio exceeded Shaanxi's by nearly four times in 2017.

The nonagricultural output value ratio of China's regions generally showed an upward trend from 2007 to 2017 (**Figure 1C**), except that the ratios in Heilongjiang decreased after 2010. Shanghai, Beijing, Tianjin, Zhejiang, Guangdong, and Shanxi ranked among the top six regions in terms of the nonagricultural output value ratio in 2017. Guangxi, Xinjiang, Yunnan, Guizhou, Heilongjiang, and Hainan were the six regions with the lowest nonagricultural output value ratio in 2017. However, Hunan, Sichuan, Jilin, Guangxi, Anhui, and Hainan were the top six regions with the fastest growth rate of nonagricultural output value ratio from 2007 to 2017.

The nonagricultural employment ratio of all regions in China from 2007 to 2017 showed an overall increasing trend (**Figure 1D**), except for Shaanxi where the trend fluctuated significantly; it increased first (2007–2011) and then decreased (2011–2012), and it increased again in the end (2012–2017). Shanghai, Beijing, Tianjin, Zhejiang, Jiangsu, and Guangdong ranked among the top six regions in terms of the nonagricultural employment ratio in 2017. Inner Mongolia, Shaanxi, Guangxi, Yunnan, Gansu, and Guizhou were the six regions with the lowest nonagricultural employment ratio in 2017. However, Guizhou was the region with the most rapid growth in the nonagricultural employment ratio from 2007 to 2017.

The per capita GDP of all regions in China also showed an overall upward trend from 2007 to 2017 (**Figure 1E**), except for Inner Mongolia, which had a downward trend after 2016; Liaoning, which had a downward trend in 2016, showed rebound in 2017. Beijing, Shanghai, Tianjin, Jiangsu, Zhejiang, and Fujian ranked among the top six regions in terms of the per capita GDP, while Shanxi, Guangxi, Heilongjiang, Guizhou, Yunnan, and Gansu were the six regions with the lowest per capita GDP in 2017. The top six regions in terms of per capita GDP nearly exceeded the lowest six regions by nearly one time in 2017.

The pattern of changes in the proportion of added value of industry in the total added value of commodity of each region from 2007 to 2017 was divided into three cases (**Figure 1F**): 1) The proportion of added value of industry in the total added value of commodity of Hebei, Jilin, Anhui, Fujian, Jiangxi, Henan, Hubei, Hunan, Guangdong, and Sichuan regions maintained a positive growth trend; 2) The proportion of added value of industry in the total added value of commodity of Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang, Shandong, and Guangxi remained relatively constant (with ± 2 gap stabilized in a fixed range); 3) The proportion of added value of industry in the total added value of commodity in Shanxi, Inner Mongolia, Liaoning, Heilongjiang, Hainan, Chongqing, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang changed with a negative trend.

The contribution of different indicators to SED is shown in **Figure 2**. The proportion of added value of industry in the total added value of commodity had the largest contribution, followed by per capita GDP and population urbanization rate. This result corresponds to the researchers' finding that the country's industrialization process drove the increase in economic output and contributed to the shift of labor from rural to urban areas (Li et al., 2019). The trends in the overall level of SED of China's regions from 2007 to 2017 are shown in **Figure 3**. The SED among China's regions showed an imbalance. The overall level of SED in the coastal regions of China was generally higher than in the central and western regions.

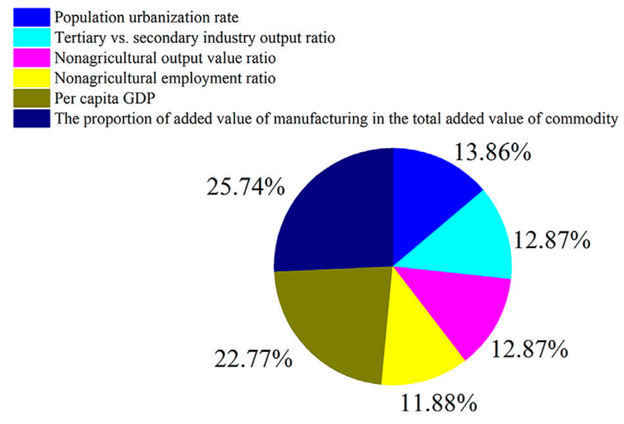

FIGURE 2 | Contribution of different indicators to SED.

Penetration Rate of Rural Harmless Sanitary Toilets From 2007 to 2017

The penetration rate of RHST in all regions of China showed an increasing trend from 2007 to 2017 (**Figure 4**), except for Beijing, Tianjin, Hebei, Heilongjiang, Henan, Hubei, Chongqing, Shaanxi, and Xinjiang, which declined after 2016. The top six rural areas in China in terms of the penetration rate of RHST in 2017 included Shanghai, Beijing, Zhejiang, Fujian, Tianjin, and Guangdong, all of which are located in China's coastal areas, except for Beijing, the capital of China. Gansu, Inner Mongolia, Shaanxi, Jilin, Qinghai, and Heilongjiang were the six regions with the least penetration rate of RHST in China, which are located in North China, Northwest China, and Northeast China. The imbalance in the penetration rate of RHST between regions in China was still significant. Notably, the Chinese government has launched a series of special actions for rural toilet retrofitting since 2018, and it has formulated a number of policies, such as the *Three-Year Action Plan for Rural Living Environment Improvement* and the Guiding Opinions on *Promoting the Special Action of Rural "Toilet Retrofitting*," which offers new opportunities to improve the imbalance in the penetration rate of RHST among China's regions (Central People's Government of the People's Republic of China, 2018; Ministry of Agriculture and Rural Affairs of the People's Republic of China, 2019). However, each region needs to improve its SED according to the actual situation to improve the penetration rate of RHST and achieve sustainable sanitation.

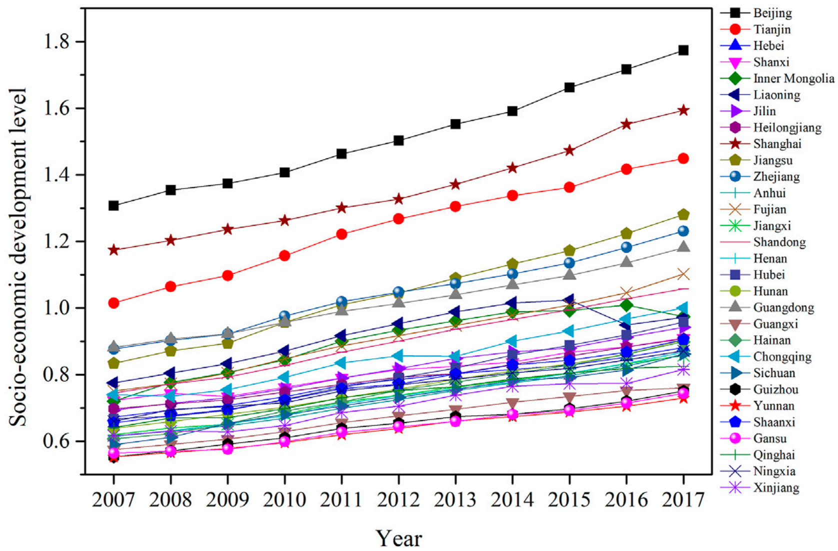

FIGURE 3 | Progress of SED in the 30 regions in China from 2007 to 2017.

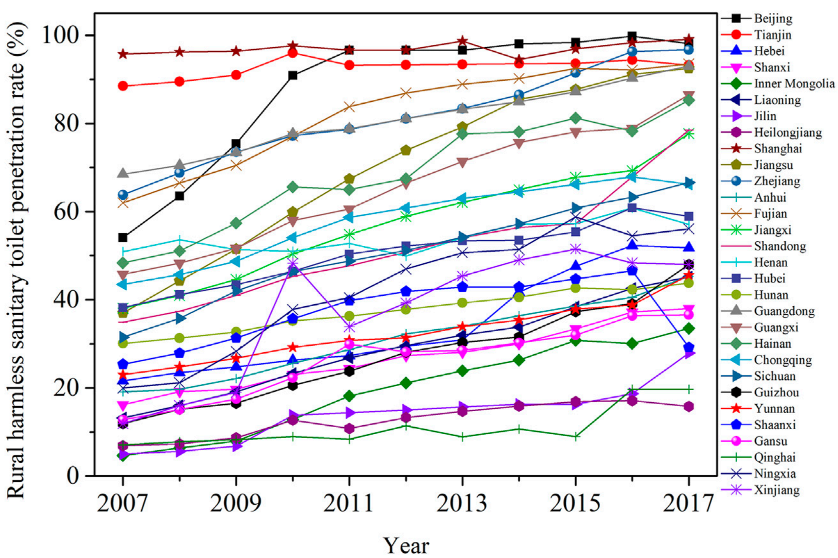

FIGURE 4 | Process of change in the penetration rate of rural harmless sanitary toilets (RHST) in 30 regions of China from 2007 to 2017.

Association Rules Between Socio-Economic Development Indicators and the Penetration Rate of Rural Harmless Sanitary Toilets in China

A summary of the association rules between the six selected SED indicators and the penetration rate of RHST is shown in **Supplementary Table S3A**. **Table 2** summarizes the association rules between the six selected SED indicators and the high penetration rate of RHST. Given that the population urbanization rate ranged from 60.30 to 69.85% and from 76.31 to 89.60%, the tertiary vs. secondary industry output ratio ranged between 1.09 and 1.59, the nonagricultural output value ratio ranged from 93.09 to 96.26% and from 97.90 to 99.64%, nonagricultural employment ratio ranged from 68.28 to 82.30% and from 83.20 to 96.91%, per capita GDP ranged between 54,838 and 128,994, and the proportion of added value of industry in the total added value of commodity ranged between 77.21 and 89.58; RHST was of high penetration rate. A set of reasonable ranges of the population urbanization rate, the tertiary vs. secondary industry output ratio, nonagricultural output value ratio, the nonagricultural

TABLE 2 | Association rules between one SED indicator and high penetration rate of RHST.

Indicators	Indicator interval value	RHST penetration rate level	RHST penetration rate level interval value	Degree of RHST penetration rate
P5	(60.30, 69.85)	R5	(83.20, 99.80)	Very high
P6	(76.31, 89.60)	R5	(83.20, 99.80)	Very high
T3	(1.09, 1.59)	R5	(83.20, 99.80)	Very high
V6	(93.09, 96.26)	R5	(83.20, 99.80)	Very high
V7	(97.90, 99.64)	R5	(83.20, 99.80)	Very high
E4	(68.28, 82.30)	R5	(83.20, 99.80)	Very high
E5	(83.20, 96.91)	R5	(83.20, 99.80)	Very high
G3	(54838, 85,213)	R5	(83.20, 99.80)	Very high
G4	(86,969, 128,994)	R5	(83.20, 99.80)	Very high
I4	(77.21, 89.58)	R5	(83.20, 99.80)	Very high
P5	(60.30, 69.85)	R4	(62.00, 81.20)	High
T2	(0.80, 1.08)	R4	(62.00, 81.20)	High
V6	(93.09, 96.26)	R4	(62.00, 81.20)	High
E4	(68.28, 82.30)	R4	(62.00, 81.20)	High
G2	(30873, 53,868)	R4	(62.00, 81.20)	High
G3	(54838, 85,213)	R4	(62.00, 81.20)	High
I4	(77.21, 89.58)	R4	(62.00, 81.20)	High

TABLE 3 | Association rules between one SED indicator and penetration rate of RHST.

Indicators	Indicator interval value	RHST penetration rate level	RHST penetration rate level interval value	Degree of RHST penetration rate
P1	(28.24, 38.16)	R1	(4.70, 23.90)	Very low
P2	(33.50, 45.2)	R1	(4.70, 23.90)	Very low
P4	(52.43, 60.05)	R1	(4.70, 23.90)	Very low
T1	(0.53, 0.80)	R1	(4.70, 23.90)	Very low
V2	(79.35, 83.71)	R1	(4.70, 23.90)	Very low
V3	(83.95, 86.83)	R1	(4.70, 23.90)	Very low
V4	(86.99, 89.71)	R1	(4.70, 23.90)	Very low
V5	(89.75, 92.89)	R1	(4.70, 23.90)	Very low
E1	(25.88, 47.05)	R1	(4.70, 23.90)	Very low
E2	(47.36, 58.05)	R1	(4.70, 23.90)	Very low
E3	(58.20, 68.12)	R1	(4.70, 23.90)	Very low
G1	(7,878, 29,963)	R1	(4.70, 23.90)	Very low
I2	(47.43, 65.22)	R1	(4.70, 23.90)	Very low
I3	(65.78, 76.97)	R1	(4.70, 23.90)	Very low
P2	(33.50, 45.2)	R2	(24.40, 42.30)	Low
P3	(45.6, 52.01)	R2	(24.40, 42.30)	Low
T1	(0.53, 0.80)	R2	(24.40, 42.30)	Low
T3	(1.09, 1.59)	R2	(24.40, 42.30)	Low
V3	(83.95, 86.83)	R2	(24.40, 42.30)	Low
V4	(86.99, 89.71)	R2	(24.40, 42.30)	Low
E1	(25.88, 47.05)	R2	(24.40, 42.30)	Low
E3	(58.20, 68.12)	R2	(24.40, 42.30)	Low
G1	(7,878, 29,963)	R2	(24.40, 42.30)	Low
I2	(47.43, 65.22)	R2	(24.40, 42.30)	Low
I3	(65.78, 76.97)	R2	(24.40, 42.30)	Low
P3	(45.6, 52.01)	R3	(42.60, 60.90)	Moderate
P4	(52.43, 60.05)	R3	(42.60, 60.90)	Moderate
T2	(0.80, 1.08)	R3	(42.60, 60.90)	Moderate
V3	(83.95, 86.83)	R3	(42.60, 60.90)	Moderate
V4	(86.99, 89.71)	R3	(42.60, 60.90)	Moderate
V5	(89.75, 92.89)	R3	(42.60, 60.90)	Moderate
E2	(47.36, 58.05)	R3	(42.60, 60.90)	Moderate
E3	(58.20, 68.12)	R3	(42.60, 60.90)	Moderate
G2	(30,873, 53,868)	R3	(42.60, 60.90)	Moderate
I3	(65.78, 76.97)	R3	(42.60, 60.90)	Moderate

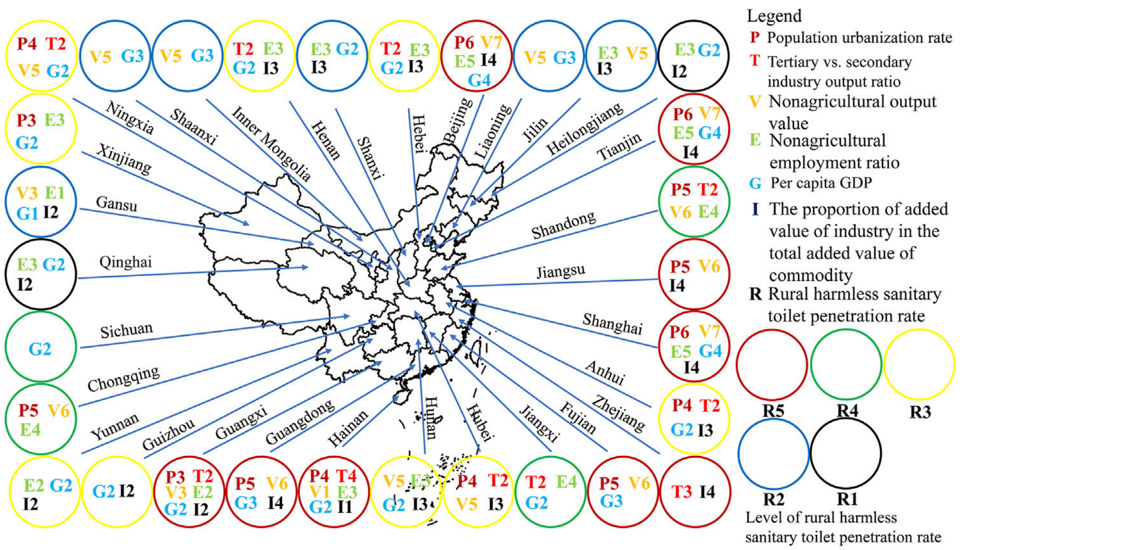

FIGURE 5 | SED indicators of regions associated with RHST penetration rate in China.

employment ratio, per capita GDP, and the proportion of added value of industry in the total added value of commodity can be found in **Table 2** for high RHST penetration degree.

Table 3 summarizes the association rules between SED indicators and the penetration rate of RHST. We found that a low level of RHST penetration rate was significantly correlated with the population urbanization rate, ranging from 28.24 to 38.16% and from 33.5 to 45.2%. The low penetration rate of RHST with low population urbanization rate may be caused by inadequate rural infrastructure. The low penetration rate of RHST also existed in areas where the tertiary vs. secondary industry output ratio ranged between 0.53 and 0.80%, the nonagricultural output value ratio ranged between 79.35 and 83.71%, between 83.95 and 86.83%, between 86.99 and 89.71%, and between 89.75 and 92.89%, the nonagricultural employment ratio ranged between 25.88 and 47.05%, between 47.36 and 58.05%, and between 58.20 and 68.12%, per capita GDP ranged between 7,878 and 29,963, and the proportion of added value of industry in the total added value of commodity ranged between 47.43 and 65.22% and between 65.78 and 76.97%. Therefore, the association rule analysis showed that the low value of the six selected indicators of SED determined the low level of penetration rate of RHST.

Differentiated Development Strategies to Increase the Rural Harmless sanitary Toilets Penetration Rate

We identified SED indicators related to the penetration rate of RHST by region in China in 2017 according to **Supplementary Table S4A**, as shown in **Figure 5**, to propose differentiated development strategies to increase the penetration rate of RHST.

For Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang, Fujian, and Guangdong, the six SED indicator values all corresponded to high RHST penetration rates (R5), and these regions can maintain their current rate of SED to increase per capita GDP. With income increases, local rural residents have more ability to improve household sanitation. Local governments will also have more financial resources for the construction, operation, and maintenance of sanitation facilities.

We found that the SED indicators of Guangxi and Hainan were at the lower rank, except for Hainan where the tertiary vs. secondary industry output ratio was in the T4 range, but they corresponded to a high RHST penetration rate in 2017 (at the R5 rank) given that they belong to the coastal region. Guangxi and Hainan should further increase the proportion of added value of industry in the total added value of commodity, such as investing in high-tech industry technologies, because they are in the lower rank of I2 and I1, respectively. The tertiary industry needs to be optimized to create more jobs and raise the resident's per capita GDP. Local governments not only need to improve the wastewater treatment facilities in each rural area but also need to form a long-term management and maintenance mechanism due to the abundant water resources, to reduce the pollution of water sources by toilet wastewater.

Among the six socioeconomic indicators studied, the E4, T2, and G2 indicators in Jiangxi, V6, P5, T2, and E4 indicators in Shandong, V6, E4, and P5 indicators in Chongqing, and G2 indicator in Sichuan were associated with the penetration rate of RHST at the R4 level. However, the abovementioned SED indicators associated with the penetration rate of RHST were all at moderate levels in the aforementioned regions, which means that more investments could be made in the tertiary industry and further attract more manufacturers to increase the proportion of added value of industry in the total added value of commodity for enhancing the household wealth of the residents in these regions. The population urbanization rates of Jiangxi and Sichuan were P4 and P3, respectively, which were at middle level. In the process of SED, on one hand, improving household sanitation facilities needs to rely on the efforts of rural residents, and on the other hand, the proportion of financial support from local governments needs to be increased to help more rural residents with financial difficulties, thereby increasing the penetration rate of local RHST. Liu et al. studied the rural toilet retrofitting model in Jiaozhou (located in Shandong Province, China) and found that local rural residents have achieved full access to RHST and have also constructed a complete sustainable sanitation service chain covering collection, transportation, treatments, disposal, and resource recovery of fecal sludge relying on financial support from the provincial and municipal governments (Liu et al., 2019). However, the constructed sustainable sanitation service chain in rural areas requires a large amount of operating capital, part of which needs to be paid by rural residents, such as the cost of manure pumping by septic tankers and the maintenance of sanitation facilities, which is difficult for poor rural households (Roubík et al., 2020). Therefore, preferential policies and funding to help serve families with financial difficulties are also a guarantee of sustainable sanitation (Kaiser, 2015).

Regions in Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Anhui, Henan, Hunan, Guizhou, Yunnan, Ningxia, Xinjiang, Shaanxi, Gansu, and Qinghai did not have SED indicators associated with high penetration rate of RHST. Therefore, these regions should increase investment in industry to enhance SED. In Guizhou and Yunnan, the tertiary vs. secondary industry ratio (at T3 level) was better than other SED indicators, but the proportion of added value of industry in the total added value of commodity was at I2 level and needs to be further strengthened. Sun et al. also evaluated the SED of Guizhou province finding that regions with proportion of secondary industry have a prosperous economy (Sun et al., 2020). In Heilongjiang and Qinghai, the RHST penetration rate was at R1 level, which was mined by the association analysis to be related to the low nonagricultural employment ratio, per capita GDP, and the proportion of added value of industry in the total added value of commodity. Therefore, the local government should increase investment and attract more domestic and international manufacturers with preferential policies to improve the level of SED indicators. Guo et al. surveyed villages in western China (Gansu and Qinghai) and found that poor sanitation awareness and attitudes impede the progress of the rural toilet revolution (Guo et al., 2021). We hypothesized that sanitation services would be enhanced if the level of SED in the western region also approached that of the coastal region. However, achieving more than 60% RHST penetration rate in a short period based on the current rate of SED alone is difficult given that huge challenges exist in the SED process. Therefore, the national central government should allocate a greater proportion of central financial resources for rural toilet retrofitting in these areas during the rural "toilet revolution" process. Overall, the identification of regional SED indicators related to the penetration rate of RHST can help develop targeted regional SED plans to achieve the penetration of RHST in China.

Influence of Policy on the Penetration Rate of Rural Harmless Sanitary Toilets

Variability exists in rural infrastructure investments in different regions of China (Li et al., 2020). Nevertheless, the implementation of the policy successfully promotes SED. However, inadequate financial resources still constrain rapid SED in some rural areas, such as those with low rural infrastructure penetration rates (Zhang et al., 2020). Fortunately, to achieve universal access to sanitation with "safe management services," which is defined as "access to a sanitation facility that is not shared with other households and where excreta produced can be safely disposed of on-site, or transported and disposed of off-site" (WHO and UNICEF, 2017), China's central government gives provincial governments the freedom to decide on strategies and methods for rural toilet retrofitting policies to achieve the desired outcomes. Hueso and Bell noted that policies should be people-centered, demand-, incentive-, and practice-oriented, which is ideal for addressing the rural sanitation crisis (Hueso and Bell, 2013). However, the researchers found that availability of policy information, the percentage of subsidies, and the difficulty of obtaining subsidies affected the motivation of rural residents to participate in rural toilet retrofitting, especially poor rural households (Kaiser, 2015; Roubík et al., 2020).

Chinese provinces should clarify short-term development goals and long-term development goals when formulating policies. On the one hand, for economically developed provinces with high penetration of RHST, the supporting facilities to have access to safe transportation, treatment, and disposal of toilet wastes are imperfect. In addition to focusing on SED, the local government needs to formulate more policies to serve the improvement and operation of supporting facilities for toilet waste treatment. On the other hand, for backward economic developing provinces with low penetration of RHST, local governments should focus on the continuity convergence of policies. In a short period of time, the penetration rate of RHST should be improved by adhering to the short-term promotion strategy of "quantity follows quality and progress follows effectiveness." When the penetration rate of RHST is raised, the policy should focus on the improvement of supporting facilities for toilet waste treatment.

CONCLUSION

We studied the association pattern between SED indicators and the penetration rate of RHST by regions in China from 2007 to 2017. Overall, the selected six categories of SED indicators of Chinese regions have been increasing in population urbanization rate, tertiary vs. secondary industry output ratio, nonagricultural output value ratio, nonagricultural employment ratio, and per capita GDP. The proportion of added value of industry in the total added value of commodity showed three trend changes, which were 1) a positive trend change, 2) a stable fixed interval with a ±2 ratio difference, and 3) a negative trend change. The proportion of added value of industry in the total added value of commodity accounted for the highest proportion of the level of SED. The penetration rate of RHST continuously increased in all regions of China from 2007 to 2017. The results of the association rule emphasize that reasonable SED indicators are essential for high RHST penetration rate. Differentiated development strategies were proposed to optimize SED indicators in different regions for improving RHST penetration rate.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

YL contributed to the writing of the original draft and visualization of the study. SC contributed to the conceptualization, methodology, writing, reviewing and editing of the manuscript, and supervision of the study. JC contributed to the data curation of the study. MG contributed to the data curation and software of the study. ZL contributed to the methodology, writing, reviewing, and editing of the manuscript. LW, CC, and DB contributed to the methodology of the study. TL contributed to the funding acquisition and supervision of the study. All authors approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.817655/full#supplementary-material

REFERENCES

Agarwal, R. C., Aggarwal, C. C., and Prasad, V. V. V. (2000). "Depth First Generation of Long Patterns," in Proceedings of the sixth ACM SIGKDD international conference on Knowledge discovery and data mining, Boston, MA, August 2000 (Association for Computing Machinery), 108–118. doi:10.1145/347090.347114

Agarwal, S. (2013). "Data Mining: Data Mining Concepts and Techniques," in 2013 International Conference on Machine Intelligence and Research Advancement, Katra, December 21–23, 2013, 203–207. doi:10.1109/ICMIRA.2013.45

Aggarwal, C. C. (2014). "An Introduction to Frequent Pattern Mining," in *Frequent Pattern Mining* (Cham: Springer), 1–17. doi:10.1007/978-3-319-07821-2_1

Aggarwal, C. C., Bhuiyan, M. A., and Hasan, M. A. (2014). "Frequent Pattern Mining Algorithms: A Survey," in *Frequent Pattern Mining* (Cham: Springer), 19–64. doi:10.1007/978-3-319-07821-2_2

Agrawal, R., Imieliński, T., and Swami, A. (1993). "Mining Association Rules between Sets of Items in Large Databases," in Proceedings of the 1993 ACM SIGMOD international conference on Management of data, Washington, DC, June 1, 1993 (Association for Computing Machinery) 22, 207–216. SIGMOD Rec. doi:10.1145/170036.170072

Ahmed, S. A., and Nath, B. (2021). Identification of Adverse Disease Agents and Risk Analysis Using Frequent Pattern Mining. *Inf. Sci.* 576, 609–641. doi:10.1016/j.ins.2021.07.061

Assis, B. d. S. d., Ogasawara, E., Barbastefano, R., and Carvalho, D. (2021). Frequent Pattern Mining Augmented by Social Network Parameters for Measuring Graduation and Dropout Time Factors: A Case Study on a Production Engineering Course. *Socio-Econ. Plan. Sci.*, 101200. doi:10.1016/j.seps.2021.101200

Çakır, E., Fışkın, R., and Sevgili, C. (2021). Investigation of Tugboat Accidents Severity: An Application of Association Rule Mining Algorithms. *Reliability Eng. Syst. Saf.* 209, 107470. doi:10.1016/j.ress.2021.107470

Central People's Government of the People's Republic of China (2018). Three-Year Action Plan for Rural Living Environment Improvement. Available at: http://www.gov.cn/zhengce/2018-02/05/content_5264056.htm (Accessed November 5, 2021).

Chandana, N., and Rao, B. (2022). A Critical Review on Sludge Management from Onsite Sanitation Systems: A Knowledge to Be Revised in the Current Situation. *Environ. Res.* 203, 111812. doi:10.1016/j.envres.2021.111812

Chen, J., Huang, Q., and Zhong, H. (2006). The Synthetic Evaluation and Analysis on Regional Industrialization. *Econ. Res. J.* 6, 4–15. [in Chinese, with English summary].

Chenery, H. B. (1960). Patterns of Industrial Growth. *Am. Econ. Rev.* 50, 624–654.

Cheng, S., Li, Z., Uddin, S. M. N., Mang, H.-P., Zhou, X., Zhang, J., et al. (2018). Toilet Revolution in China. *J. Environ. Manage.* 216, 347–356. doi:10.1016/j.jenvman.2017.09.043

China National Health Commission (2018). *China Health Statistics Yearbook*. Beijing: China Peking Union Medical University Press, 278. (in Chinese).

Deshpande, A., Miller-Petrie, M. K., Lindstedt, P. A., Baumann, M. M., and Johnson, K. B. (2020). Mapping Geographical Inequalities in Access to Drinking Water and Sanitation Facilities in Low-Income and Middle-Income Countries, 2000-17. *Lancet Glob. Health* 8, e1162–e1185. doi:10.1016/S2214-109X(20)30278-3

Gasana, J., Morin, J., Ndikuyeze, A., and Kamoso, P. (2002). Impact of Water Supply and Sanitation on Diarrheal Morbidity Among Young Children in the Socioeconomic and Cultural Context of Rwanda (Africa). *Environ. Res.* 90, 76–88. doi:10.1006/enrs.2002.4394

Ghosh, A., and Cairncross, S. (2013). The Uneven Progress of Sanitation in India. *J. Water Sanitation Hyg. Dev.* 4, 15–22. doi:10.2166/washdev.2013.185

Guo, S., Zhou, X., Simha, P., Mercado, L. F. P., Lv, Y., and Li, Z. (2021). Poor Awareness and Attitudes to Sanitation Servicing Can Impede China's Rural Toilet Revolution: Evidence from Western China. *Sci. Total Environ.* 794, 148660. doi:10.1016/j.scitotenv.2021.148660

Han, J., Pei, J., Yin, Y., and Mao, R. (2004). Mining Frequent Patterns without Candidate Generation: A Frequent-Pattern Tree Approach. *Data Mining Knowledge Discov.* 8, 53–87. doi:10.1023/b:dami.0000005258.31418.83

Heng, J., Wang, J., Xiao, L., and Lu, H. (2017). Research and Application of a Combined Model Based on Frequent Pattern Growth Algorithm and Multi-Objective Optimization for Solar Radiation Forecasting. *Appl. Energ.* 208, 845–866. doi:10.1016/j.apenergy.2017.09.063

Hueso, A., and Bell, B. (2013). An Untold story of Policy Failure: the Total Sanitation Campaign in India. *Water Policy* 15, 1001–1017. doi:10.2166/wp.2013.032

Kaiser, J. (2015). For Toilets, Money Matters. *Science* 348, 272. doi:10.1126/science.348.6232.272

Kaus, W. (2013). Beyond Engel's Law - A Cross-Country Analysis. *The J. Socio-Economics* 47, 118–134. doi:10.1016/j.socec.2013.10.001

Li, T., Li, Y., An, D., Han, Y., Xu, S., Lu, Z., et al. (2019). Mining of the Association Rules between Industrialization Level and Air Quality to Inform High-Quality

Development in China. *J. Environ. Manage.* 246, 564–574. doi:10.1016/j.jenvman.2019.06.022

Li, Y., Cheng, S., Li, Z., Song, H., Guo, M., Li, Z., et al. (2020). Using System Dynamics to Assess the Complexity of Rural Toilet Retrofitting: Case Study in Eastern China. *J. Environ. Manage.* 111655, 1–10. doi:10.1016/j.jenvman.2020.111655

Liu, J., Shi, D., Li, G., Xie, Y., Li, K., Liu, B., et al. (2020). Data-driven and Association Rule Mining-Based Fault Diagnosis and Action Mechanism Analysis for Building Chillers. *Energy and Buildings* 216, 109957. doi:10.1016/j.enbuild.2020.109957

Liu, Z., Xu, Y., Liu, B., Liu, Z., and Zang, J. (2019). *Study on Jiaozhou Model of Toilet Renovation in Rural China*. Beijing: China Society Press. (in Chinese).

Ministry of Agriculture and Rural Affairs of the People's Republic of China (2019). Guiding Opinions on Promoting the Special Action of Rural "Toilet Retrofitting". Available at: http://www.moa.gov.cn/gk/tzgg_1/tz/201901/t20190108_6166292.htm (Accessed November 5, 2021).

Ministry of Health of the People's Republic of China (2008). *China Health Statistics Yearbook*. Beijing: Peking Union Medical College Press of China, 251. (in Chinese).

National Bureau of Statistics of China (2018). *China Statistical Yearbook*. Beijing: China Statistics Press. (in Chinese).

National Health and Family Planning Commission of the People's Republic of China (2013). *China Health and Family Planning Statistical Yearbook*. Beijing: Peking Union Medical College Press of China. (in Chinese).

Novotný, J., Ficek, F., Hill, J. K. W., and Kumar, A. (2018a). Social Determinants of Environmental Health: A Case of Sanitation in Rural Jharkhand. *Sci. Total Environ.* 643, 762–774. doi:10.1016/j.scitotenv.2018.06.239

Novotný, J., Humňalová, H., and Kolomazníková, J. (2018b). The Social and Political Construction of Latrines in Rural Ethiopia. *J. Rural Stud.* 63, 157–167. doi:10.1016/j.jrurstud.2018.08.003

Roubík, H., Mazancova, J., Rydval, J., and Kvasnicka, R. (2020). Uncovering the Dynamic Complexity of the Development of Small–Scale Biogas Technology through Causal Loops. *Renew. Energ.* 149, 235–243. doi:10.1016/j.renene.2019.12.019

Shabtay, L., Fournier-Viger, P., Yaari, R., and Dattner, I. (2021). A Guided FP-Growth Algorithm for Mining Multitude-Targeted Item-Sets and Class Association Rules in Imbalanced Data. *Inf. Sci.* 553, 353–375. doi:10.1016/j.ins.2020.10.020

Sun, M., Li, X., Yang, R., Zhang, Y., Zhang, L., Song, Z., et al. (2020). Comprehensive Partitions and Different Strategies Based on Ecological Security and Economic Development in Guizhou Province, China. *J. Clean. Prod.* 274, 122794. doi:10.1016/j.jclepro.2020.122794

Tian, Y., and Wang, L. (2019). Mutualism of Intra- and Inter-prefecture Level Cities and its Effects on Regional Socio-Economic Development: A Case Study of Hubei Province, Central China. *Sust. Cities Soc.* 44, 16–26. doi:10.1016/j.scs.2018.09.033

Tilley, E., Strande, L., Lüthi, C., Mosler, H.-J., Udert, K. M., Gebauer, H., et al. (2014). Looking beyond Technology: An Integrated Approach to Water, Sanitation and Hygiene in Low Income Countries. *Environ. Sci. Technol.* 48, 9965–9970. doi:10.1021/es501645d

Trimmer, J. T., Lohman, H. A. C., Byrne, D. M., Houser, S. A., Jjuuko, F., Katende, D., et al. (2020). Navigating Multidimensional Social-Ecological System Trade-Offs across Sanitation Alternatives in an Urban Informal Settlement. *Environ. Sci. Technol.* 54, 12641–12653. doi:10.1021/acs.est.0c03296

United Nations (2017). *World Population Prospects (2017). The 2017 Revision*. New York: United Nations Department of Economic and Social Affairs, Population Division.

Wei, W., Guo, Z., Xie, B., Zhou, J., and Li, C. (2020). Quantitative Simulation of Socio-Economic Effects in mainland China from 1980 to 2015: A Perspective of Environmental Interference. *J. Clean. Prod.* 253, 119939. doi:10.1016/j.jclepro.2019.119939

WHO (2020a). *Hygiene: UN-water GLAAS Findings on National Policies, Plans, Targets and Finance*. Geneva: World Health Organization.

WHO (2020b). *World Health Statistics 2020: Monitoring Health for the Sdgs, Sustainable Development Goals*. Geneva: World Health Organization.

WHO, UNICEF (2017). *Progress on Drinking Water, Sanitation and hygiene: 2017 Update and Sustainable Development Goal Baselines*. Geneva: World Health Organization (WHO) and the United Nations Children's Fund UNICEF.

Wolfe, M. (1955). The Concept of Economic Sectors. *Q. J. Econ.* 69, 402–420. doi:10.2307/1885848

Zhang, S., Li, Y., Zhang, Y., Lu, Z.-N., and Hao, Y. (2020). Does Sanitation Infrastructure in Rural Areas Affect Migrant Workers' Health? Empirical Evidence from China. *Environ. Geochem. Health* 42, 625–646. doi:10.1007/s10653-019-00396-2

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Generation and Management of Faecal Sludge Quantities and Potential for Resource Recovery in Phnom Penh, Cambodia

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At the current rate of progress, there will probably still be 2.8 billion people world-wide without safely managed sanitation by 2030. To incentivise and increase implementation of sustainable faecal sludge management (FSM), especially in low and middle-income countries like Cambodia, human waste must be regarded as a resource. However, planning data, e.g. on the quantities, composition and fate of faecal sludge after leaving households, are inadequate and lack accuracy. The aim of this study was to provide baseline data for effective FSM planning by sanitation stakeholders in Phnom Penh. This was done by quantifying sludge volumes generated, transport logistics and resource recovery potential to incentivise sustainable management. Interviews were conducted with users and emptying and transportation contractors, together with collection of technical data about on-site sanitation systems. Geographical coordinates of household sampling locations and disposal sites were also mapped. The results revealed that Cheung Ek and Kob Srov wetlands are the main recipients of faecal sludge collected in Phnom Penh with the amount of 18,800 m^3 and 13,700 m^3 annually, respectively. The analysis showed that faecal sludge in Phnom Penh contains valuable resources such as nitrogen (6 tons), phosphorus (13 tons) and energy (148-165 GWh) annually, but in-depth investigations of appropriate treatment options for resource recovery are required. Detailed documentation of the location of potential recoverable resources from faecal sludge would assist decision-makers in developing action plans for sustainable FSM in Phnom Penh and similar cities.

Keywords: faecal sludge management (FSM), geographic information system (GIS), nutrient recovery, onsite sanitation, sanitation service chain, spatial analysis

INTRODUCTION

Nearly half the world's population lacks access to safely managed sanitation services. Meeting the goal of universal access to safely managed sanitation services by 2030 will require at least a four-fold increase in current rates of progress, depending on the national context (WHO and UNICEF, 2021). This implies that there will likely still be 2.8 billion people world-wide without safely managed sanitation services by 2030 (WHO and UNICEF, 2017). Safely managed sanitation is defined as the use of improved human waste facilities with safe disposal *in situ* or off-site transportation and treatment (Borja et al., 2019; Chandana and Rao, 2022). In many low-income cities, the majority of faecal sludge collected in on-site sanitation technologies, such as pit latrines, is not safely managed (Hafford et al., 2018). Studies in 12 cities have shown that only 37% have safely managed sanitation and that faecal sludge ends up in the immediate urban environment, posing risks to humans and the environment (Peal et al., 2015; Hafford et al., 2018). Environmental impacts from excess nutrients include eutrophication and algal blooms in surface waters, altering the ecosystem functions (Andersson et al., 2016; Singh et al., 2017). This means that increasing the sanitation coverage by expanding the number of toilets cannot be the only solution to controlling waterborne disease and achieving United Nations Sustainable Development Goal 6 (UN SDG) target 6.2 (Strande et al., 2014; Chandana and Rao, 2022). Increasing toilet coverage would reduce open defecation, but is not a stand-alone solution to achieving safely managed sanitation. Rather, solutions and funding are needed to maintain the functionality of the entire faecal sludge management service chain. Appropriate faecal sludge collection and transportation is one of the major future challenges for low-and middle-income countries and efficient Faecal Sludge Management (FSM) is a pressing need (Chandana and Rao, 2021).

There is a misconception that on-site sanitation systems are simpler to manage than centrally based systems, resulting in adequate funding often not being allocated (Strande et al., 2018). Likewise, effective and proper FSM requires attention to the entire service chain (Boot and Scott, 2008; Strande et al., 2014), components of which include collection, transportation, treatment and safe end-uses or disposal (Klingel et al., 2002) and resource recovery (Zewde et al., 2021). In addition to considering all these components, for effective and sustainable FSM at city scale, data on the qualities and quantities of faecal sludge generated are required (Boot and Scott, 2008). However, accurate estimation of the qualities and quantities of faecal sludge on a city-wide level is complicated and such data are often lacking (Strande et al., 2018; Chandana and Rao, 2022). Faecal sludge characteristics differ widely by region, between cities, districts and households, and by source, for instance public and private toilet sludge (Appiah-Effah et al., 2014b; Gudda et al., 2017). Furthermore, there are variations in the characteristics of faecal sludge due to socio-economic status of source households, types of on-site sanitation technologies and collection system (Chandana and Rao, 2022). Selection of appropriate treatment technology is difficult due to these wide ranges of characteristics and unknown stabilisation status of collected faecal sludge (Dodane et al., 2012; Bassan et al., 2013; Appiah-Effah et al., 2014a). Reliable estimates of the qualities and quantities of faecal sludge are important when designing treatment, to avoid over- or under-dimensioned infrastructure. Inadequately sized or non-existent primary treatment and management solutions impact treatment plant operations and pose a direct risk to public health (Strande et al., 2018). For instance, Phnom Penh, the capital city of Cambodia, has no treatment facility in place to receive and treat faecal sludge. Only 22% of on-site sanitation users in the city report emptying their sludge container and only 12% of emptied sludge reaches authorised disposal sites (Peal et al., 2015), while the rest is probably discharged directly into open canals, the sewerage system or surrounding lakes (PPCH, 2021).

Treated faecal sludge is a potential source of fuel (Hafford et al., 2018) and a soil amendment for crop production (Zewde et al., 2021), benefits that could offset the upfront costs of treatment (Hafford et al., 2018; Zewde et al., 2021). Indeed, there is an on-going paradigm shift from viewing human excreta as a waste to seeing it as a resource (Andersson et al., 2016). High value of the recoverable product from faecal sludge could serve as an incentive for appropriate faecal sludge management (Diener et al., 2014), while improving access to sanitation and renewable agricultural inputs (Echevarria et al., 2021). Different types of faecal sludge treatment products could be recovered as resources, such as energy, animal food, building materials, nutrients and water (Schoebitz et al., 2016). Faecal sludge is currently attracting attention as a potentially valuable resource for two reasons. First, it has high potential for generation of biogas, and therefore energy. Second, the digested sludge has good potential to be recycled and re-used as a fertiliser on agricultural land (Yin et al., 2016). However, accurate estimation of the resources contained in sludge is needed to prove the potential benefit to sanitation planners. Information on the quantities and flows of sludge after removal from households is lacking for Phnom Penh and for other similar cities world-wide.

Efficient waste collection and transportation could be a cost-saving option for municipalities (Kinobe et al., 2015), but setting up resource recovery systems from FSM requires planning and efficient logistics within the service chain. Application of spatial Geographic Information System (GIS) tools can facilitate logistics planning by reducing the number of trips and travel distance, thereby decreasing fuel consumption and vehicle emissions and providing cost savings in overall sanitation provision (Schoebitz et al., 2017). Using GIS tools for optimisation of faecal sludge collection and transportation at city-wide scale can thus provide opportunities to increase sustainable management of faecal sludge. GIS-based methods are applicable everywhere, but there is a need for local data inputs (Schoebitz et al., 2017). Moreover, there is often no baseline information, e.g. on the overall sanitation landscape, faecal sludge generation rates and faecal sludge transportation pathways (from source to final disposal), to support sanitation stakeholders in efficient planning and decision making for sustainable FSM.

The overall aims of this study were to provide baseline data for effective FSM planning to sanitation stakeholders in Phnom Penh

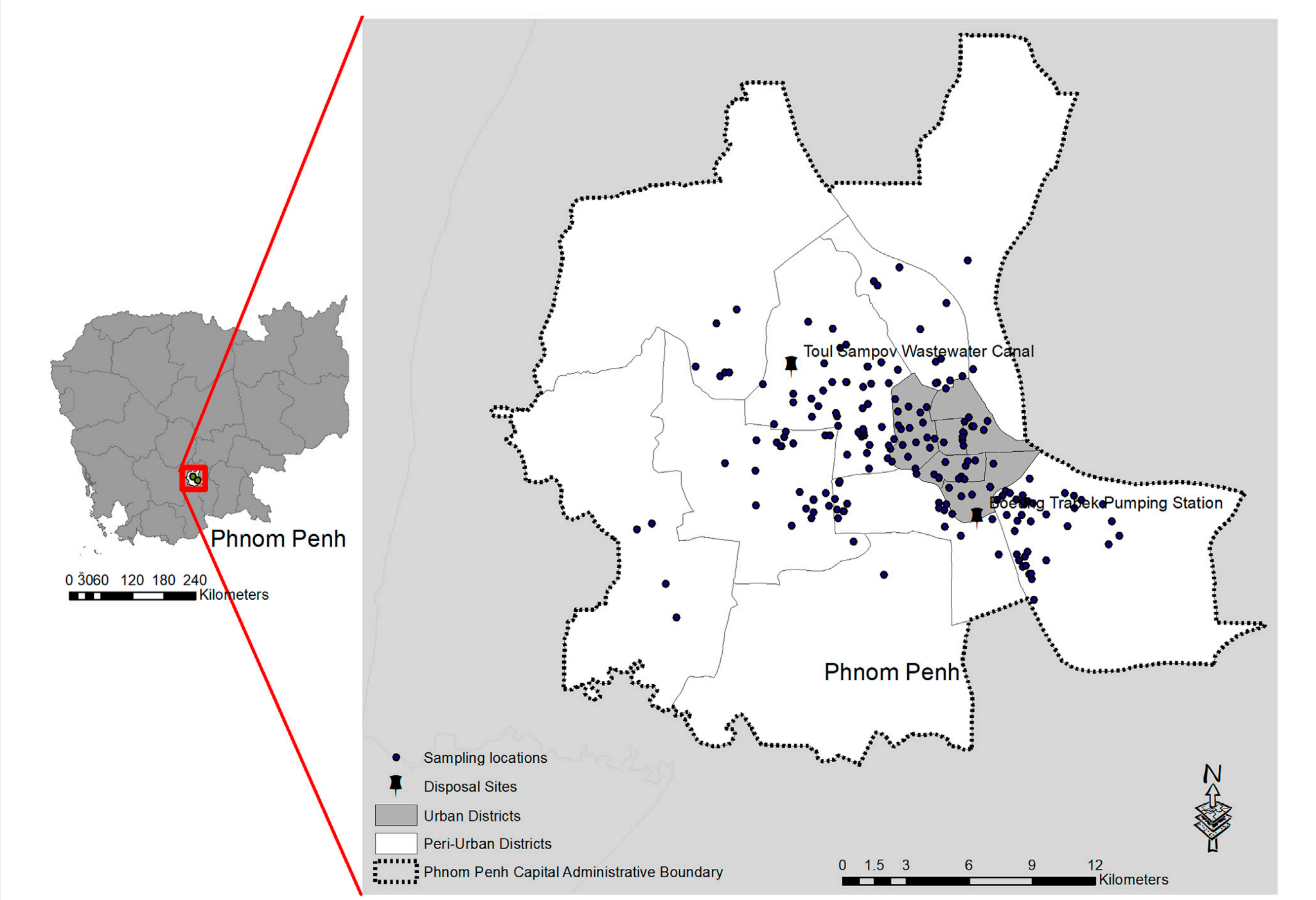

FIGURE 1 | Map showing the areas in Phnom Penh where data collection was conducted. The black dots indicate the locations of households surveyed about their sanitation management practices.

and to identify resource recovery potential in order to incentivise sustainable FSM. Specific objectives were to: 1) map FSM practices by households in Phnom Penh; 2) identify where faecal sludge is disposed of within neighbourhoods and the environment; 3) quantify faecal sludge production from household on-site sanitation systems (excreta generation rate, faecal sludge generation rate, faecal sludge collected and faecal sludge discharged); and 4) estimate the amounts of potential resources (nitrogen, phosphorus, energy) that could be recovered from faecal sludge and within the sanitation service chain.

METHODS

Data were collected through a literature review, surveys of householders in Phnom Penh, interviews with vacuum truck drivers and manual sludge tank emptying operatives, and field observations. The protocols employed in the study were approved by the National Ethics Committee for Health Research, Ministry of Health, Cambodia. The following section provides detailed information on the study area, data collection methods employed and data analysis performed in this study.

Study Area

Phnom Penh, the capital city of Cambodia (approximately 11°34″N, 104°55″E), is located on the Mekong floodplain, above the confluence of the Mekong, Tonle Sap and Bassac rivers (JICA, 2016). Phnom Penh has undergone rapid development and urbanisation in the past few decades. Recently, the whole city was divided into 14 districts, classified as urban areas (5 districts) and peri-urban areas (9 districts). The total land area of the city is about 679 km^2, with a population of approximately 2 million people in around 500,000 households (NIS, 2020).

Urban areas located in the centre of Phnom Penh are provided with full services in terms of water supply and sanitation (connection to sewerage network). The available network comprises a closed sewer system or an open canal system, depending on the location of the household within the city. Peri-urban areas can be described as adjoining areas, located outside formal urban boundaries and urban jurisdictions, that are in the process of urbanisation. These peri-urban areas can also be described as an interface, i.e., a transition zone or interactive zone, between urban and rural areas (Appiah-Effah et al., 2014b). **Figure 1** shows a map of the study area, including the location of interviews, sampling sites and disposal sites for faecal sludge investigated in this study.

Phnom Penh still uses a combined drainage system that transports domestic, commercial and industrial wastewater, as well as stormwater flow during storm events. The combined wastewater is pumped into natural wetlands surrounding the city for treatment, before flowing to the final recipient waters (Mekong river and Tonle Sap river). There are two extensive wetlands that play key roles in treating wastewater from the whole city, Cheung Ek to the south of the city and Kob Srov to the north. However, the area of these wetlands is declining, due to the current rapid urbanisation and development in the city, as they are being filled with earth to reclaim land for development purposes (Doyle, 2013). Kob Srov wetland is a sewer entry point for Sen Sok district and high levels of untreated wastewater and faecal sludge are off-loaded into the wetland, accompanied by high levels of pathogens (Min, 2019). The Tonle Sap river is the final recipient of wastewater and faecal sludge from Kob Srov wetland.

Untreated faecal sludge can pose a significant health risk when dumped in the open environment, due to the presence of significant amount of bacteria, viruses and other pathogens (Strande et al., 2014). This is certainly the case in Phnom Penh, where downstream communities living along Tonle Sap are dependent on river water for their livelihoods and for key functions, including cooking and drinking and where river water contains varying levels of pathogens that carry risks of infection and illness (Min, 2019). Cheung Ek wetland, a seasonally inundated area located about 5 km to the south of Phnom Penh, receives around 80% of wastewater from Phnom Penh's urban population and from factories (garment and others). This wetland is also used for aquatic plant and fish production, with harvesting being undertaken throughout the year.

Study Design and Data Collection

Household survey: The household survey was designed to collect demographic information on on-site sewage containment users and to map the entire sanitation service chain, by tracking faecal sludge from source through emptying to the final disposal site. The survey was conducted in the period May-September 2020, and an attempt was made to include representative households in door-to-door data collection using a structured questionnaire. Households were selected based on information received from sewage emptying contractors about households requesting their services. These contractors normally offer two different types of service, either emptying sewage containers when full or de-clogging the containment/drainage network. Desludging is therefore included in both services. A total of 195 households were surveyed, representing both urban and peri-urban areas in Phnom Penh. Sampling was planned to collect proportional numbers of samples for urban and peri-urban areas, based on the local population in these areas. In total, 144 households in peri-urban areas and 51 households in urban areas were interviewed. Since the population in peri-urban versus urban areas in Phnom Penh is approximately 3:1 (NIS, 2020), the household sampling is representative.

The structured questionnaire included a combination of dichotomous, multiple choice and open-ended questions (see **Supplementary Information**). It was developed in English, before being translated into Khmer to simplify the interview sessions by using the local language. The questionnaire covered aspects of the household's socioeconomic profile (including sex, education level, employment status, type of residential building, age of building, access to water), household sanitation practices (sewage container type and size, frequency of faecal sludge emptying, volume emptied) and householders' perceptions of faecal sludge management. A draft questionnaire was pre-tested during 1 week at the beginning of the study and refined based on feedback from this field testing. A few modifications were made before the actual survey conducted. The final questionnaire version took around 20 min to complete and targeted any person in the household between 18 and 70 years old and aware of the sanitation system in the house. In most cases, the study team interviewed the head of the family. All households were allocated an identification code and the geo-coordinates (coordination system WGS 1984) of participating households were recorded using a handheld global positioning device (Garmin GPSMAP 60CSx).

Survey of emptying and transportation contractors: Another structured questionnaire was used for interviewing vacuum and manual sludge emptying contractors (see **Supplementary Information**). The purpose of interviewing contractors providing emptying services was to track the final fate of faecal sludge after removal from households. These interviewees were asked about the quantity of faecal sludge they collected and, where possible, the geo-coordinates (coordination system WGS 1984) of the disposal site of faecal sludge from each household was recorded using a handheld global positioning device (Garmin GPSMAP 60CSx). A specific name was assigned to each disposal site at which sludge was deposited. However, private contractors in Phnom Penh sometimes dump sludge illegally (Peal et al., 2015) and some sludge disposal sites had to be recorded as unknown, since a member of the study team was not allowed to accompany the truck driver to the disposal site in all cases.

Field observation: In addition to the interviews with householders and sewage emptying contractors, the study team observed the work performed by operatives during each emptying event. This allowed observations of the accessibility of the containers, respondents' willingness to have faecal sludge treatment before final disposal, and whether the container emptying operatives used personal protection equipment while they performed the work. The study team also accompanied truck drivers to the disposal site and observed the surroundings at the sites, such as presence of water sources and the possibility of the neighbouring community using the site for swimming or for daily water extraction for general purposes.

Literature review: In addition to primary data collection, secondary data were collected from the literature in order to enable quantification of faecal sludge and resources. Data sources included government reports on population census, published literature on the population served by on-site sanitation in Phnom Penh and published information on average urine and faeces generation rates in the city. Statistical data from the Food and Agriculture Organization (FAO) on the total nutrient content in staple foods consumed by Cambodians

TABLE 1 | Sanitation management practices employed by responding households in peri-urban and urban areas of Phnom Penh. Values in brackets are percentage of the respective total. Values in bold indicate significant difference between peri-urban and urban settings ($p < 0.05$).

Variable	Total *n* = 195 (%)	Peri-Urban *n* = 144 (%)	Urban *n* = 51 (%)	*p*-value
Type of containment system				
Cesspit	181 (92.8)	135 (93.7)	46 (90.2)	0.527
Septic tank	14 (7.2)	9 (6.3)	5 (9.8)	0.527
Connection to drainage network				
Yes	138 (70.8)	90 (62.5)	48 (94.1)	**<0.001**
No	57 (29.2)	54 (37.5)	3 (5.9)	**<0.001**
Toilet type				
Auto flush	94 (48.2)	66 (45.9)	28 (54.9)	0.341
Pour flush	77 (39.5)	65 (9.0)	12 (21.6)	**0.010**
Both	24 (12.3)	13 (45.1)	11 (23.5)	**0.036**
Water-tight container				
Yes	92 (47.2)	58 (40.3)	34 (66.7)	**0.002**
No	103 (52.8)	86 (59.7)	17 (33.3)	**0.002**
Only blackwater				
Yes	36 (18.5)	30 (20.8)	6 (11.8)	0.220
No	159 (81.5)	114 (79.2)	45 (88.2)	0.220
Age of toilet/container				
<3	32 (17.8)	25 (18.5)	7 (15.6)	0.821
3–10	72 (40.0)	63 (46.7)	9 (20.0)	**0.002**
11–20	58 (32.2)	40 (29.6)	18 (40)	0.269
>20	18 (10.0)	7 (5.2)	11 (24.4)	**<0.001**
Reason for emptying				
Clogged	111 (56.9)	76 (52.8)	35 (68.6)	0.071
Filled	68 (34.9)	60 (41.7)	8 (15.7)	**0.001**
Other	16 (8.2)	8 (5.5)	8 (15.7)	**0.035**

were used to calculate the nutrient content in combined excreta and in faecal sludge.

Data Analysis

Statistical analysis: Microsoft Excel 2010 and R software version 4.0.4 were used for data handling and analysis. Descriptive statistics were calculated, such as proportion test and Chi-square test/ Fisher's exact test (where the number of samples (n) broke the rule of thumb that n (1-p) >10. Samples must be taken for household data to reveal socio-economic status in relation to sanitation practices at household level, especially as regards FSM. *p*-values <0.05 were considered statistically significant.

Spatial analysis of faecal sludge disposal sites: Geo-coordinate data on households and sludge disposal sites were processed using Microsoft Excel 2010. The distance from each household to its sludge disposal site was calculated using ArcMap 10.8. The drainage network system serving households within the coverage area was used to identify the final disposal site (recipient waters) for faecal sludge. The linear distance calculation method was used to estimate the distance between source household and final sludge disposal site. Three transport zones (4, 9 and 14 km) were added to the map to assess the distance between the two main disposal sites and the households from which the faecal sludge was obtained.

Faecal sludge quantification: The sludge collection method developed by (Strande et al., 2014) was used to quantify the amount of faecal sludge handled throughout the entire sanitation service chain. Based on population data for 2020, the amounts were quantified at six different stages of the chain, using a modified approach taken from Strande et al. (2018). The parameters determined at these stages were excreta generation rate (Q_1), faecal sludge generation rate (Q_2), faecal sludge accumulation rate (Q_3), amount of faecal sludge emptied (Q_4), amount of faecal sludge collected and delivered to Boeung Trabek pumping station (Cheung Ek wetland) (Q_5), and amount of faecal sludge collected and delivered to Prek Pnov open canal (Kob Srov wetland) (Q_6).

Q_1 was calculated as:

$$\text{Excreta produced } Q_1\,(\text{L/year}) = P_{(\text{served})} \text{x} \left(Q_{(\text{urine})} + Q_{(\text{faeces})}\right) \tag{1}$$

where $P_{(served)}$ is the population served by on-site sanitation in Phnom Penh; $Q_{(urine)}$ is urine generation rate, which was set at 1.42 L/cap/day (Rose et al., 2015); and $Q_{(faeces)}$ is estimated faecal generation rate, set at 0.236 L/cap/day for low-income countries (Strande et al., 2018).

Q_2 was calculated as:

$$\text{Faecal sludge produced } Q_2\,(\text{L/year}) = Q_1 + \text{Total container inflow}_{(\text{septic tank} + \text{pit latrine})} \quad (2)$$

where:

$$\text{total container inflow}_{(\text{septic tank+pit latrine})} = P_{(served)} \text{ x } C_w \quad (3)$$

and C_w is the quantity of water inflow to the container (septic tank and cesspit). Key assumptions made were 1) that water inflow is similar for septic tanks and latrines, 2) that type of container does not influence faecal sludge characteristics (based on Eliyan et al. (2022)); and 3) that water and excreta are the only substances entering the container, since water is used for anal cleansing and households predominantly have a piped water connection, while the small proportion of the population that use toilet tissue for wiping usually dispose of it in trash bins with other types of solid waste. According to Koppelaar et al. (2018), an average of 58.6 L/cap/day of water enter the sewage container (C_w) in developing countries.

Q_3 was calculated as:

$$\text{Faecal sludge accumulation } Q_3\,(\text{L/cap/year}) = \frac{Emptied\ volume}{Number\ of\ users.Emptying\ frequency} \quad (4)$$

The input values used for calculating Q_3, i.e., emptied volume, number of users and emptying frequency, were the average value for each category based on the household questionnaire and triangulated with data from the container emptying contractors.

The amount of faecal sludge emptied (Q_4) was calculated based on observations during each emptying event. All faecal sludge in the container was removed and only a small amount of water was sprayed to clean the container, so it was assumed that faecal sludge emptied (Q_4) was equal to faecal accumulation rate (Q_3). The analysis covered only faecal sludge collected by mechanical emptying contractors.

Faecal sludge collected and delivered to Cheung Ek wetland (Q_5) was estimated as the amount of sludge collected from household containers and delivered to the authorised disposal site. According to Peal et al. (2015), Boeung Trabek pumping station is the only authorised disposal site for Phnom Penh. Therefore Q_5 was determined based on data collected from the interviews with container emptying contractors on whether they discharge the sludge they collect at Boeung Trabek pumping station or directly into Cheung Ek wetland. Q_6 was defined similarly as the amount of faecal sludge collected from households and discharged into Toul Sampov wastewater canal or Kob Srov wetland, based on response from contractors during interviews and on field observations. Toul Sampov canal, which is located to the north of the city (see **Figure 1**), is 5 km long and carries wastewater from the Sen Sok area to Kob Srov wetland.

Resources quantification: Resources can be described as the amount of nutrients and energy that could be recovered from faecal sludge. According to FAO (2019), the total protein content in food consumed by the Cambodian population is 65.53 g/cap/day and the protein content in vegetable products consumed is 46.81 g/cap/day. The total amounts of the macronutrients nitrogen (N) and phosphorus (P) in faecal sludge in Phnom Penh were calculated using **Eqs. 5** and **6**, respectively (Jönsson et al., 2004) and considering the fact that only 22% of on-site sanitation users report employing a contractor to empty their sewage container (Frenoux et al., 2011).

$$\text{Content of nitrogen (N)} = 0.13\,x\ \text{Total food protein} \quad (5)$$

$$\text{Content of phosphorus (P)} = 0.011x\,(\text{Total food protein} + \text{vegetable food protein}) \quad (6)$$

The nutrient resource in faecal sludge was also calculated based on concentration of total nitrogen (N_{tot}) and total phosphorus (P_{tot}) in faecal sludge according to (Eliyan et al., 2022).

The potential for energy generation from faecal sludge was estimated based on Ahmed et al. (2019), who concluded that the energy potential in faecal sludge lies within the range 16.39–18.31 MJ/kg at a sludge density of 1,001 kg/m^3 (Radford and Sugden, 2014).

RESULTS

Results are presented below for FSM throughout the entire service chain, from source (households) to the final disposal site, divided into five parts: demography of respondents; sanitation management practices by households in Phnom Penh; current disposal sites for faecal sludge removed by vacuum operators; faecal sludge quantities; and resources contained in faecal sludge flows through current pathways.

Demography of Respondents

There was no statistical correlation between demographics of the respondents and geographical locations (see **Supplementary Table S1**).

Sanitation Management Practices

Two types of on-site sewage containment system are used in Phnom Penh, cesspits and septic tanks, According to our survey of households, cesspits dominate, serving up to 92.8% of the population, a trend seen in both urban and peri-urban areas. Around 95% of urban households reported having their sludge container connected to the sewer network, while only 62.5% of households in peri-urban areas reported have a direct connection ($p < 0.001$). Concerning the sanitation management practices performed

TABLE 2 | Summary statistics on final disposal sites of faecal sludge on Phnom Penh (*N* = number of samples, SD = standard deviation).

Disposal Site	N	% Of Total	Min Transport Distance (km)	Max Transport Distance (km)	Mean Transport Distance (km)	SD (km)
Cheung Ek wetland	63	57.8	0.00	13.9	4.34	2.78
Kob Srov wetland	46	42.2	0.00	12.7	3.87	2.89
Total	109	100				

by respondents, type of containment system and type of wastewater received by the system (only blackwater or not) were found to be unaffected by location in urban or peri-urban areas in Phnom Penh (**Table 1**). However, the age of the sewage container differed significantly with the geographical location of the household. The containers at houses in peri-urban areas of the city tended to be newer, reflecting the fact that the city is developing and expanding outwards. Mechanical emptying services is the only preferred method for households in Phnom Penh when their containments were full or clogged. No evidence of manual emptying practices was found. According to the observation by the study team during data collection, none of pit emptiers used personal protective equipment during emptying events. Hence, it might potentially pose risks to their health.

Faecal Sludge Disposal Sites

There is no faecal sludge treatment facility in Phnom Penh and Boeung Trabek pumping station is the only authorised sewage disposal site (Peal et al., 2015; JICA, 2016). The disposal sites identified in this study included public manholes near the households where faecal sludge was collected, fields around the Kob Srov area, Toul Sampov wastewater canal, a smaller canal (1 km) connected to Toul Sampov wastewater canal, and Boeung Trabek pumping station (Cheung Ek wetland). The survey also revealed that Cheung Ek wetland is the main disposal site (receiving 54.1% of all sludge collected), followed by the small canal and Toul Sampov wastewater canal itself (34.5%). Toul Sampov canal receives wastewater from the Sen Sok area, which flows onwards by gravity to Kob Srov wetland, with the Tonle Sap river being the final receiving reservoir. The remaining 11.4% of collected faecal sludge goes to open fields in the Kob Srov area and public manholes near source households. Since those two main disposal sites are pumping stations, there is limited risk for spillage and spread of faecal matter to local people living around those areas.

Wherever faecal sludge is disposed of within the drainage network, it ends up in one of the two main receiving wetlands, namely Cheung Ek and Kob Srov. The results obtained in this study indicated that Cheung Ek wetland is the main faecal sludge disposal site for container-emptying contractors (57.8%), while Kob Srov receives 42.2% of all sludge collected from household sewage containers by mechanical emptiers (**Table 2**). The mean travel distance from source households to Cheung Ek was found to be 4.34 km, while that from source households to Kob Srov was around 3.87 km. The shortest estimated distance observed was 0 km, in cases where the faecal sludge removed from a household's containment system was disposed of in a manhole located in front of the household. This only occurred for households with drainage network coverage.

The linear distance from source (extraction household) to each disposal site was used to estimate the travel distance for discharging emptied faecal sludge from households in Phnom Penh. Three zones were created around the two main disposal sites, to group travel distances for emptying events. The resulting map revealed that most travel distances for emptying faecal sludge fell within the first and second zones, with few distances within the third outer zone (**Figure 2**). This reflects the current practice of contractors, who prefer not to travel long distances to discharge collected sludge when there is an opportunity to dispose of it somewhere that could reduce their travel distance, thereby saving transportation time and fuel costs.

Faecal Sludge Quantities

Estimation of excreta production (Q_1) and faecal sludge generation (Q_2) was based on secondary data taken from the literature, based on Strande et al. (2014) as indicated in data analysis section. The production rate of excreta in Phnom Penh was taken to be 604 L/cap/year for all types of containment system, based on findings (Eliyan et al., 2022) that type of containment system does not influence the characteristics of faecal sludge. The faecal sludge generation rate (Q_2) was estimated to be 21,993 L/cap/year. Based on the primary data collected in the study, faecal sludge accumulation (Q_3) was estimated to occur at a rate of 106 L/cap/year for all types of containment system. This was only around half the value reported previously for the city of Kampala in Uganda (Strande et al., 2018). However, an earlier study conducted in 12 Asia and Africa cities found faecal sludge accumulation rates varying from 35.6 to 959 L/cap/year (Chowdhry and Kone, 2012). The accumulation rates in Phnom Penh are at the lower end of that reported range, possibly because containment systems in Phnom Penh are usually connected to the sewerage network, which allows daily overflow of supernatant from the sludge container to the drain network. In addition, many of the household containment systems in the city are not watertight, which allows the liquid portion of wastewater in the container to drain out to surrounding soil. According to our calculations, the total amount of faecal sludge emptied (Q_4), and thus collected (Q_5), was 32,500 m^3/year (**Table 3**).

Our calculations showed that around 52.5% (18,800 m^3/year) of total faecal sludge emptied from household containment systems during the study period was taken to Cheung Ek

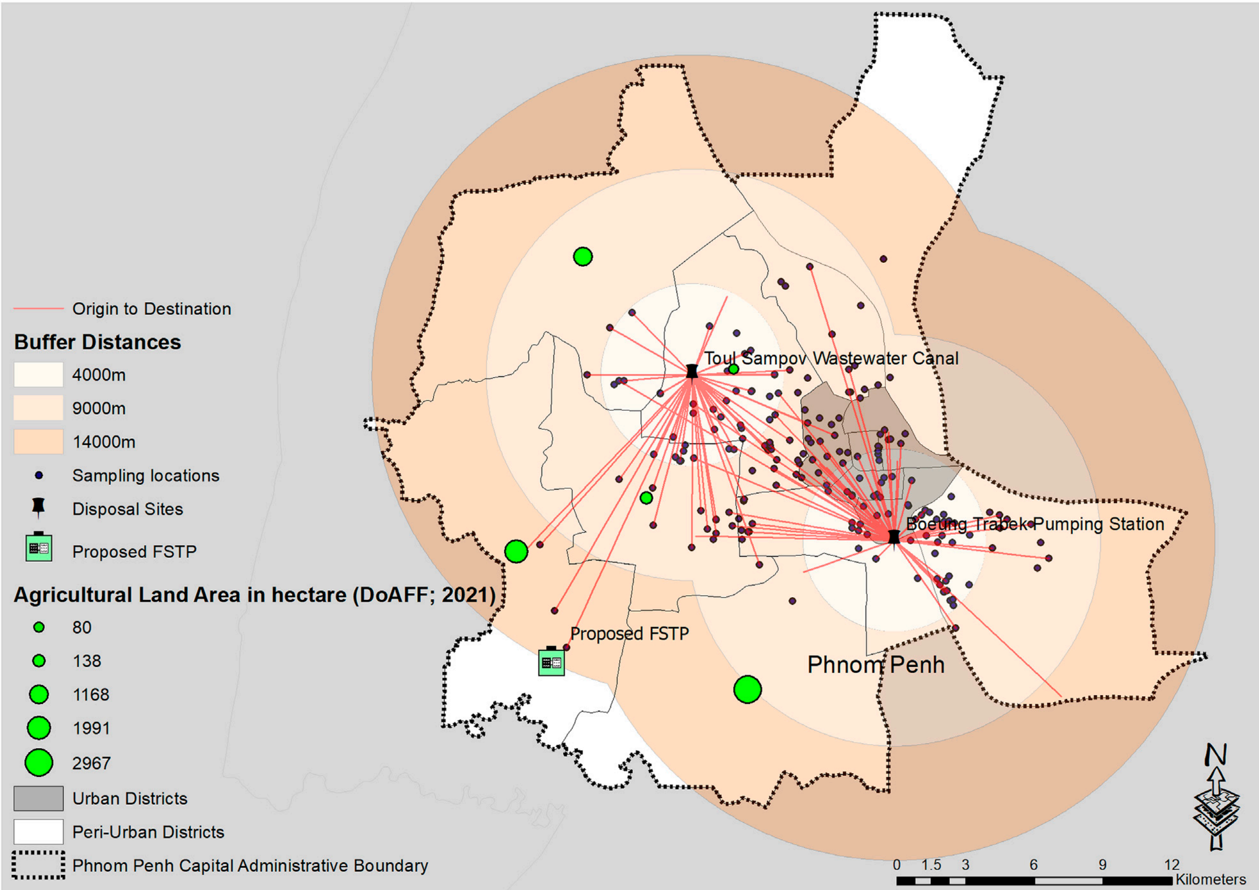

FIGURE 2 | Transport distance zones (within 4, 9 and 14 km) around Toul Sampov wastewater canal and Boeung Trabek pumping station, the two main final disposal sites of faecal sludge in Phnom Penh identified in the study.

TABLE 3 | Faecal sludge quantities at different stages along the on-site sanitation service chain for households in Phnom Penh.

Faecal Sludge Quantification as	Amount (L/cap/year)	Total Quantity (m^3/year)
Excreta produced (Q_1)	604	1,380,000
Faecal sludge produced (Q_2)	21,990	50,190,000
Faecal sludge accumulation (Q_3)	106	32,500
Total faecal sludge emptied (Q_4)	106	32,500
Total faecal sludge collected (Q_5)		32,500
Faecal sludge collected, delivered to Cheung Ek wetland (Q_{5a})	-	18,800
Faecal sludge collected, delivered to Kob Srov wetland (Q_{5b})	-	13,700

wetland and 42.2% (13,700 m^3/year) was discharged in the Kob Srov catchment.

Estimation of Resources Content in Excreta and Faecal Sludge

Potential resources assessed in this study were the amount of nitrogen, phosphorus and energy contained in faecal sludge. Based on FAO protein consumption data and resulting N and P in excreta (**Eqs. 5** and **6**), it is estimated that each individual excretes around 3.12 kg N and 0.45 kg P per year (**Table 4**), the total amount of nitrogen theoretically present in excreta (urine plus faeces) was thus estimated to be 955 tons/year, while the amount that could potentially be extracted from faecal sludge was only 6 tons/year (Jönsson et al., 2004). Thus, according to these findings faecal sludge in Phnom Penh contains less than 1% of total nitrogen excreted by humans. Nitrogen in wastewater is mostly found in the water-soluble form as ammonia and follow the liquid fraction into the sewer network or into the ground due to non-watertight containers.

TABLE 4 | Estimated amounts of resources (total nitrogen (N_{tot}) and total phosphorus (P_{tot})) contained in excreta (urine + faeces) and in faecal sludge generated annually in Phnom Penh and discharged to Cheung Ek wetland and Kob Srov wetland.

Resource	Generation rate[a] (kg/cap/year)	Amount in excreta[b] (kg/year)	Amount in Faecal sludge[c] (kg/year)
Total nitrogen in excreta	3.12	955,500	-
N_{tot} in faecal sludge	-	-	6,100
N_{tot} to Cheung Ek	-	552,000	3,530
N_{tot} to Kob Srov	-	403,000	2,580
Total phosphorus in excreta	0.45	137,000	
P_{tot} in faecal sludge			12,980
P_{tot} to Cheung Ek	-	79,600	7,500
P_{tot} to Kob Srov	-	58,200	5,480

[a]*Equations 5 and 6.*

[b]*The number of population used for this calculation was 306,238, represented the population used onsite sanitation with experiences of emptying their containments (Frenoux et al., 2011; Peal et al., 2015; NIS, 2020).*

[c]*The concentration of total nitrogen and total phosphrus were 188 mg/L and 400 mg/L, respectively (Eliyan et al., 2022). Note that it is Q_4 x concentration.*

The results for phosphorus showed that a larger fraction, around 9%, remains in faecal sludge (**Table 4**), presumably because phosphorus tends to precipitate as metal phosphate and attach to solid particles in sludge and is less water-soluble than nitrogen. However, a high proportion of both nutrients (nitrogen and phosphorus) remains in the liquid wastewater fraction, which with improved wastewater treatment could be captured and treated as part of achieving the UN SDG goal 6, under target 6.2 and 6.3, as well as meeting the Cambodian wastewater discharge standard (RGC 2017; RGC, 2021) and to avoid environmental impacts. In conclusion, around 6 tons of nitrogen and 13 tons of phosphorus could be recovered from faecal sludge annually.

Potential energy generation was calculated based on the total faecal emptied annually (Q_4). Based on energy potential from Ahmed et al. (2019), the estimated amount of potential energy that could be captured from faecal sludge annually was within the range 532,571–594,959GJ, or 148-165 GWh.

DISCUSSION

The baseline data obtained in this study can support sanitation stakeholders in future decision-making for more sustainable FSM, while the logistical data obtained, such as volumes of sludge generated and travel distance from source to disposal site, are critical for planning FSM at city-wide scale. The study also indicated that recovery of resources (plant nutrients, energy) from faecal sludge could potentially be an incentive for FSM in the long run.

Factors such as household connection to the city's sewerage network and age of sewage containment systems were found to differ significantly between geographical areas of Phnom Penh, particularly between urban and peri-urban areas. It emerged that urban area generally had full drainage coverage, while some parts of peri-urban area still had limited access to the sewerage network due to slow development in the city's wastewater management sector. Data on the age of the containment systems and toilets in the households surveyed indicated that there are more new households in peri-urban settings, since in most cases houses and toilet are built at the same time. The city is developing and expanding rapidly, while wastewater management services have not kept pace with the rate of development.

Different factors were found to lead to indiscriminate disposal of faecal sludge at sites other than at the official designated site, Cheung Ek wetland. One such factor was related to cost and travel distance between households and Cheung Ek wetland. The unofficial cost of 2.50 USD per truck and km travel distance between Cheung Ek wetland and the next household served by the truck. Frenoux et al. (2011) found that reducing the travel distance from extraction household to faecal sludge disposal site, by dumping sludge at an unauthorised site closer to the household, would enable truck drivers to increase their income by up to 10%, through faster turn-around and potential cost savings on transport. The largest company among the sludge-emptying contractors surveyed in this study owns around seven trucks and pays monthly discharge fees at Cheung Ek wetland, so it is most likely that faecal sludge extracted by this company is discharged at the official site. Other survey responses indicated that the truck drivers would prefer not to travel more than 9 km between source household and sludge disposal site, for reasons of turn-around speed and transport distance. This supports findings by Frenoux et al. (2011) that the shorter the travel distance to sludge disposal, the more savings the contractor can make, e.g. by only travelling within 4 km distance to disposal site, they could save up to 10% of their extraction income. Travel distance and traffic congestion are also the main business constraints identified by operators (PPCH, 2021). The first faecal sludge management strategy for Phnom Penh Capital Administration (2035) pointed out the need to build up to four treatment plants to treat faecal sludge for the whole city. The location for the first treatment plant has been established as Kamboul district, in one of the peri-urban areas of Phnom Penh (PPCH, 2021). This site lies around 20 km from the two main sludge disposal sites identified in this study, which is rather far for transporting sludge from households located in the centre of the city and likely poses a risk of indiscriminate dumping still happening to some extent.

The faecal sludge generation rate was found to be quite high compared with the excreta production rate (**Table 3**). The calculation was based on the total generation rate, which included the supernatant that continuously flows into the drainage network for households located within the coverage area. The discrepancy reflects the fact that on-site containment systems in Phnom Penh are either connected to the drainage network, or not, depending on household location, e.g., urban households located within the drainage coverage area are typically connected to the network. The amounts of faecal sludge emptied and disposed of are equal in Phnom Penh, since all mechanical operators (based on our observations during the study period) normally removed all faecal sludge from the containers at each emptying event. With this current practice, more trucks would be needed to transport the required emptied volume to authorised disposal sites. PPCH (2021) found that business activity in the faecal sludge empting and transportation sector in Phnom Penh has increased by at least 5% in the past 8 years, including the number of vacuum trucks and intensification of the service. Greater efficiency in logistics and transportation is needed to cope with the required transportation of collected sludge along the entire service chain, which has been identified as one of the business constraints for sludge collection contractors in the sector (PPCH, 2021). Similarly, a study conducted in informal settlements of Kampala, Uganda, found that three key factors for improving service provision were truck capacity, fuel costs and travel distance (Murungi and van Dijk, 2014). Another issue in Phnom Penh is that the supernatant which flows continuously from household containment systems goes directly to the drainage network and eventually reaches natural recipient wetlands without any treatment. The quality of this supernatant may barely meet the effluent standard for wastewater discharge (RGC, 2017) and it should be collected and treated when planning for safely managed sanitation in Phnom Penh.

The two big natural wetlands in Phnom Penh, Cheung Ek and Kob Srov, play an important role as recipients and in treatment of faecal sludge before final discharge. With the current practice, the nutrients contained in faecal sludge act as pollutants, with environmental implications for the wetlands. For example, high ammonia concentrations inhibit algal growth and impair plant growth in wetland treatment systems (Koné and Strauss, 2004). Excess nutrients could lead to eutrophication and algal blooms in surface water (Andersson et al., 2016; Singh et al., 2017). It is possible to change this pollutant loading into resource recovery, particularly of plant nutrients, as fertiliser plays a key role in crop productivity and food security. The demand for fertiliser in Cambodia increased sharply, by around 210%, between 2002 and 2011 (Vuthy et al., 2014). The present study demonstrated good potential for nutrient recovery from faecal sludge in Phnom Penh and the recovered nutrients could potentially replace commercial fertiliser use in some agricultural applications in Phnom Penh. According to the Cambodian Department of Agriculture, Forestry and Fishery, 6,300 ha of agricultural land in Phnom Penh, located within five of its peri-urban districts, are farmed in the wet season. According to a market study conducted by GRET (2019) the amount of N and P fertiliser used in agricultural applications in Phnom Penh is around 1,460 ton/year. Therefore, the 6 tons of N and 13 tons of P that could be recovered from faecal sludge could replace part of chemical fertiliser use in Phnom Penh, while avoiding logistics costs in transportation and adding more value to the final product from wastewater treatment facilities. It would therefore reduce the total cost of agricultural production, since fertiliser use is the major determining factor in variable costs (Vuthy et al., 2014).

In addition to the nutrients contained in faecal sludge, it is also possible to recover energy for domestic use. For instance, based on the assumption that the average household in Phnom Penh consumes around 1723 kWh/year (Sovanndara, 2002), the amount of energy generated from faecal sludge, if converted into electricity, would be enough to supply 85,900–95,900 households, replacing electricity generated from non-renewable sources or imported.

CONCLUSION

The comprehensive baseline information obtained in this study can be used as input for FSM planning throughout the entire service chain in Phnom Penh. An estimated amount of 32,500 m^3 of faecal sludge is emptied from household containment each year. The results also revealed that the current practice of indiscriminate disposal of faecal sludge will likely cause environmental problems, such as eutrophication, in recipient natural wetlands (Cheung Ek, Kob Srov), which currently act as natural treatment systems. Annually, approximately 18,800 m^3 and 13,700 m^3 of faecal sludge are emptied untreated into Cheung Ek and Kob Srov wetlands respectively. Treatment of faecal sludge before release into the environment is thus crucial to meet the goal of safely managed sanitation in the city. When planning future faecal sludge treatment plants, our results indicate that efficient transportation logistics will be needed to maximise the income level of private contractors, cope with a rising faecal sludge generation rate and improve the cost effectiveness of FSM. In the case of Phnom Penh city, there should be at least two treatment plant nodes, one located in the south and the other in the north of the city. Our study showed that private operators prefer to discharge the sludge they collect within a 9-km zone, a finding that should be taken into account at an early stage when considering possible locations for wastewater treatment plants. Alternatively, setting up several faecal sludge transfer stations at regular intervals could be a solution to avoid long transport distances to wastewater plants for vacuum truck drivers, and thus reduce the likelihood of indiscriminate dumping. The supernatant that currently flows continuously from households' on-site containment systems should also be properly treated as part of the goal to achieve safe sanitation management in Phnom Penh. Depending on plant design, this supernatant could be treated in faecal sludge treatment plants or sent to a combined wastewater treatment plant.

To incentivise contractors and compensate for the operational costs of sludge treatment, resource recovery from faecal sludge treatment products could be considered. This study indicated a possibility for alternative FSM through recovering resources from faecal sludge. Nutrients (6 tons/year of nitrogen and 13 tons/year of phosphorus) and energy (148-165 GWh/year) could be recovered from faecal sludge. This could be used to partly replace chemical fertiliser and imported electricity for agricultural applications and household usage. However, resource recovery alternatives need to be investigated more thoroughly to enable proper planning of sustainable faecal sludge management in Phnom Penh and similar cities world-wide.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

All participating households were informed about the purpose of the study and asked for their voluntary participation. Verbal consent was obtained from each household and documented in the questionnaire. The protocols employed in this study were also approved by the National Ethics Committee for Health Research, Ministry of Health, Cambodia.

AUTHOR CONTRIBUTIONS

CE: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing-original draft, Writing-review and editing. JM: Conceptualization, Investigation, Validation, Methodology, Supervision, Writing-review and editing. CZ: Methodology, Supervision, Writing-review and editing. TK: Methodology, Supervision, Writing-review and editing. KS: Funding acquisition, Methodology, Supervision, Writing-review and editing. BV: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing-review and editing.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.869009/full#supplementary-material

REFERENCES

Ahmed, I., Ofori-Amanfo, D., Awuah, E., and Cobbold, F. (2019). A Comprehensive Study on the Physicochemical Characteristics of Faecal Sludge in Greater Accra Region and Analysis of Its Potential Use as Feedstock for Green Energy. *J. Renew. Energ.* 2019, 11. doi:10.1155/2019/8696058

Andersson, K., Rosemarin, A., Lamizana, B., Kvarnström, E., McConville, J., Seidu, R., et al. (2016). *Sanitation, Wastewater Management and Sustainability: From Waste Disposal to Resource Recovery*. Nairobi and Stockholm: United Nations Environment Programme and Stockholm Environment Institute.

Appiah-Effah, E., Nyarko, K. B., and Awuah, E. (2014a). Characterization of Public Toilet Sludge from Peri-Urban and Rural of Ashanti Region of Ghana. *J. Appl. Sci. Environ. Sanitation.* 9 (3), 175–184.

Appiah-Effah, E., Nyarko, K. B., Gyasi, S. F., and Awuah, E. (2014b). Faecal Sludge Management in Low Income Areas: a Case Study of Three Districts in the Ashanti Region of Ghana. *J. Water Sanitation Hyg. Development.* 4 (2), 189–199. doi:10.2166/washdev.2014.126

Bassan, M., Tchonda, T., Yiougo, L., Zoellig, H., Mahamane, I., Mbéguéré, M., et al. (2013). "Characterization of Faecal Sludge during Dry and Rainy Seasons in Ouagadougou," in Burkina Faso 36th WEDC International Conference. Nakuru, Kenya.

Boot, N. L. D., and Scott, R. E. (2008). "Faecal Sludge Management in Accra, Ghana: Strengthening Links in the Chain," in 33rd WEDC International Conference (Accra, GhanaGhana: Accra).

Borja, V., Garcia, M., and Gonzalez, J. A. (2019). Incidence of Subsidies in Residential Public Services in Mexico: The Case of the Water Sector. *Water.* 11 (10), 2078. doi:10.3390/w11102078

Chandana, N., and Rao, B. (2021). Status of Sustainable Sanitation Chain in Rural, Semi-urban, and Urban Regions: a Case Study of Maharashtra, India. *J. Water Sanitation Hyg. Development.* 11 (1), 112–125. doi:10.2166/washdev.2020.020

Chandana, N., and Rao, B. (2022). A Critical Review on Sludge Management from Onsite Sanitation Systems: A Knowledge to Be Revised in the Current Situation. *Environ. Res.* 203, 111812. doi:10.1016/j.envres.2021.111812

Chowdhry, S., and Kone, D. (2012). *Business Analysis of Faecal Sludge Management: Emptying and Transportation Services in Africa and Asia*. Seatle, Washington D.C.: Bill & Melinda Gates Foundation.

Diener, S., Semiyaga, S., Niwagaba, C. B., Muspratt, A. M., Gning, J. B., Mbéguéré, M., et al. (2014). A Value Proposition: Resource Recovery From Faecal Sludge—Can it be the Driver for Improved Sanitation? *Resour. Conservation Recycling.* 88, 32–38. doi:10.1016/j.resconrec.2014.04.005

Dodane, P.-H., Mbéguéré, M., Sow, O., and Strande, L. (2012). Capital and Operating Costs of Full-Scale Fecal Sludge Management and Wastewater Treatment Systems in Dakar, Senegal. *Environ. Sci. Technol.* 46 (7), 3705–3711. doi:10.1021/es2045234

Doyle, S. E. (2013). *City of Water: Architecture, Infrastrcuture and the Floods of Phnom Penh*. Ames, IA: Iowa State University.

Echevarria, D., Trimmer, J. T., Cusick, R. D., and Guest, J. S. (2021). Defining Nutrient Colocation Typologies for Human-Derived Supply and Crop Demand to Advance Resource Recovery. *Environ. Sci. Technol.* 55 (15), 10704–10713. doi:10.1021/acs.est.1c01389

Eliyan, C., Vinnerås, B., Zurbrügg, C., Koottatep, T., Sothea, K., and McConville, J. (2022). Factors Influencing Physicochemical Characteristics of Faecal Sludge in Phnom Penh, Cambodia. *J. Water Sanitation Hyg. Development.* 12 (1), 129–140. doi:10.2166/washdev.2021.193

FAO (2019). FAOSTAT Nutrition Data-Food Supply-Crops Primary Equivalent. Available at: https://www.fao.org/faostat/en/#compare (Accessed Janurary 03, 2022).

Frenoux, C., Tsitsikalis, A., Corre, M. L., and Carlier, R. (2011). *Landscap Analysis and Bussiness Model Assessment in Faecal Sludge Management: Extraction and Transportation Model-Cambodia1-Main Report)*. Phnom Penh, Cambodia: GRET.

Gudda, F. O., Moturi, W. N., Omondi, S. O., and Muchiri, E. W. (2017). Analysis of Physiochemical Characteristics Influencing Disposal of Pit Latrine Sludge in Nakuru Municipality, Kenya. *Afr. J. Environ. Sci. Technol.* 11 (3), 139–145. doi:10.5897/ajest2016.2226

Hafford, L. M., Ward, B. J., Weimer, A. W., and Linden, K. (2018). Fecal Sludge as a Fuel: Characterization, Cofire Limits, and Evaluation of Quality

Improvement Measures. *Water Sci. Technol.* 78 (12), 2437–2448. doi:10.2166/wst.2019.005

JICA (2016). *The Study on Drainage and Sewerage Improvement Project in Phnom Penh Metropolitan Area*. Cambodia: Japan International Cooperation Agency, Department of Public Work and Transportation. Final Report 2.

Jönsson, H., Stinzing, A. R., Vinnerås, B., and Salmon, E. (2004). *Guidline on the Use of Urine and Faeces in Crop Production*. Stockholm, Sweden: EcoSanRes Publications Series: the EcoSanRes Programme and the Stockholm Environment Institute.

Kinobe, J. R., Bosona, T., Gebresenbet, G., Niwagaba, C. B., and Vinnerås, B. (2015). Optimization of Waste Collection and Disposal in Kampala City. *Habitat Int.* 49, 126–137. doi:10.1016/j.habitatint.2015.05.025

Klingel, F., Montangero, A., Koné, D., and Straus, M. (2002). *Fecal Sludge Management in Developing Countries: A Planning Manual.* Dubendorf, Switzerland: Swiss Federal Institute for Environmental Science & Technology. Department for Water and Sanitation in Developing Countries.

Koné, D., and Strauss, M. (2004). "Low-cost Options for Treating Faecal Sludges (FS) in Developing Countries – Challenges and Performance," in IWA Specialist Group Conference on Waste Stabilization Ponds, 27 September–1October. Avignon, France.

Koppelaar, R. H. E. M., Sule, M. N., Kis, Z., Mensah, F. K., Wang, X., Triantafyllidis, C., et al. (2018). Framework for WASH Sector Data Improvements in Data-Poor Environments, Applied to Accra, Ghana. *Water.* 10 (9), 1278. doi:10.3390/w10091278

Min, L. L. (2019). *Is it Safe in My Place? A Quantitative Microbial Risk Assessment to Study Risk Levels in Drinking Water and Recreational Water of Sensok District*. Cambodia: Phnom Penh.

Murungi, C., and van Dijk, M. P. (2014). Emptying, Transportation and Disposal of Feacal Sludge in Informal Settlements of Kampala Uganda: The Economics of Sanitation. *Habitat Int.* 42, 69–75. doi:10.1016/j.habitatint.2013.10.011

NIS (2020). *General Population Census of the Kingdom of Cambodia 2019: National Report on Final Census Results*. Cambodia: National Institute of Statistics, Ministry Planning.

Peal, A., Evans, B., Blackett, I., Hawkins, P., and Heymans, C. (2015). *A Review of Fecal Sludge Management in 12 Cities World Bank, Water and Sanitation Program*. Washington, D.C.

PPCH (2021). *2035 Fecal Sludge Management Strategy for Phnom Penh Capital Administration SIA Ingénieurie Conseil and Phnom Penh Capital Adminstration*. Phnom Penh: Phnom Penh City Administration.

Radford, J. T., and Sugden, S. (2014). Measurement of Faecal Sludge *In-Situ* Shear Strength and Density. *Water SA.* 40 (1),11. doi:10.4314/wsa.v40i1.22

RGC (2017). *Sub-decree on Management of Drainage and Wastewater Treatment*. Cambodia: Royal Government of Cambodia.

RGC (2021). *Sub-decree on the Revision of the Sub-decree on Water Pollution Control*. Cambodia: Royal Government of Cambodia.

Rose, C., Parker, A., Jefferson, B., and Cartmell, E. (2015). The Characterization of Feces and Urine: A Review of the Literature to Inform Advanced Treatment Technology. *Crit. Rev. Environ. Sci. Technology.* 45 (17), 18271827–18791879. doi:10.1080/10643389.2014.1000761

Schoebitz, L., Andriessen, N., Bollier, S., Bassan, M., and Strande, L. (2016). *Market Driven Approach for Selection of Faecal Sludge Treatment Products*. Dübendorf, Switzerland: Eawag: Swiss Federal Institute of Aquatic Science and Technology.

Schoebitz, L., Bischoff, F., Lohri, C., Niwagaba, C., Siber, R., and Strande, L. (2017). GIS Analysis and Optimisation of Faecal Sludge Logistics at City-wide Scale in Kampala, Uganda. *Sustainability.* 9 (2), 194. doi:10.3390/su9020194

Singh, S., Mohan, R. R., Rathi, S., and Raju, N. J. (2017). Technology Options for Faecal Sludge Management in Developing Countries: Benefits and Revenue from Reuse. *Environ. Technology Innovation.* 7, 203–218. doi:10.1016/j.eti.2017.02.004

Sovanndara, N. (2002). *Household Electricity Use Analysis and Forecasting: The Case of Phnom Penh, Cambodia. Diss*. Bangkok, Thailand: The Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi.

Strande, L., Ronteltap, M., and Brdjanovic, D. (2014). *Faecal Sludge Management: Systems Approach for Implementation and Operation*. London, United Kingdom: IWA Publishing.

Strande, L., Schoebitz, L., Bischoff, F., Ddiba, D., Okello, F., Englund, M., et al. (2018). Methods to Reliably Estimate Faecal Sludge Quantities and Qualities for the Design of Treatment Technologies and Management Solutions. *J. Environ. Manage.* 223, 898–907. doi:10.1016/j.jenvman.2018.06.100

Vuthy, T., Pirom, K., and Dany, P. (2014). *Development of the Fertiliser Industry in Cambodia: Structure of the Market, Challenges in the Demand and Supply Sides and the Way Forward*. Phnom Penh, Cambodia: Cambodia's leading independent development policy resereach institute.

WHO and UNICEF (2017). *Progress on Drinking Water, Sanitation and Hygiene: 2017 Update and SDG Baselines*. Geneva.

WHO and UNICEF (2021). *Progress on Household Drinking Water, Sanitation and hygiene 2000-2020: Five Years into the SDGs*. Geneva: World Health Organization and the United Nations Children's Fund. Licence: CC BY-NC-SA 3.0 IGO.

Yin, F., Li, Z., Wang, D., Ohlsen, T., and Dong, H. (2016). Performance of thermal Pretreatment and Mesophilic Fermentation System on Pathogen Inactivation and Biogas Production of Faecal Sludge: Initial Laboratory Results. *Biosyst. Eng.* 151, 171–177. doi:10.1016/j.biosystemseng.2016.08.019

Zewde, A. A., Li, Z., and Xiaoqin, Z. (2021). Improved and Promising Fecal Sludge Sanitizing Methods: Treatment of Fecal Sludge Using Resource Recovery Technologies. *J. Water Sanitation Hyg. Development.* 11 (3), 335–349. doi:10.2166/washdev.2021.268

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Barriers and Enablers to the Regulation of Sanitation Services: A Framework for Emptying and Transport Services in Sub-Saharan African Cities

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Onsite sanitation is the dominant form of sanitation in Sub-Saharan African cities. Services for emptying the fecal sludge from these facilities and transporting it to safe disposal or treatment plants are crucial to public and environmental health. While these services are becoming increasingly regulated, implementation of the regulation remains a challenge. Through a multiple-case study anchored in the Contextual Interaction Theory, this research investigated the barriers and enablers to regulating emptying and transport services for fecal sludge. Looking at the cases of Kampala, Lusaka, and Freetown, this research found that both the content of the regulation and the regulatory process (initiation, creation or reform through to implementation) play a key role in the extent to which the regulation is or can be implemented. New elements relating to the knowledge, motivation, and resources of all stakeholders are identified as crucial to achieve regulated services. The findings have resulted in a framework that identifies the key elements to consider when regulating services. This framework would prove useful to practitioners and researchers engaged through all stages of creating, implementing, and evaluating regulatory practices.

Keywords: enabling environment, waste management, urban, onsite sanitation, faecal sludge management (FSM), policy implementation

1 INTRODUCTION

In Sub-Saharan African cities, the majority of the population relies on onsite sanitation facilities, that typically generate fecal sludge (WHO/UNICEF, 2021). Services that operate to empty and transport fecal sludge from on-site sanitation containment systems (without which sludge would be left on-site, pits and septic tanks would overflow, and sludge would not reach treatment or safe disposal sites), are crucial to enable a safely managed sanitation chain[1] in cities, to protect public and environmental health (Ibid, 2021). When inaccessible, unhygienic, or inadequate, these services contribute to the negative impacts of poor sanitation (disease, environmental pollution, financial loss, lower quality of life, etc.), especially for those living in low-income urban settlements.

[1]The sanitation chain is composed of all the steps taken by the fecal sludge and wastewater produced by people, from generation to end disposal or reuse (user interface, collection, transport, treatment or disposal or reuse) (Strande et al., 2014).

To address the adverse impacts and the inadequacy of many such emptying and transport services, local governments and national entities have started organizing and regulating them (ESAWAS Regulators Association, 2019; Gero and Willetts, 2020). Regulation can be divided into three main approaches: command and control, support and incentivize, and leave to self-regulate (Baldwin and Cave, 1999; Vedung, 2017). Previous research shows that there are a variety of regulatory situations in sub-Saharan African cities. Many cities have at least some regulation in place for emptying and transport services, covering five categories of regulatory mechanisms: rules, sanctions, monitoring and control mechanisms, support and incentive mechanisms and pro-poor measures (Lerebours et al., 2021b).

The implementation of the regulation is often partial or non-existent (Weststrate et al., 2019; Lerebours et al., 2021b). Earlier research identified certain elements of the regulation that influence its implementation, either from the perspective of the regulated (Lerebours et al., 2021a; Lerebours et al., 2021b), financial constraints (Jenkins et al., 2015; Acey et al., 2019; Doe and Aboagye, 2020), or the enabling environment for sanitation (Mumssen et al., 2018; Sinharoy et al., 2019; Weststrate et al., 2019). There is, however, no overall analysis of what, both in the content of the regulation and in the regulatory process itself, influence its degree of implementation.

An investigation of specific cases was thus needed to understand better what contributes to and hinders the implementation of regulation of fecal sludge emptying and transport services. Through document analysis, an online survey and semi-structured interviews, this multiple-case study set out to identify barriers to and enablers of the implementation of regulation, using Contextual Interaction Theory as the conceptual lens for the design and analysis.

2 MATERIALS AND METHODS

For this research, investigating multiple cases was necessary to identify commonalities and differences regarding the barriers to and enablers of the implementation of regulation in different cities. As general patterns were sought, a single unit of analysis was chosen: a city in sub-Saharan Africa. Using the data collected and analyzed during previous research (Lerebours et al., 2021a; 2021b), three cities which have regulation in place were selected (Kampala, Lusaka, and Freetown) that provide insights into the contextual, process and regulatory elements regarding the creation of the regulation, the resulting content of the regulation, and the degree of implementation. While these three cities are not intended to be representative of all cities in sub-Saharan Africa, they share traits with many other cities, such as population growth and considerable unplanned settlements where access to basic services is limited. The knowledge generated through this study contains generalizable elements, as shown in the results and discussion sections.

2.1 Contextual Interaction Theory

As this study investigates the implementation of regulation in particular, implementation theories were explored. Building on the work from previous scholars, Contextual Interaction Theory (CIT) belongs to the third generation of implementation theories which combines both top-down and bottom-up approaches (O'Toole, 2004), recognizing that policymaking and policy implementation are interdependent, where all actors interact, exchange, and learn from each other (Bressers, 2004; Bressers and de Boer, 2013). CIT provides a lens with which to analyze the course and outcomes of a policy process, looking at three core characteristics of actors involved: motivation, knowledge, and resources (Bressers, 2004). It is based on the assumption that policy processes do not depend only on inputs, but are human-social interaction processes between actors, both individuals or collectives. CIT also assumes that many factors, including external factors, influence the activities and interactions of the actors, and that their characteristics influence the policy process but are also influenced by it (Bressers, 2004; Bressers and de Boer, 2013). The interactions between actors are analyzed within their own contexts, which also influence the resulting policy implementation. This theory has been applied to various policy processes, such as river management policy, health policy, and to sanitation campaign programs (Bressers and de Boer, 2013; Hueso and Bell, 2013).

CIT investigates the complexity of the implementation process while providing a lens for analysis, distinguishing actors' "core characteristics" from contextual factors. Contextual factors consist of 1) specific context (goals, instruments, resources, and timing); 2) structural context (governance elements); and 3) wider contexts (political, economic, cultural, and technological). The core characteristics of actors to be studied are 1) knowledge, or "cognitions" (information and interpretation of reality); 2) motives or motivation (drivers, values, and perceptions); and 3) resources (financial and non-financial capacity, skills, and decision-making power) (O'Toole, 2004; Bressers and de Boer, 2013). Contextual Interaction Theory is presented in **Figure 1**.

2.2 Data Collection and Analysis

This study used multiple sources of evidence for each city: 1) A document review, including legal documents (to develop a context summary). Documents selected were census surveys, legal documents, policies, and strategies developed by the country, region, and city studied. 2) Interviews with three regulators in each city. Interviewees were selected because they were working for the active regulators in their cities: i.e., the national or city utility and local authority in all three cities, plus the national regulator and policy maker in two cities. Interview guides were developed based on the CIT elements (Bressers, 2004; Bressers and de Boer, 2013). Interviews were held online, in English, and transcribed. Private emptiers were not interviewed for this study but their perspectives, collected in a previous study (Lerebours et al., 2021a), were used to triangulate and discuss the findings of this research. 3) A pre-interview online survey asking questions related to the governance in place in the interviewees' cities (structural context). This survey was administered in English and adapted from the Governance Assessment Tool developed as part of the CIT (Bressers, 2004). All interviewees completed the pre-interview survey. The context summaries were

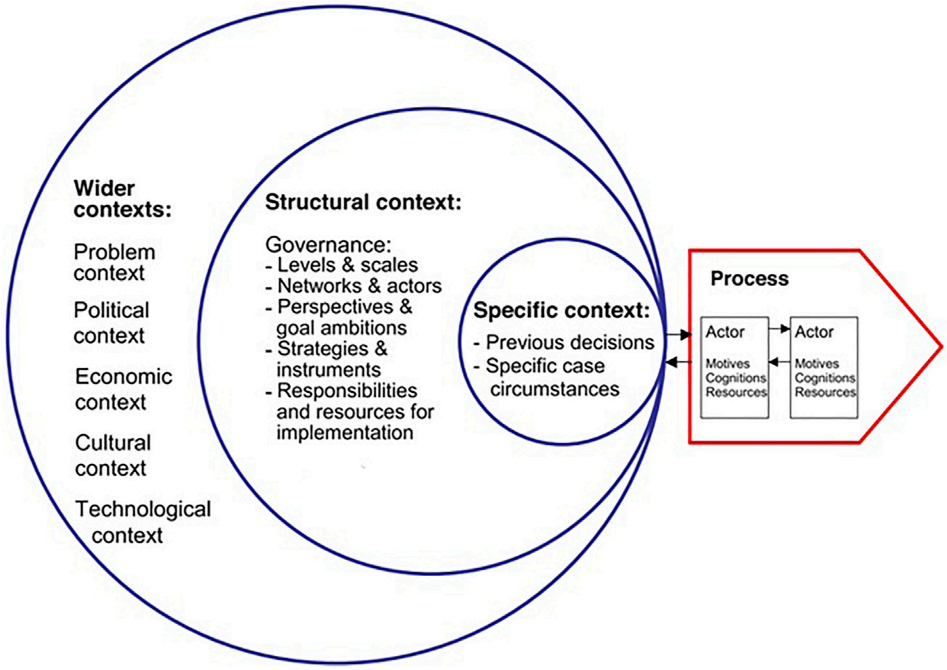

FIGURE 1 | Contextual Interaction Theory elements (Bressers, 2004).

also shared with the interviewees, so they could confirm, complement, or amend them; and emails were exchanged with interviewees to clarify or confirm information where required during the analysis. **Table 1** below summarizes the sources of evidence for this study.

The data analysis comprised multiple steps: 1) the initial document analysis and inputs from respondents led to case summaries (see above). 2) the transcribed semi-structured interviews were coded and thematically analyzed. An initial coding guide was developed before the analysis, based on CIT, and iteratively modified during the coding process. All interviews were then coded against this guide to ensure consistency across all interviews. 3) each case was analyzed individually against the CIT elements (contextual factors and core characteristics); and 4) a cross-case analysis was carried out. The cross-case analysis consisted of identifying commonalities and differences among the three cases, regarding the actors' core characteristics and the contextual factors, to identify barriers to and enablers of implementing regulation. The resulting analysis is presented below in the results section.

Based on the cross-case analysis, tables were developed (**Tables 2–6**) to summarize the findings for the contextual factors and the core characteristics. They present the key elements identified by the respondents as influencing the implementation of the regulation in their cities, either in a positive way (enabler +) or negative way (barrier −), or a mix of both (+/−). Using these findings and those from previous research, a new framework was developed that incorporates the key elements directly influencing regulation of emptying and transport services recommended to be taken into account through the regulatory process (**Figure 2**).

2.3 Ethical Considerations

Ethical approval for the study was obtained from Loughborough University (Reference: DT_10496). Participation was voluntary,

TABLE 1 | Sources of evidence for the study.

	Contextual factors			Actors' core characteristics		
Sources	**Specific inputs or context**	**Structural context**	**Wider context**	**Knowledge**	**Motivations**	**Resources**
Document review	x	X	X			
Pre-interview online survey		X				
Semi-structured interview	x			X	x	x

study participants provided prior written informed consent and all data was securely stored and fully anonymized to protect privacy.

3 RESULTS

The findings and discussions presented in this paper are structured following CIT: the contextual factors (wider, structural, and specific contexts) and the actors' core characteristics (knowledge, motivation, and resources). Applying the CIT lens for design and analysis provides a comprehensive and robust way to ensure all elements relevant to the practice of relevant actors and the broader context within which they interact are accounted for.

3.1 Contextual Factors

3.1.1 Wider Context: Description of the Cities

The three cities studied are the capital cities of their respective countries. Their populations are all over one million and growing fast. 60% or more of their residents live in low-income areas, with limited access to basic services. 85% or more of their residents use onsite sanitation facilities, which are typically emptied by vacuum tankers, Gulpers, and manual emptiers. While Kampala and Lusaka have treatment facilities in operation for fecal sludge, Freetown's facility was not operational at the time of the research. **Table 2** below summarizes the contexts of the three cities.

3.1.2 Structural Context: Governance of the Cities

Emptying and transport services for fecal sludge are regulated by the local governments, supported by their line ministries, in all three cities. The environmental regulator is also involved in Kampala and Lusaka, along with the water and sanitation regulator and the utility in Lusaka. **Table 3** below summarizes the main stakeholders involved in the regulation of emptying and transport services.

3.1.3 Specific Context: The Regulatory Process and the Regulation in Place

All three cities started their regulatory processes recently (post-2010), following regular disease outbreaks and the offer of support from donors and development partners. They all benefitted from external support to develop their regulation and implement it, as part of wider sanitation improvement projects. Lusaka and Kampala received substantial financial support from donors and development partners (including funding for fecal sludge treatment plant construction and rehabilitation, for toilet construction and rehabilitation, support to subsidized emptying, etc.). Indeed, the Lusaka Sanitation Program, led by LWSC and funded by the World Bank, the European Investment Bank, the African Development Bank, and the German Development Bank had a budget of US$350 million (2016–2021). In all three cities, the regulatory processes began with initial assessments of the sanitation market, stakeholders and specificities. This was followed by engagement of a wide range of stakeholders, including emptiers; sanitation marketing and other awareness-raising activities targeted at households; capacity building of all stakeholders, especially of the regulators and the emptiers; and the development of regulatory documents, some of which are yet to be approved.

The regulations developed in the three cities have some similarities. Emptiers in each city should register their businesses, obtain licenses to operate from the local government and/or the utility, and licenses for their trucks. They must follow standard operating procedures, key performance indicators or minimum operating standards, and report on their work. The bylaws developed by the three local governments (two pending approval) cover the entire sanitation chain and emphasize health and safety requirements, mandatory sites for disposal, and operational standards. All three cities have set up call centers, together with monitoring and information systems (under development in Lusaka and Freetown). They all gather customer feedback through their call centers and other complaint hotlines. Local government and other regulators monitor emptiers through this feedback and spot checks, including visits to emptying sites. However, mapping sanitation facilities (even if only partial), standards for sanitation facilities, licenses from the environmental regulator, self-reporting by emptiers, and regulation by contract, in which emptiers are under contract with the municipality or utility to provide a specific service with measurable performance indicators, can only be found in Kampala and Lusaka. Lusaka is the only city in which pit-emptiers are not allowed to operate without a contract and consequently charge a specific fee set by the utility. In Kampala, emptying prices are not fixed, except when the service is subsidized by KCCA.

Penalties in place when emptiers break the rules cited above include fines, arrest, loss of license, loss of contract, loss of access to disposal site(s) and suspension from the call center registry. In Freetown for example, the FCC draft bylaws specify that emptiers who do not abide by standard operating procedures or use the mandatory disposal site can be fined up to 500,000 SLL[2] and given a prison sentence of up to 6 months.

All three cities have taken steps to support emptiers and incentivize them to operate in a formal and regulated manner. They were engaged early in the regulatory process, to ensure the acceptability of the regulation and buy-in of emptiers. Initiatives to increase demand for services included marketing of safe services, call centers, and in Kampala and Lusaka, subsidies to empty pits and tanks and to build or upgrade toilets that are emptiable. Support to formalize businesses took the form of training, and the supply of PPE and tools in the three cities. Business clinics or equivalent were provided in Kampala and Lusaka and mobile transfer stations occasionally provided in Kampala.

The implementation status of these somewhat similar regulations varies widely. In Kampala and Lusaka, while not fully implemented, according to the regulators the rules described above are known and followed by the majority of the emptiers. Kampala's compliance approach (handholding of emptiers, incentives and support to be regulated) has led to delaying full enforcement of the rules in place on paper, but a number of

[2]500,000 Sierra Leonean Leone = US$45 (March 2022).

TABLE 2 | Cities' wider context (source: document analysis and respondents).

	Kampala	Lusaka	Freetown
Location	Capital of Uganda. Bordering Lake Victoria, at an altitude of 1,140 m; total area 178 km^2	Capital of Zambia. Altitude 1269m; total area 360 km^2	Capital of Sierra Leone On the coast of the Atlantic Ocean at sea level; total area 82 km^2
Climate	Tropical, two rainy seasons	Subtropical, three seasons	Tropical, one rainy season
Administration	Kampala Capital City Authority (KCCA)	Lusaka City Council (LCC)	Freetown City Council (FCC)
Population	1.5 million that doubles during the day due to commuting. Projected to grow to 1.9 million by 2025	2.3 million inhabitants. Average population growth of 4% pa	1.2 million people. Growth rate of 4.2% pa. Expected to double by 2028
Low-income settlements	60% of the population live in the 72 informal low-income settlements that cover almost 11% of the city area	Approximately 70% of Lusaka's residents live in the 35 informal and unplanned peri-urban areas	60% of the residents live in low-income areas, the majority located on the hills and floodplains
Access to sanitation	99% of Kampala's residents have access to sanitation facilities, with 92.5% of the inhabitants using onsite sanitation facilities, mostly pit latrines, septic tanks and VIP latrines. 60% of Kampala's population had access to safely managed sanitation in 2019	85% of Lusaka's residents have access to onsite sanitation facilities (partially lined or lined pit latrines and septic tanks), 14% are connected to sewers and 1%–4% practice open defecation. 17% of the population has access to safe sanitation	90% of Freetown's residents use onsite sanitation facilities (pits and septic tanks), 6% are connected to sewers, 4%–5% practice open defecation or use hanging toilets (toilets located directly over bodies of water)
Type of fecal sludge emptying and transport	Vacuum truck in high- and mid-income areas and some low-income areas. Gulper and manual emptiers in low-income areas	Vacuum trucks mostly operating in planned urban areas. Manual pit emptiers in peri-urban areas	Vacuum trucks, Gulper operators and manual emptiers. Some facilities empty directly into drains and waterways
Treatment facilities	Bugolobi and Lubigi wastewater and fecal sludge treatment plants	Manchinchi wastewater treatment plant, or Chazanga and Kanyama fecal sludge treatment plant	Disposal at Kingtom dumpsite (not a treatment facility). A treatment facility has been built (2021) and will start operating shortly

emptiers are already registered, licensed, and operating under the existing regulations. Lusaka's implementation of the regulation has focused so far on pit-emptiers, and while they are waiting for the final approval of the bylaws before enforcing all the rules with all emptiers (to include septic tanks emptiers), pit-emptiers are already operating under the new regulations. In Freetown, however, the standard operating procedures are only followed by emptiers hired by development partners. The new bylaws, once approved by parliament, will need time to be rolled out to all service providers.

3.2 Actors' Core Characteristics

3.2.1 Knowledge

All interviewees reported experience and knowledge of the sanitation sector in general, including fecal sludge management services. They assessed the knowledge and technical skills of their institutions as sufficient to do their work, in Kampala and Lusaka, while additional capacity building is needed in Freetown. Respondents found the regulation to be clear and consistent across regulatory documents.

In all three cities, emptiers were involved in the development of and trained on the regulatory process. However, all respondents agree that additional training and outreach is needed. Similarly, there have been outreach efforts in the three cities studied to ensure households are aware of the regulation in place, although respondents said that further awareness campaigns were needed. In Freetown, respondents shared that many were still not aware of the regulations. Outreach efforts, both towards emptiers and households, have not focused on what the rules and sanctions are, but rather on why they are needed (with emphasis on the negative impact of unsafe services), and how they can be implemented.

The availability of data was in general deemed good enough by respondents in Kampala and Lusaka, thanks to previous scoping studies, surveys, and systematic data collection. In these two cities, the majority of emptiers are known by at least one of the regulators, except for some informal manual emptiers, especially in Kampala. Specific data are still lacking, such as a hydrogeological survey in Lusaka. In Freetown, however, more extensive data are still lacking about sanitation facilities and services. In all three cities, monitoring and evaluation (M&E) systems are being developed. Respondents highlighted the need for a sound understanding of the baseline situation when starting the regulatory process, including identifying existing sanitation facilities and infrastructures, stakeholders, the state of the sanitation market and services, assessing the whole sanitation chain to identify gaps, existing solutions and acceptable minimums. Sharing of data seem to be done easily and routinely in the three cities among sanitation regulators, and upon request with others.

Table 4 summarizes the findings of barriers and enables across the elements under the Knowledge theme.

3.2.2 Motivation

In all three cities, respondents shared their personal commitment to implementing the regulation in place, along with their pride in

TABLE 3 | Main stakeholders involved in provision and regulation of emptying and transport services.

	Kampala	Lusaka	Freetown
Local government	Kampala Capital City Authority (KCCA) is responsible for sanitation and public health; licenses service providers; and can make and enforce bylaws	Lusaka City Council (LCC) is responsible for sanitation and drainage; conserving water supplies and preventing pollution; and can make bylaws	Freetown City Council (FCC) is responsible for regulation and delivery of sanitation services; can raise local taxes; and can make and enforce bylaws
National government	The Ministry of Water and Environment formulates policies, long-term objectives, mobilizes financial resources and oversees the sector	The Ministry of Water Development, Sanitation and Environmental Protection (MWDSEP) provides oversight and coordination	The Ministry of Health and Sanitation (MoHS) and the Ministry of Internal Affairs, Local Government and Rural Development are responsible for sanitation
Utility	National Water and Sewerage Corporation (NWSC) is responsible for water and sewerage, including the operation of wastewater and fecal sludge treatment plants	Lusaka Water and Sanitation Company (LWSC) provides water and sanitation services. It delegates emptying services to private operators	Guma Valley Water Company is responsible for water supply and sewerage in Freetown, but has no responsibility for onsite sanitation
Independent regulator for water and sanitation	None dedicated	The National Water Supply and Sanitation Council (NWASCO, since 1997) sets and enforces standards and guidelines, licenses and advises institutions and service providers	None dedicated
Independent environmental regulator	National Environmental Management Agency (NEMA) sets waste disposal and transportation standards, and licenses environmentally hazardous practices	Zambia Environmental Management Agency (ZEMA) sets waste disposal and waste management standards, enforces them, licenses and advises institutions	The Environmental Protection Agency (EPA) sets standards and guidelines to protect the environment, but until now, is not active for onsite sanitation
Emptying and transport service providers	• KCCA (mechanical) • Formal and informal private mechanical and semi-mechanical (Gulper) emptiers • Informal manual emptiers	• Formal private mechanical emptiers • Formal manual emptiers, subcontracted by LWSC • Informal manual emptiers	• FCC (mechanical) • Formal private mechanical and Gulper emptiers • Informal mechanical and manual emptiers
Emptiers' association	• The Private Emptiers Association Uganda (PEAU) • Kampala Emptiers Association Limited (KEALtd) • The Gulpers Association of Uganda	Mechanical and formal manual emptiers are represented by the Zambia Emptiers Association	Private emptiers are represented by an emptiers' association

TABLE 4 | Barriers and enablers for knowledge from interviews.

Knowledge elements	Kampala	Lusaka	Freetown
Knowledge and technical skills of the regulator(s)	+	+	+/–
Clear regulation on paper	+	+	+
Knowledge of the regulation by emptiers	+	+	+
Knowledge of the regulation by households	+/–	+/–	–
Understanding of the need for regulation by the regulated	+	+	+/–
Knowledge of the emptiers by the regulators	+/–	+	+
Availability of data	+	+	–
Sharing of data	+	+	+

Note: this table assesses the different elements of CIT's knowledge with three potential outcomes: enablers (+), barriers (–), or a mix of enablers and barriers (+/–).

seeing the positive outcomes. In Kampala and Lusaka, interviewees also appreciated the national and international recognition their institutions are receiving. Respondents expressed that regulators should be champions of the reform and vision they are pursuing and advocate for these with all other stakeholders.

The regulators' decision to start regulating in the cities studied was driven by several reasons. First, the respondents all agreed that it was part of the mandate of their respective institutions. Second, they shared a will to address public health issues and disease outbreaks. The support received from development partners also drove them to lead reforms, especially in Freetown where it was reported to be the main reason for regulating services. Finally, respondents wanted to address the lack, or inadequacy of previous regulations, roles, and responsibilities. Indeed, Lusaka had almost no regulation for emptying and transport services for fecal sludge, while in Kampala and Freetown the previous rules were seen as confusing and too vague to be enforced. In the three cities, regulators received support from higher authorities to enact the regulation. Respondents highlighted the need to engage politicians early to gain their support, which is seen as critical.

The households' motivation to implement regulation was built through education in all three cities, explaining the need for safe services, how to access them, and how to report issues. In Kampala and Lusaka, a compliance approach with light enforcement has been used, while in Freetown, offenders are first warned and given the opportunity to comply, before being fined and prosecuted. Respondents emphasized the importance of making the steps of hiring safe services clear, easy, and well-known.

In the three cities, emptiers were engaged early to help them understand the regulation and why it was needed. They contributed to the content of the regulation, as it was seen to make the regulation more acceptable to them and more context specific. The three cities host emptiers' associations, which were consulted throughout the regulatory process, enabling regular communication and feedback between regulators and those to be regulated. Building trust between the regulators and the regulated was mentioned by respondents in Kampala and Lusaka as a key component of regulating. The requirements and bidding processes practiced in both cities are said to be transparent, so that any decision from the regulators would be accepted. In Freetown, however, emptiers find the bidding process unfair as public and private operators have different rules. In Freetown, emptiers are required to pay an unfixed registration fee, which is not less than SLL 200,000 (US$17) annually, plus at least SLL 100,000 (US$ 8.50) every dumping trip at the Kingtom disposal plant. The emptiers complained not only about the high fees, but also about the fact that the fees vary from one client to another, and that they continually go up. They also find the requirements to dispose of sludge at a disposal site and pay disposal fees illogical when the disposed sludge remains untreated.

Emptiers have also received support to help implement the new regulation (support and incentive mechanisms). This is in the form of training (technical, health and safety, business management, regulation), provision of tools and PPE, and building demand for services through awareness campaigns. These support mechanisms were mostly provided by or with financial support from development partners. Respondents shared the will of their institution to favor compliant emptiers. The call centers established in the three cities link potential customers with emptiers practicing safe emptying. Contracts given by the utility in Lusaka, the municipality in Kampala, and development partners in Freetown are restricted to registered and compliant emptiers. The goal is then to convince other emptiers that they would benefit from becoming formal and following the regulation. In the three cities, there are monitoring and reporting mechanisms in place to help regulators identify compliant and non-compliant emptiers, including self-reporting tools for emptiers and opportunities for communities to report issues, for example through mobile apps and call centers. The threat of being penalized when caught breaking the rules (see earlier examples in **Section 3.1.3**) was mentioned in all three cities as a motivation to compliance, although enforcement is still limited.

Finally, other stakeholders' motivation to implement the new regulation has been built through clearer roles and responsibilities in the three cities, strong relationships among the regulators, and involvement of all. In Kampala and Lusaka, regulators all shared the supportive relationships between the institutions involved in fecal sludge management (FSM), and between the institutions and development partners, while in Freetown, coordination between institutions and development partners remained difficult. Respondents recommended to create a roadmap towards change and agree on a shared vision with other institutional stakeholders, and to seek opportunities to support each other, while ensuring external partners are on board and target their resources to the priorities identified.

Table 5 summarizes the findings across the elements under the Motivation theme.

3.2.3 Resources

All three cities have the legal power to enact and implement the regulation for sanitation services. Local government can make and enforce bylaws, following their respective procedures. While the final approval of sanitation bylaws is pending in Lusaka and Freetown, once they are approved local officers will have the legal power to enforce them, impose sanctions or take offenders to courts. The roles and responsibilities of each stakeholder in implementing the regulation are reported by the interviewees to be clear, at least on paper. In Lusaka, LWSC has the right to subcontract emptiers with NWASCO approval and is held accountable by NWASCO. In Kampala, NWSC is responsible for managing its treatment plants and therefore can bar emptiers if necessary. In Freetown, respondents shared that in practice, there is some confusion in who does what, as interventions are led by funding opportunities. The enactment and implementation of the new regulation has received political support in the three cities studied. However, respondents were mindful that their institutions are operating in a sensitive political environment and were careful to avoid sanitation becoming politicized.

In the three cities, resources were provided to the regulators to help establish the new regulation and then implement it, as part of larger enabling environment-strengthening projects or program components. This included technical support, through hiring consultants and providing training for staff; financial support to enable stakeholder engagement meetings, council meetings, and communication campaigns; and development of sanitation infrastructure and equipment, such as treatment plants, vacuum trucks and toilet facilities. Support and incentive mechanisms for emptiers and households discussed above were mostly provided through funding from development partners. This is especially the case in Lusaka and Kampala where the sanitation sector still receives substantial support, as highlighted in **Section 3.1.3**. However, while in the three cities new institutional arrangements have been put in place, the staff incorporated into the utility or local government structures, and new M&E tools institutionalized, according to the interviewees additional human resources are needed to enable adequate monitoring and smooth running. In Kampala and Lusaka, day-to-day operations

TABLE 5 | Barriers to and enablers for motivation from interviews.

Motivation elements	Kampala	Lusaka	Freetown
Personal motivation/pride of regulators	+	+	+
Motives of regulators to start regulating			
Mandate of the institution	+	+	+
Address public health issues	+	+	+
External support	+	+	+
Inadequate previous regulation	+	+	+
Government support or directive	+	+	+
Motives of regulators to implement regulation			
Public health issues	+	+	+/−
External support	+	+	+
Government support	+	+	+
Support among the regulators	+	+	−
Households' motivation to abide by the regulation			
Awareness of the need for safe services	+	+/−	−
Handholding approach to enforcement	+	+	+/−
Emptiers' motivation to abide by the regulation			
Early engagement in the regulatory process	+	+	+
Regular communication and feedback	+	+	+/−
Support for emptiers to enable them to implement regulation	+	+	+
System favoring compliant emptiers	+	+	+/−
Trust between regulators and regulated	+	+	−
Threat of punishment by regulator/police	+/−	+/−	+
Shaming of unsafe practices and reporting of issues	+	+/−	−
Other stakeholders' motivation to implement			
Clarity of the new regulation, roles and responsibilities	+	+	+
Coordination among all stakeholders	+	+	−

Note: this table assesses the different elements of CIT's motivation with three potential outcomes: enablers (+), barriers (–), or a mix of enablers and barriers (+/–).

are now financially sustainable; however, subsidies and infrastructure investment still depend on development partners. The hand-holding approach taken with households and emptiers requires time and resources. In Freetown, the fecal sludge management unit, set up within FCC, and other FCC officers lack basic fuel, car repairs, stationery, and other essential funds to monitor services and engage communities.

In the three cities studied, households' own resources to access safe emptying and transport services for fecal sludge are limited. Indeed, according to the interviewees, the service, at its full cost, is not affordable for many poor households. The COVID-19 outbreak and its financial impact on households' finances have exacerbated this. Through targeted subsidies, Kampala and Lusaka have boosted demand for safe services. In Kampala, subsidized emptying campaigns have allowed households who were previously hiring manual emptiers, to hire formal emptiers. Similarly in Lusaka, through partial subsidies, the price for formal pit emptying is similar to that for manual informal emptying. In Freetown, however, no subsidies are available beyond specific development partners' programs. FCC is planning to provide services on a cost-recovery basis in due course. The option of cross-subsidies has been explored by two cities. In Kampala, KCCA explored the possibility of attaching a sanitation tax to the property tax, but an outcry against taxation prevented this. In Lusaka, a sanitation surtax added to the water bill is under consideration.

The emptiers' resources to implement the new regulation vary according to the types of emptiers and across cities. Indeed, in all three cities, respondents reported that many small-scale emptiers have low administrative and mechanical skills and/or are illiterate, and therefore need further education and training to understand and abide by the regulation. Likewise, they are limited by poor access to financing, high-quality trucks, spare parts, etc. Moreover, emptiers experience external challenges that hinder their capacity to implement regulation. Traffic congestion, remote emptying locations and poor-quality roads were identified in the three cities. To address the transportation challenge, in Kampala mobile transfer stations are set up regularly for emptying events organized by the municipality, and in Lusaka, new treatment plants are being strategically located. Other steps of the sanitation chain also limit the capacity of emptiers to implement new regulations, over which they have no power. Indeed, in all three cities, pits and septic tanks are not all accessible and/or safe to empty and the treatment capacity does not meet the potential demand. To address this issue, in Kampala and Lusaka, minimum standards for containment have been created, and communities and masons engaged to improve facilities. All three cities are also increasing their fecal sludge treatment capacities.

Table 6 summarizes the findings across the elements under the Resources theme.

4 DISCUSSION

4.1 Contextual Factors

4.1.1 Wider Context: The Three Cities

Kampala, Lusaka, and Freetown are all capital cities, with over a million residents each and undergoing rapid growth. They have large unplanned settlements, hosting over 60% of their population. These three cities illustrate well the situation in many sub-Saharan African countries, which are experiencing high rates of urbanization and population growth (United Nations Department of Economic and Social Affairs Population Division, 2019). Sierra Leone and Uganda are among the most urbanized countries in the region (United Nations Department of Economic and Social Affairs Population Division, 2019). It is estimated that sub-Saharan African cities commonly have between one-third and two-thirds of their population living in poor-quality housing (AfDB, UNEP, and GRID-Arendal, 2020). City planners, city infrastructure and service providers struggle to meet the demand for basic services, which keeps increasing due to the high urbanization rates and population growth (Mitlin and Satterthwaite, 2012; AfDB, UNEP, and GRID-Arendal, 2020).

In the three cities studied, a large majority of residents use onsite sanitation facilities and services, with sewerage limited to central and formal areas. Access to safe sanitation is low, reflecting the region's situation, where it is estimated that only 21% of the population had access to safely managed sanitation in 2020, a very limited increase since 2015 (19%), showing that the region is not on track to achieve universal access to safely managed sanitation by 2030, despite progress (WHO/UNICEF, 2021). As in Kampala, Lusaka and Freetown, onsite sanitation is predominant in urban sub-Saharan Africa (62% of the urban population uses onsite sanitation, 16% sewered sanitation) (WHO/UNICEF, 2021).

The treatment capacity of fecal sludge is limited in the three cities, with no treatment facility operating in Freetown, and insufficient capacity to treat all the sludge generated in both Kampala and Lusaka. The three cities studied are, however, addressing this issue, at least partially. While there are overall very limited data available on fecal sludge and wastewater treatment in sub-Saharan Africa (SSA) (AfDB, UNEP, and GRID-Arendal, 2020; WHO/UNICEF, 2021), it has been estimated that only 8% of the wastewater generated is treated in low-income countries in general (AfDB, UNEP, and GRID-Arendal, 2020) and 1% in SSA (WHO/UNICEF, 2021).

TABLE 6 | Barriers to and enablers for resources from interviews.

Resources elements	Kampala	Lusaka	Freetown
External support to create regulation	+	+	+
External support to implement regulation	+	+	+/–
Legal power to enact regulation	+	+	+
Legal power to implement regulation			
Regulatory documents finalized and approved	+	+/–	–
Threat of sanction in regulatory documents	+	+	+
Clear roles and responsibilities to implement regulation	+	+	+/-
Regulators' resources to implement over time			
FSM staff and units incorporated into structures	+	+	+
M&E tools institutionalized	+	+	+
M&E tools in place	+/–	+/–	+/–
Human resources to monitor	+/–	+/–	–
Financial resources to monitor	+/–	+	–
Subsidies and infrastructure developments dependent on external partners	–	–	–
Political interferences in implementation	+/–	+	–
Households' ability to abide by regulation			
Capacity to pay for safe services without subsidy	–	–	–
Subsidies availability	+/–	+/–	–
Emptiers' ability to abide by regulation			
Emptiers' resources to implement	+/–	+/–	–
Influence of containment step of the chain	+/–	+/–	–
Influence of treatment step of the chain	+/–	+/–	–

Note: this table assesses the different elements of CIT's resources with three potential outcomes: enablers (+), barriers (–), or a mix of enablers and barriers (+/–).

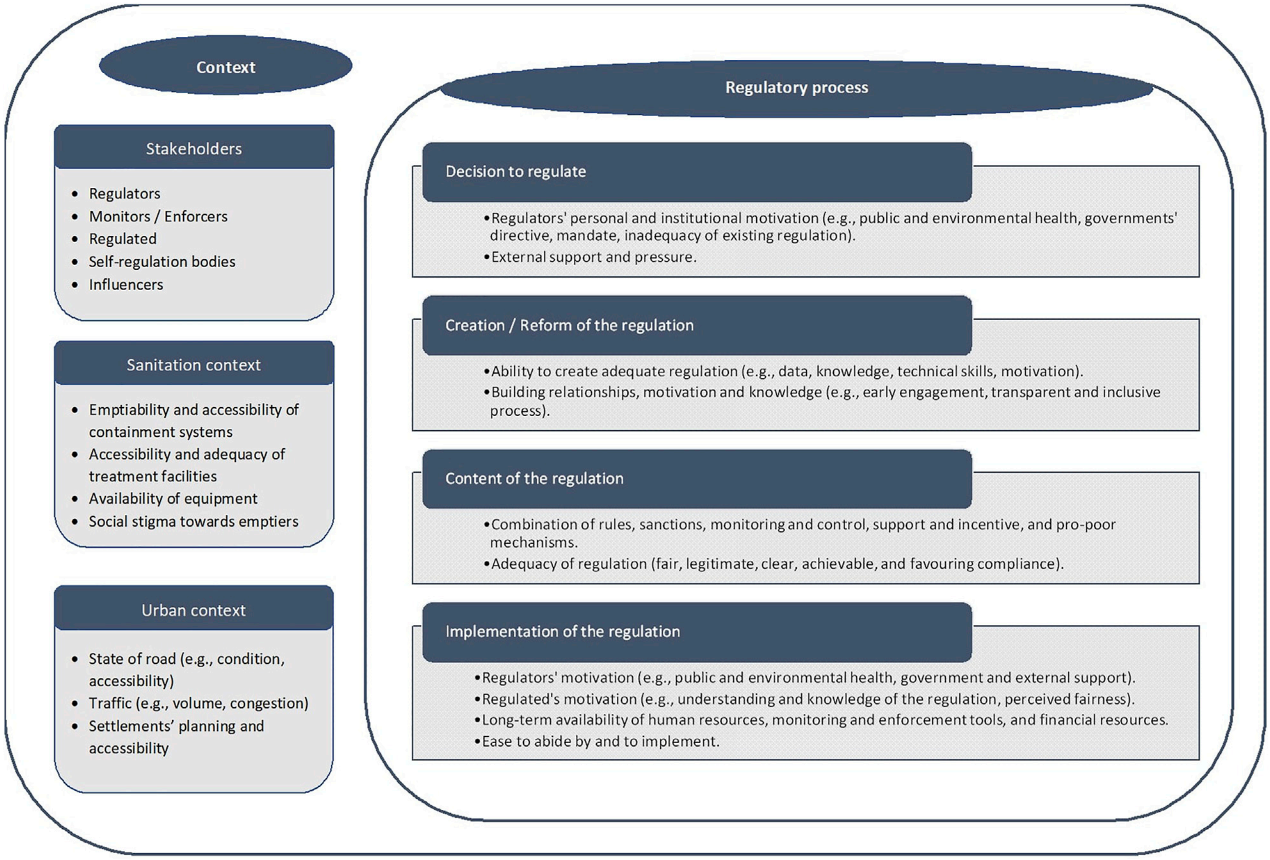

FIGURE 2 | Elements influencing the regulation of emptying and transport services for fecal sludge.

Kampala, Lusaka and Freetown, while not representative of the whole region, do reflect the situation of many sub-Saharan African cities. They are capital cities, large urban centers experiencing rapid growth (over 4% of annual population growth), with an important proportion of their residents living in unplanned settlements and, notably in the case of Kampala, a substantial number of daily commuters. Access to sanitation is low, especially to safely managed sanitation. The increase in access to basic sanitation facilities, along with the ongoing urbanization, is likely to put more pressure on the other steps of the sanitation chain in the future, as pits and tanks will need to be emptied, and the removed fecal sludge treated. Sanitation being only one of many basic services requiring improvement in these cities (Mitlin and Satterthwaite, 2012; Scott et al., 2019), city planners and service providers are thus faced with the challenge of providing safe services to both a growing and fluctuating population in an environment of competing priorities.

4.1.2 Structural Context: The Governance of Sanitation Services

In the three cities studied, responsibility for sanitation lies with local government, who can provide or organize services, license service providers, make and enforce bylaws. National governments are responsible for policies, national laws, technical guidance, coordination of the sector, and approval of bylaws made by local governments. Only Zambia has a national water and sanitation regulator. Thus, the number of regulators involved in FSM services varies: two in Kampala (KCCA and NEMA), four in Lusaka (LCC, LWSC, ZEMA and NWASCO), and two in Freetown (MoHS and FCC). Independent national regulators have been recommended previously (ESAWAS Regulators Association, 2019; Franceys, 2020), or at least a clear division of roles between service provision and regulation (African Ministers' Council on Water, 2021), which does not seem to be the case in Freetown and Kampala. Environmental regulators have become common in sub-Saharan Africa over the past 20 years (Sommerer and Lim, 2016); however, as in the case of Sierra Leone, not all are involved in sanitation services (ESAWAS Regulators Association, 2019). In Uganda, the involvement of NEMA in fecal sludge management is also recent. These three cities confirm the critical role of both local and national government in the regulation of sanitation services (Mulenga, 2011; AfDB, UNEP, and GRID-Arendal, 2020).

Emptying and transport services for fecal sludge is mostly provided in the three cities by a range of private emptiers (manual, semi-mechanical or mechanical). In Kampala and Freetown, the local government provides limited services as well, making KCCA and FCC both service providers and regulators. Kampala and Lusaka have utilities providing onsite sanitation services: NWSC (Kampala) only provides treatment of the fecal sludge, LWSC (Lusaka) provides treatment of the fecal sludge and contracts pit-emptiers to provide emptying services. These three service delivery models correspond to those previously identified in the literature: a mix of public and private service provision, as in Kampala and Freetown, where the private sector is the main provider; and a fully private service provision, as in Lusaka (Mbéguéré et al., 2010; Rao et al., 2016). Yet, Lusaka is an unusual case for the region, with a contract-based service delivery model for emptying pit latrines. The only similar case in the literature is the South African franchising model of emptying services to schools and households (Rao et al., 2016). The approach can support innovation and greater efficiencies in arrangements, with a clear division of roles and responsibilities for stakeholders within well-defined rules and penalties. It also requires additional supervision and management for the contracting authority and has not yet been sufficiently tested to analyze sustainability of the model at scale.

There are active private emptiers' associations in the three cities. The prevalence and roles of these associations have not yet been explored in depth by researchers, although recent literature suggests that they are important stakeholders in the FSM sector (Gero and Willetts, 2020; Peletz et al., 2020). This study shows that these associations are indeed playing a role in the coordination of emptiers among themselves and alongside the regulators.

4.1.3 Specific Context: The Regulatory Process and the Regulation in Place

The three cities have all started their regulatory processes recently and received external support. Urban sanitation and its enabling environment have indeed received more attention in recent years, with development banks increasing their focus on institutional capacity building and policy changes (Hutchings et al., 2018). The cities studied are examples of cities following the citywide inclusive sanitation (CWIS) approach, supported by their donors. With the approach focusing on (Gambrill et al., 2020), this may explain the similarities, may explain the similarities identified between the regulations set up. The influence of donors on the regulations enacted has been little studied.

The steps taken in the three cities of assessing the situation, engaging the stakeholders, and building their capacities have all been previously recommended by the literature as pre-requisite to planning and reform in the sanitation sector, and thus to enacting adequate regulation. Similarly, the need for support mechanisms to enable service providers to provide safe services while remaining financially viable has been recommended previously (Sinharoy et al., 2019; Weststrate et al., 2019; African Ministers' Council on Water, 2021). The CWIS approach, adopted by the three cities studied, also encourages supporting service providers to enable services to reach all residents (Gambrill et al., 2020; Spuhler and Lüthi, 2020). The variety in implementation across the three cities studied confirms previous findings: much of the regulation is not fully implemented (Weststrate et al., 2019; Lerebours et al., 2021b); implementation takes time and effort (Sinharoy et al., 2019; Franceys, 2020).

4.2 Actors' Core Characteristics

4.2.1 Knowledge

This study's findings confirm existing literature on both sanitation planning and regulation, which identified skills and capacity as key to planning and delivering sanitation services (Strande et al., 2014; Franceys, 2020). The capacity of the regulators and not just of those providing services must be considered. The importance of the availability of data was shown in the findings. The need for data for sound sanitation planning was previously identified in the literature (Schoebitz et al., 2017; Mumssen et al., 2018), but the detail of what this entails has been less discussed. The findings of this study thus highlight the variety of data needed by regulators when creating, reforming, and implementing the regulation.

Previous research showed the importance of clear and coherent sanitation policies (Hueso and Bell, 2013; Mulumba et al., 2015). It highlights that knowledge of the regulation by the regulated is crucial to its implementation: they cannot be expected to respect rules, understand sanctions, or benefit from support and incentive mechanisms if they are not aware of them (Bressers and de Boer, 2013; Weststrate et al., 2019). Findings from this research show that the regulation or how to access safe services is not well known in Freetown. This may partly explain the difference between the cities regarding the hiring of safe emptiers by households, which is common in Kampala and Lusaka but rare in Freetown.

4.2.2 Motivation

The importance of personal commitment to the reforms was highlighted by respondents. While the institutional commitment to change has been previously advocated for by researchers (Parkinson et al., 2014; Sinharoy et al., 2019), the personal commitment and pride of those responsible for enacting the regulation was not identified as an enabling element in the literature review.

The drivers to create and implement regulation on the regulators' side can be summarized as 1) the protection of public health and the environment; 2) ongoing external support; and 3) ongoing government support. The will to protect public health and the environment corresponds to the traditional rationale for regulation: unjust or undesirable market results (market failure) and protection of the interest of the current and future population (external effect) (Baldwin and Cave, 1999); and to the sanitation sectors' commonly cited regulatory objectives (Mumssen et al., 2018; Weststrate et al., 2019). However, the role of the development partners as initiators of regulation has been little researched. Political will has long been seen as crucial for reform in the sanitation sector (Sinharoy et al., 2019; Weststrate et al., 2019) and this study confirms this is also the case for regulation of services.

Respondents emphasized the need for an education-focused approach to implementing regulation and the importance of making the steps of hiring safe services clear, easy, and well-known. The literature shows the importance of educating the population to increase demand for safe services (Jenkins et al., 2015; Peletz et al., 2020). This study illustrates how these recommendations have now been included in practice. A new point identified, beyond clear, well-known regulation, is the need for a simple process for households to hire safe services. Call centers and mobile apps present in the three cities studied show signs of being useful tools, as they facilitate access for customers to providers of safe services, while making reporting processes easier for the service providers. While a call center has proved useful in Dakar (Spuhler and Lüthi, 2020), those in the cities studied are too recently established to assess their effectiveness and sustainability.

The emptiers' motivation to implement the regulation has been addressed by the regulators in the cities studied through 1) engaging them early and continuously to convince them of the need and adequacy of the regulation; 2) support and incentives to help them comply; and 3) monitoring and reporting of their practices. While the value of engaging the regulated was already discussed as an enabler to enacting implementable regulation and to ensure the buy-in of the regulated (Sinharoy et al., 2019; Spuhler and Lüthi, 2020; African Ministers' Council on Water, 2021), these results show how this advice has now been integrated into practice. The role of the emptiers' association seems to be growing, both in the creation and implementation of regulation, despite not being documented yet.

The importance of fair and predictable rules, incentives and penalties, and of trust between regulators and regulated was shown previously in the literature (Mbéguéré et al., 2010; Acey et al., 2019; Eales and Blackett, 2019). In the three cities studied, respondents confirmed this by sharing that resistance to change has been overcome at least partially in Lusaka and Kampala through continuous engagement and transparency, while it is said to be still high in Freetown, where a lower level of engagement and trust exists between emptiers and authorities.

In this study, the threat of fines and courts is seen by the respondents as a useful deterrent for offenders, although all want to focus on educating households and emptiers first. The approach taken by regulators to favor compliant emptiers corresponds to the "support and incentivize" regulatory approach (Baldwin and Cave, 1999; Vedung, 2017) and goes beyond enabling emptiers. While the review of literature identified examples of support mechanisms (Doe and Aboagye, 2020; Gero and Willetts, 2020), incentive mechanisms are rarely documented and correspond to the "advise and persuade" enforcement style (Ayres and Braithwaite, 1992; Baldwin and Cave, 1999). The threat of sanction is a tool included in the "command and control" regulatory approach and the "punish" enforcement style. Although only light enforcement is pursued, it may be enough to discourage offences if non-compliance is seen as more costly than compliance (Baldwin and Cave, 1999; Vedung, 2017). In this study, the cost identified by service providers may go beyond the fines offenders are charged. Indeed, the sensitization among the population made communities aware of good and bad practices and willing to report them, especially in Kampala, where online shaming happens regularly. In Freetown, however, where the population is less aware of the need for safe services, the local authorities say they do not receive many complaints about unsafe practices. The social cost of being identified as a "bad" service provider and the potential loss of future customers may also be acting as deterrents for emptiers.

4.2.3 Resources

This study shows that, while regulators need to have the legal power to use such instruments to deter multiple offenders, they prefer combining different regulatory approaches and tools, and to focus on the "advise and persuade" enforcement style (Ayres and Braithwaite, 1992; Baldwin and Cave, 1999). This strategy corresponds to what Ayres and Braithwaite called for: "responsive regulation" (Ayres and Braithwaite, 1992), which requires the regulator to be legally empowered, flexible, and predictable.

As discussed above, clarity of roles and official responsibilities is necessary to implement the regulation. Findings of this research illustrate the interdependence of regulators (operating collectively in one context), and with the other stakeholders (Parkinson et al., 2014; Spuhler and Lüthi, 2020). It thus shows that, beyond ad hoc support and collaboration, the institutionalization of lines of accountability between stakeholders and/or supporting systems between the various regulators contribute to effective and clear regulation.

Interference and resistance to change were experienced at the local councilors' level in both cities, in Kampala and Freetown, and with some development partners in all cities. Knowledge of the influence of political turnover and interference in sanitation planning and regulating is still limited; however, protection from political interference is one of the rationales for regulation (Baldwin and Cave, 1999; Mulenga, 2011). Regulation protects the sector from short-term change for political gain and provides a stable environment where service providers can flourish (Eales and Blackett, 2019). The process of creating regulation, however, is politically sensitive, emphasizing within this research the need to gain buy-in from politicians, especially local ones.

This study's findings show the importance of the availability of resources to create and implement the regulation, highlighting the cost of regulation for the regulator. While there has been research on the cost-benefits and cost-effectiveness of regulation in high-income countries, there is little literature looking at the costs of enacting and implementing regulation for sanitation services in low- and middle-income countries (one example being Guasch and Hahn, 1999). The three cities studied here show that development partners are taking these costs into account and are providing at least some of the resources required. This study thus raises the question of sustainability once development projects finish and the importance of sound exit strategies.

In the three cities studied, households' resources to access safe emptying and transport services for fecal sludge are limited. The limited capacity to pay for safe sanitation services of poor households has been well demonstrated by researchers (Jenkins et al., 2015; Peletz et al., 2020). While cross-subsidies across services, or from higher-income to lower-income customers, is common for water and sewerage services, they are rarely reported at-scale for FSM services, despite being seen as potentially effective tools to enable universal access to safe sanitation (Acey et al., 2019; Doe and Aboagye, 2020; Gambrill et al., 2020). This study illustrates both the attractiveness and the complexity of cross-subsidies for emptying and transport services for fecal sludge. Indeed, the additional charge on property tax was not pursued in Kampala due to political reasons, and the sanitation surcharge on the water bill in Lusaka has taken time to be approved by the economic regulator.

Findings also point to the cost of regulation for the emptiers. Previous literature identified that emptiers providing unhygienic services usually operate at a lower cost than compliant service providers, thus favoring unsafe practices (Mbéguéré et al., 2010; Peletz et al., 2020). Addressing each of the operational and administrative costs, financial and non-financial, would aid implementing the regulation.

The capacity of emptiers to abide by the regulation is also limited. This was highlighted in the respondents' recommendations, as they have enjoined other regulators to accommodate all education and literacy levels in their engagement of emptiers. Likewise, results emphasize the interdependencies between the steps of the sanitation chain, and the need to consider its entirety when regulating emptying and transport services for fecal sludge (Parkinson et al., 2014; Doe and Aboagye, 2020).

4.3 The Barriers and Facilitators to Regulating Emptying and Transport Services: A Framework

Using CIT as a theoretical lens through which to explore the regulation of emptying and transport services, this research identified a number of factors enabling and hindering the regulation and its implementation. The elements presented in **Tables 4–6**, and the ones identified in the discussion section above have been grouped along the different stages of the regulatory process: its initiation, the creation or reform of the regulation, and its implementation. The identification and analysis of these elements have led to the development of a framework (**Figure 2**) incorporating the key elements to be considered to enable effective regulation for safe emptying services that are accessible to all. The components of the framework are described below.

4.3.1 Initiation

The decision to start regulating or reforming emptying and transport services, and what is driving that decision, was shown to influence the implementation of the regulation. Indeed, when the drive to regulate comes only from external partners, the motivation and future efforts to implement from the regulators and enforcers may be limited, as in Freetown. This research shows the importance of considering the personal and institutional motivations of the regulator at this early stage, to ensure their commitment and leadership in the next stages of the regulatory process. The rationale to regulate identified in this research aligns with the rationale present in the literature: improving the access, quality, and efficiency of the services, protecting public health and preventing environmental pollution (Strande et al., 2014; Mumssen et al., 2018). However, the presence of external partners and their commitment to the regulatory process and the sanitation sector in general, also contributes to the drive to regulate. Other specific motives to regulate for the regulator include their belief that it is the responsibility of their institutions, the inadequacy of existing regulation, and government directives.

4.3.2 Creation/Reform

Once the decision to regulate has been made, the process of creating or reforming the regulation can start. The effect of this on future implementation is twofold: the content of the regulation influences the implementation; and its characteristics impact the relationships, motivations, and knowledge of the regulators and the regulated. All of these are crucial to its implementation. Indeed, inadequate regulation was identified as a crucial barrier to implementation. Previous research highlights the interdependency among categories of regulatory mechanisms (rules, sanctions, monitoring and control mechanisms, support and incentive mechanisms, and pro-poor measures), both in their existence and in their implementation, and the influence of the extent of regulation on its implementation (Lerebours et al., 2021b). The different categories of regulatory mechanisms should all be included in regulation, confirming the recommendations of previous research to provide support and incentives to emptiers and subsidies to households (Mulumba et al., 2015; Lerebours et al., 2021a, 2021b). The perception of regulation also influences its implementation. It must be fair, legitimate, clear, achievable, and favoring compliance, as well as perceived as such. These requirements have been discussed individually in the sanitation literature before (Mbéguéré et al., 2010; Mulumba et al., 2015; Mumssen et al., 2018; African Ministers' Council on Water, 2021).

4.3.3 Implementation

At the implementation stage, some of the elements presented in the results enhance points identified in the literature: lack of capacity, inadequate regulation, unclear roles and responsibilities, limited monitoring and enforcement capacities, lack of autonomy for the regulator and lack of data (Strande et al., 2014; Schoebitz et al., 2017; Weststrate et al., 2019). This research adds to this list the understanding and knowledge of regulation by the regulated; the support available to regulators and regulated; the costs, financial and non-financial, and the ease of implementing the regulation for all stakeholders; together with the relationships and trust among the stakeholders.

4.3.4 Context-Related Factors

Finally, this study shows how context-related factors have an impact on the implementation of the regulation. The sanitation-related factors identified through this research are linked to the containment and treatment stages of the sanitation chain, the accessibility of emptying and transport equipment and the social stigma around sanitation work. These factors emphasize the need to look at the entire sanitation chain when planning and regulating emptying and transport services, in line with the recent sanitation literature (Franceys, 2020; Gambrill et al., 2020; African Ministers' Council on Water, 2021). Sanitation services operate in a wider urban context and are thus affected by urban issues. Most cities in sub-Saharan Africa are home to many residents living in poor-quality housing and are experiencing high urbanization rates and population growth (Mitlin and Satterthwaite, 2012). As a result, cities' planners and service providers are faced with the challenge of providing safe services to a growing population in an increasingly competitive environment. While research has already shown the importance of integrating sanitation planning to other essential services planning, due to funding and institutional constraints, it is not always done (Scott et al., 2019). This study confirms that regulation of emptying and transport services for fecal sludge must form a core aspect of all stages of initiating, creating, and implementing service legislation, firmly grounded in the context and integral to the planning of other services.

4.4 Limitations

Due to COVID-19 travel restrictions, this study was conducted fully online, and thus relied on the documents accessible online and through respondents, and on the respondents' accounts. However, the research design facilitated the collection of diverse types of data, triangulating findings and enhancing their validity and credibility. This research did not seek a representative sample of respondents for two of the sources of evidence, but rather to consult relevant working professionals corresponding to specific criteria. It is possible that certain perspectives were not included due to an inability of some professionals to answer online surveys, their limited availability, or unwillingness to participate.

To address potential biases in the data analysis, the qualitative analysis followed a theory-informed coding guide, and the interviews were re-coded after the final coding guide was developed iteratively. It was checked by the researcher at the end of the overall analysis and when writing up the results.

5 CONCLUSION

Through multiple-case analysis using Contextual Interaction Theory, this study investigated the barriers to and enablers of implementing regulation of emptying and transport services for fecal sludge in sub-Saharan African cities. This research has identified several new factors of significance, such as the motivation, capacity, resources and relationships of all stakeholders, the external support available, the adequacy of the regulation, and how easy it is to abide by and implement the regulation. The cities studied illustrate the variety of governance arrangement and regulatory processes in sub-Saharan Africa. They demonstrate the crucial role of local government in the organization and regulation of emptying and transport services, highlight the complexity of FSM services and their regulation, and the importance of contextualized solutions. This study also points to the costs, financial and non-financial, of regulating emptying and transport services, both for regulators and the regulated.

When analyzing the regulation of fecal sludge emptying and transport services, both the content of the regulation and the regulatory process (initiation, creation/reform, implementation) must be considered. Content and process influence one another, while the desired outputs of safe services for all can be enabled or hindered by both contextual and regulatory factors. The motivation, capacity, knowledge, and resources of all stakeholders are crucial to achieve regulated services. These can be enhanced through early and continuous engagement and support. Barriers to and enablers of implementing the regulation identified in this research can be found at different stages of the regulatory process and have led to the creation of a framework describing the key elements and stages to take into consideration when regulating emptying and transport services.

Any city contemplating improving the regulation of sanitation should consider comparisons with other similar cities, where improvements have been made, as has been done in this paper, using a consistent methodology. This study and the resulting frameworks would prove useful to regulators, sanitation planners and their development partners 1) when starting to initiate regulating services, ensuring the consideration of key elements in the regulatory process from the start, enabling regulation to be successfully enacted and implemented; and 2) when wanting to understand why the enacted regulation is not being implemented as planned, providing suggestions of additional elements to consider, activities to lead, and stakeholders to engage to offset the issues being faced. It would also be useful for researchers analyzing regulatory processes in low- and middle-income country cities, as a framework to identify the key contextual and regulatory process-related elements to include in their analysis.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical clearance was obtained from Loughborough University for the online survey and interviews (Reference: DT_10496). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

Conceptualization, AL, RS, KS and SK. Data curation and formal analysis, AL. Methodology, AL, RS, KS and SK. Validation, AL, RS, KS and SK. Writing—original draft, AL. Writing—review and editing, RS, KS and SK.

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REFERENCES

Acey, C., Kisiangani, J., Ronoh, P., Delaire, C., Makena, E., Norman, G., et al. (2019). Cross-subsidies for Improved Sanitation in Low Income Settlements: Assessing the Willingness to Pay of Water Utility Customers in Kenyan Cities. *World Dev.* 115, 160–177. doi:10.1016/j.worlddev.2018.11.006

AfDB, UNEP, and GRID-Arendal (2020). *Sanitation and Wastewater Atlas of Africa. Abidjan, Nairobi and Arendal: AfDB, UNEP and GRID-Arendal.*

African Ministers' Council on Water (2021). *African Sanitation Policy Guidelines*. Nigeria: Abuja.

Baldwin, R., and Cave, M. (1999). *Understanding Regulation. Theory, Strategy and Practice*. Oxford: Oxford University Press.

Bressers, H., and de Boer, C. (2013). "Water Governance, Policy and Knowledge Transfer," in *Water Governance, Policy and Knowledge Transfer: International Studies on Contextual Water Management*. Editors C. de Boer, J. Vinke-de Kruiff, G. Ozerol, and H. Bressers (London: Routledge), 36–54. doi:10.4324/9780203102992

Bressers, J. T. A. (2004). "Implementing Sustainable Development: How to Know what Works, where, when and How," in *Governance for Sustainable Development: The challenge of Adapting Form of Function* (Cheltenham: Edward Elgar), 284–318.

Doe, B., and Aboagye, P. D. (2020). The Place of Subsidy: Affordable Sanitation Service Delivery in Slums of Kumasi, Ghana. *GeoJournal* 87, 295–317. doi:10.1007/s10708-020-10256-7

Eales, K., and Blackett, I. (2019). *FSM5 Thematic Papers*. Bremen: FSM5.

ESAWAS Regulators Association (2019). *Regulation Strategy and Framework for Inclusive Urban Sanitation Service Provision Incorporating Non-sewered Sanitation Services*. Lusaka, Zambia.

Franceys, R. (2020). *Referee! Responsibilities, Regulations and Regulating for Urban Sanitation*. London.

Gambrill, M., Gilsdorf, R. J., and Kotwal, N. (2020). Citywide Inclusive Sanitation-Business as Unusual: Shifting the Paradigm by Shifting Minds. *Front. Environ. Sci.* 7, 1–10. doi:10.3389/fenvs.2019.00201

Gero, A., and Willetts, J. (2020). Securing a Conducive Environment for WASH Markets: the Role of Local Government. *Waterlines* 39, 44–60. doi:10.3362/1756-3488.18-00026

Guasch, J. L., and Hahn, R. W. (1999). The Costs and Benefits of Regulation: Implications for Developing Countries. *The World Bank Res. Observer* 14, 137–158. doi:10.1093/wbro/14.1.137

Hueso, A., and Bell, B. (2013). An Untold story of Policy Failure: The Total Sanitation Campaign in India. *Water Policy* 15, 1001–1017. doi:10.2166/wp.2013.032

Hutchings, P., Johns, M., Jornet, D., Scott, C., and Van den Bossche, Z. (2018). A Systematic Assessment of the Pro-poor Reach of Development Bank Investments in Urban Sanitation. *J. Water Sanit. Hyg. Dev.* 8, 402–414. doi:10.2166/washdev.2018.147

Jenkins, M., Cumming, O., and Cairncross, S. (2015). Pit Latrine Emptying Behavior and Demand for Sanitation Services in Dar Es Salaam, Tanzania. *Ijerph* 12, 2588–2611. doi:10.3390/ijerph120302588

Lerebours, A., Scott, R., Sansom, K., and Kayaga, S. (2021b). Regulating Sanitation Services in Sub-saharan Africa: An Overview of the Regulation of Emptying and Transport of Faecal Sludge in 20 Cities and its Implementation. *Utilities Policy* 73, 101315. doi:10.1016/j.jup.2021.101315

Lerebours, A., Scott, R., and Sansom, K. (2021a). Private Emptiers' Perspectives on the Regulation of Faecal Sludge Emptying Services in Sub-saharan Africa. *J. Water Sanit. Hyg. Dev.* 11, 785–793. doi:10.2166/washdev.2021.026

Lodge, M., and Braithwaite, J. (2016). *Responsive Regulation: Transcending the Deregulation Debate*. Oxford: Oxford University Press. doi:10.1093/oxfordhb/9780199646135.013.40Ian Ayres and John Braithwaite,

Mbéguéré, M., Gning, J. B., Dodane, P. H., and Koné, D. (2010). Socio-economic Profile and Profitability of Faecal Sludge Emptying Companies. *Resour. Conservation Recycling* 54, 1288–1295. doi:10.1016/j.resconrec.2010.04.008

Mitlin, D., and Satterthwaite, D. (2012). *Urban Poverty in the Global South*. London: Routledge. doi:10.4324/9780203104316

Mulenga, M. (2011). *Pathfinder 2011*. London: Urban Sanitation.

Mulumba, J. N., Nothomb, C., Potter, A., and Snel, M. (2014). Striking the Balance: what Is the Role of the Public Sector in Sanitation as a Service and as a Business? *Waterlines* 33, 195–210. doi:10.3362/1756-3488.2014.021

Mumssen, Y., Saltiel, G., Kingdom, B., Sadik, N., and Marques, R. (2018). Regulation of Water Supply and Sanitation in Bank Client Countries. *Regul. Water Supply Sanit. Bank Client Ctries*. doi:10.1596/30869

O'toole, L. J. (2004). The Theory-Practice Issue in Policy Implementation Research. *Public Adm.* 82, 309–329. doi:10.1111/j.0033-3298.2004.00396.x

Parkinson, J., Lüthi, C., Walther, D., Luthi, C., and Walther, D. (2014). *Sanitation 21 - A Planning Framework for Improving City-wide Sanitation Services*. London. doi:10.1371/journal.pone.0093300

Peletz, R., MacLeod, C., Kones, J., Samuel, E., Easthope-Frazer, A., Delaire, C., et al. (2020). When Pits Fill up: Supply and Demand for Safe Pit-Emptying Services in Kisumu, Kenya. *PLoS One* 15, e0238003–21. doi:10.1371/journal.pone.0238003

Rao, K. C., Kvarnstrom, E., Di Mario, L., and Drechsel, P. (2016). Business Models for Fecal Sludge Management. *Colombo, Sri Lanka*. doi:10.5337/2016.213

Schoebitz, L., Bischoff, F., Lohri, C., Niwagaba, C., Siber, R., and Strande, L. (2017). GIS Analysis and Optimisation of Faecal Sludge Logistics at City-wide Scale in Kampala, Uganda. *Sustainability* 9, 194. doi:10.3390/su9020194

Scott, R., Scott, P., Hawkins, P., Blackett, I., Cotton, A., and Lerebours, A. (2019). Integrating Basic Urban Services for Better Sanitation Outcomes. *Sustainability* 11, 6706–6717. doi:10.3390/su11236706

Sinharoy, S. S., Pittluck, R., and Clasen, T. (2019). Review of Drivers and Barriers of Water and Sanitation Policies for Urban Informal Settlements in Low-Income and Middle-Income Countries. *Utilities Policy* 60, 100957. doi:10.1016/j.jup.2019.100957

Sommerer, T., and Lim, S. (2016). The Environmental State as a Model for the World? an Analysis of Policy Repertoires in 37 Countries. *Environ. Polit.* 25, 92–115. doi:10.1080/09644016.2015.1081719

Spuhler, D., and Lüthi, C. (2020). Review of Frameworks and Tools for Urban Strategic Sanitation Planning: Considering Technology Innovations and Sustainability. *J. Water Sanit. Hyg. Dev.* 10, 768–785. doi:10.2166/washdev.2020.062

Strande, L., Ronteltap, M., and Brdjanovic, D. (2014). *Faecal Sludge Management: Systems Approach for Implementation & Operation*. London: IWA Publishing.

United Nations Department of Economic and Social Affairs Population Division (2019). World Urbanization Prospects: The 2018 Revision. New York Available at: https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf.

Vedung, E. (2017). "Policy Instruments: Typologies and Theories," in *Carrots, Sticks & Sermons*. Editors M.-L. Bemelmans-Videc, R. C. Rist, and E. Vedung (New York: Routledge), 21–58. doi:10.4324/9781315081748-2

Weststrate, J., Gianoli, A., Eshuis, J., Dijkstra, G., Cossa, I. J., and Rusca, M. (2019). The Regulation of Onsite Sanitation in Maputo, Mozambique. *Utilities Policy* 61, 100968. doi:10.1016/j.jup.2019.100968

WHO/UNICEF (2021). *Progress on Household Drinking Water, Sanitation and hygiene 2000-2020: Five Years into the SDGs*. Geneva.

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Application of Financial Flow Simulator (eSOSView™) for Analyzing Financial Viability and Developing a Sustainable Fecal Sludge Management Business Model in Kushtia, Bangladesh

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To achieve SDG 6.2.1 (a) on safely managed sanitation services, several financial flow models (FFMs) and business models for the sanitation value chain have been implemented in Bangladesh and elsewhere; however, there is limited research on financial viability and sustainability of business models. Bangladesh has attained 99% sanitation coverage, mostly with onsite sanitation systems; however, the country is facing a second-generation sanitation challenge, fecal sludge management, encompassing the entire sanitation chain. Kushtia Municipality in Bangladesh is entirely served by onsite systems; the fecal sludge emptying service is provided by the municipality, and the fecal sludge treatment plant is managed by a private entity. This study investigated sustainability of FFMs in Kushtia by using the financial, institutional, environmental, technical, and social (FIETS) sustainability approach and applying the financial flow simulator (eSOSView™) tool to analyze financial viability. Several criteria in each aspect of the FIETS approach were developed, scored, and validated by stakeholders to determine sustainability. The study found that the financial aspect is the most important criteria for sustainability and "modified parallel tax and discharge fee" is the most sustainable business model for Kushtia.

Keywords: fecal sludge management, financial flow models, financial viability, business model, Kushtia

INTRODUCTION

The Sustainable Development Goal 6 (SDG 6) established by the United Nations in 2015 as part of the 2030 agenda for sustainable development focuses to ensure availability and sustainability of water and sanitation for all (UN, 2015). SDG 6.2 (a) targets to attain safely managed sanitation services for all. At least 1.8 billion people from developing countries are users of onsite sanitation systems (OSS) such as septic tanks, pit latrines, and ventilated improved pits (Capone et al., 2021), and partially digested material accumulating in OSS is fecal sludge (FS) (Strande et al., 2014). Many developing countries are facing challenges with management of FS from OSS due to rapid urbanization, high population density, and increased and unplanned growth (Opel, 2012).

Bangladesh is a densely populated South Asian country that had attained 99% sanitation coverage with OSS (Islam et al., 2016). Negligence toward fecal sludge management (FSM) and FS discharge to open drains by the majority of households results in environmental and public health hazards (Al-Hafiz, 2017). There is an increasing attention to safe sanitation and FSM in Bangladesh post the announcement of the National Water Supply and Sanitation Strategy, 2014, for water and sanitation through partnerships with organizations to implement Citywide Inclusive Sanitation Engagement (CWISE) in various cities of the country (Kabir and Salahuddin, 2014), and business models were introduced for sanitation services. CWISE covers the sanitation value chain (SVC), which includes superstructure (toilet), containment, emptying, transport, treatment, and safe reuse or disposal.

The business model for FSM is a new approach to enhance business opportunities in the sanitation sector (Diener et al., 2014) and business model approaches pave a way for increased private sector participation in sanitation service provision, which is dominated by public utilities (Rao et al., 2016). The financial flow is one parameter of the business model approach in FSM, and the other parameters are service arrangement and contractual arrangements (CWAS, 2020). The financial flow approach is helpful for the city administration to understand the financial sustainability of FSM in their city. Financial flow models (FFMs) show different financial transfers occurring between stakeholders in a SVC. There are several FFMs implemented in several parts of the world, which are generalized into five models (Strande et al., 2014). Model 1: discrete collection and treatment model—household pays an emptying fee to the emptying and transport (E&T) provider to empty FS, and the E&T service provider empties and transports FS into the fecal sludge treatment plant (FSTP) and pays the treatment provider a discharge fee. The treatment provider produces reusable product at FSTP which is sold for a purchase price to the end-user. Model 2: integrated collection and treatment model—E&T and treatment and reuse are handled by a single entity in which emptying fee is paid by households and the purchase price by end-users. Model 3: parallel tax and discharge fee model—household pays emptying fee to the E&T provider and sanitation tax to the government. E&T pays discharge fee to the treatment provider and the treatment provider receives a purchase price from the end-user. From the sanitation tax, the government provides some budget support to the treatment provider. Model 4: dual licensing and sanitation tax model—similar to model 3 except that the discharge fee is replaced by the discharge license, which is paid to the government. Model 5: incentivized discharge model—this model is a modification of model 4 to incentivize the E&T service provider by providing a discharge incentive instead of paying a discharge fee or discharge license. A summary of these models along with pros and cons is presented in **Table 1**.

Among many financial decision support tools, most of the tools cover FS emptying and/or treatment and/or reuse and only a couple of tools cover the entire SVC. The FSM Technical and Financial Assessment tool focuses on the technical and financial viability of diverse options across emptying, transport, and treatment and reuse of SVC (Dey et al., 2016). The CLARA Simplified Planning Tool (SPT) compares the finances of alternatives for water supply and sanitation interventions in the early planning stage, which was targeted for a few African countries (Langergraber and Weissenbacher, 2014). The SaniPlan tool covers the entire SVC with water supply and solid waste management, which was developed for Indian municipalities/cities for improving service provision and offers a comprehensive financial planning including funding (Dey et al., 2016). Climate and Costs in Urban Sanitation (CACTUS) is a tool that aids authorities to make informed decisions on urban sanitation services at the city level considering the cost of “city-wide sanitation,” “climate,” and “welfare” (University of Leeds, 2022). The Citywide Inclusive Sanitation (CWIS) Costing tool was developed to monitor CWIS principles that focus on investing in safely managed sanitation services at the city level (World Bank, 2022). The tool analyzes capital expenditure (CAPEX) and operating expenditure (OPEX) for onsite and offsite technologies such as septic tanks or pipes that convey excreta to a treatment site at each component level. Despite the tool monitoring CAPEX and OPEX for sanitation systems, it does not indicate how revenue for sustaining sanitation services by the service provider can be incorporated. There is not a single tool that can analyze the impacts of different FFMs (as described earlier) in SVC except for the financial flow simulator tool (eSOS™) (Furlong et al., 2020). eSOS™ is an Excel-based decision support tool, which needs input data on the type of user interface, containment, transport, and treatment and upon entering mentioned input data, material flows are determined. Financial flows are linked to material flows and many charges are assessed on a volume or mass basis depending on charges levied by stakeholders in SVC. Financial flow in the tool displays a variety of financial parameter, that is, CAPEX, OPEX, revenue, profit or loss for each component of SVC and entire SVC to determine the financial viability of FFMs. A summary of input data, output, and linkages within SVC in eSOS™ is presented in **Table 2**. There is flexibility in adding modified FFMs based on material and financial flows in a city.

There is a lack of information on financial transfers across the SVC despite a well-established SVC in Kushtia. Due to unavailability of information on financial transfers, the financial viability of the FSM business model could not be ascertained. Hence, this study was conducted in Kushtia Municipality with three main objectives: 1) to investigate current FSM practices to analyze existing FSM, 2) to study financial transfers to analyze the financial viability of existing FFMs, and 3) to evaluate various FFMs/business models to recommend a sustainable model.

MATERIALS AND METHODS

Kushtia Municipality is a city in Khulna division and located in southwestern Bangladesh with a population of 418,312 in 2019 living in 93,582 households with an average household size of 4.4 and 33,250 holdings (holdings are property numbers in the city with one or more households living in one holding) (Kushtia

TABLE 1 | Summary of financial flow models.

Model	Salient Feature	Pros	Cons
Model 1: discrete collection, transport, and treatment model	• The emptying and transport is operated by the private operator by collecting the emptying fee from the households. • Treatment and reuse is operated by the public utility with the discharge fee collected from the E&T service providers and selling the end-products to end-users	There is no additional fee to the public other than the emptying fee	The treatment and reuse has to be operated with the discharge fee collected from the E&T service provider
Model 2: integrated collection, transport, and treatment model	• The emptying, transport, and treatment are operated by a single private entity by collecting the emptying fee and selling the end-products to end-users	The service delivery will be very prompt as all the operations are interdependent for revenue generation	The lack of the monitoring agency can cause environmental damage and emptying tariff may be increased for profits
Model 3: parallel tax and discharge fee model	• The emptying and transport are operated by the private entity with the emptying fee collected from the households • Treatment and reuse are operated by the discharge fee from E&T service providers and marketing of end products to end-users. In addition to that, budget support by the government through the sanitation tax collected from the public will help to operate treatment service provider	The increased revenue will help to provide prompt services to public and help to invest on safe practices to benefit public and environmental health	The acceptance of public on sanitation tax is time consuming in some contexts
Model 4: dual licensing and sanitation tax model	• The emptying and transport is operated by the private operator by collecting the emptying fee from the households • The treatment service provider is operated by the public utility by licensing the E&T service provider and the support from the government through the sanitation tax revenue collected from the public along with the revenue generated from marketing the end-products	The E&T service provider will benefit by having a discharge license to empty without any discharge fee and help to solve the illegal dumping	The process of obtaining discharge license can be complicated and subject to series of examinations on the capacity and reliability of the service provider
Model 5: incentivized discharge model	• This model is similar to model 4, but additionally discharge incentive is provided to the E&T service provider	The discharge incentive will encourage the E&T service provider to promptly discharge in the FSTP	There will be a need of separate fund allocation for discharge incentive by the utility

Municipality, 2019). Based on monthly income, households are segregated in low-income (up to 117 USD), middle-income (117–588 USD), and high-income (more than 588 USD) households (Baki, 2014). The city is dependent on OSS such as septic tanks and pit latrines. FS emptying services are offered by the municipality with vacutugs and a private entity operates and maintains FSTP and runs a co-compost plant to produce co-compost from FS and municipal solid waste.

The study started with a detailed literature review of reports, documents, publications, books, and a collection of secondary data. Several unpublished data were also collected from stakeholders working in sanitation in Kushtia and reviewed. Primary data, both quantitative and qualitative were collected from key informant interviews and focus group discussions (**Table 3**). Joint stakeholder meetings (JSMs) were organized with support from the municipality comprising 30 participants—municipality officials, council members (elected representatives), representatives of household, sanitary hardware shop owners (private actors), FS emptiers, and FSTP operators. The first JSM was used to triangulate and validate data collected from primary and secondary sources. Strength, weakness, opportunities, and threat (SWOT) analysis is a strategic planning tool to assess the internal and external SWOT of stakeholders and context (Shikun et al., 2017; Shabanova et al., 2015) and was conducted in the study.

Input data including financial transfers are fed into the eSOS™ tool to analyze the financial viability of existing FFM and the five generalized FFMs and proposed FSM. The whole system approach for sustainability as used by the Dutch Water Alliance, which has five aspects of sustainability—financial, institutional, environmental, technical, and social (FIETS) (Galli et al., 2014) are used in the multi-criteria analysis for selecting a sustainable business model for the city.

A second JSM was organized to share and discuss existing FFMs, the five generalized FFMs, and proposed FFMs and suggestions for weightage of all five aspects and their criterion for the multi-criteria analysis. Stakeholders were explained about the study and were asked to award weightage for each aspect and score for each criterion for the multi-criteria analysis. The weightage of each aspect and criterion was decided from discussions/feedbacks received during the meeting and is illustrated in **Table 4**.

TABLE 2 | Summary of input, output, and links to the next SVC component in eSOSView™ (Furlong et al., 2020).

Component of the SVC	Input	Output	Data flow to the next SVC component
User interface	Type of user interface Number of toilets (household, shared, communal, or public) Number of people/toilet/day Amount of feces, urine, excreta, water usage, and black water generated/day CAPEX per unit OPEX per unit Unit cost of water, electricity, and labor	Amount of feces, urine, excreta, water, and black water/toilet/day Total CAPEX/day, month, or year Total OPEX/day, month, or year	Volume of feces, urine, excreta, water, and black water/toilet type/day
Containment	Type of containment Containment specifications: holding capacity, number of units, fecal sludge, accumulation factor, output streams, and sale price of valuable streams (e.g., biogas) CAPEX per unit OPEX per unit	Amount of fecal sludge, black water, and urine accumulated/containment unit/day Emptying frequency Number of emptying events per year Total CAPEX/day, month, or year Total OPEX/day, month, or year Revenue/day, month, or year	Volume of fecal sludge, black water, or urine accumulated/containment type/day
Emptying	Type of emptying Number of units to be emptied per time unit Emptying capacity (e.g., volume pumped/hour) Emptying fee CAPEX per unit OPEX per unit (e.g., labor, fuel, energy, technical maintenance, tax, and business operation overhead) Revenue	Volume of fecal sludge or other products emptied per day Total CAPEX/day, month, or year Total OPEX/day, month, or year Revenue/day, month, or year	Volume of fecal sludge emptied/emptying technology/day
Transport	Type of transport Carrying capacity of the transportation unit CAPEX OPEX (as with emptying) Revenue	Volume of fecal sludge transported per day Total CAPEX/day, month, or year Total OPEX/day, month, or year Revenue/day, month, or year	Volume of fecal sludge transported per day
Treatment and reuse	Type of treatment Design capacity Amount of fecal sludge received at the treatment CAPEX (e.g., construction costs and land requisition OPEX (as with emptying) Discharge fee (if applicable) Revenue	Volume of fecal sludge treated per day Total CAPEX/day, month, or year Total OPEX/day, month, or year Revenue per/day, month, or year Volume of end-products generated per day	

TABLE 3 | Field data collection and the method of data analysis.

Type of data	Data source	Method of analysis
• Quantitative (financial data) • Qualitative (existing FSM practices, challenges in FSM services, operation and maintenance of vacutugs, and challenges in operating treatment facility, demand, and challenges on the usage of co-compost)	Key Informant Interviews (KII) - 7 • Policy stakeholder (ward council members) • Municipality officials (engineers and town planners) • Emptier (vacutug operator) and treatment provider (managing partner and production manager) • Farmers	• Quantitative data (financial data)—eSOS™ tool and multi-criteria analysis • Qualitative data (spreadsheet analysis to determine SWOT and multi-criteria analysis)
• Quantitative data (financial data) • Qualitative data (existing FSM practices and challenges in FSM services)	Focus group discussions (FGDs) - 6 • Residents from different regions of the municipality	
• Qualitative and quantitative data validation • Determination of the weightage of each criterion for multi-criteria analysis	Joint stakeholder meetings (JSMs) - 2 • Policy stakeholder • Municipality officials • Emptier • Residents of Kushtia municipality • Treatment provider	

TABLE 4 | Criteria and weightage for multi-criteria analysis. Bold value is the total (sum) of values of the column i.e. weightage of each aspect totaling to 100%.

Aspect	Criteria	Sub-criteria	Weightage (%)
Financial	Financial viability	E&T	25
		Treatment and reuse	25
Institutional	Compatibility with existing regulations	E&T	2.5
		Treatment and reuse	2.5
	Institutional capacity	E&T	2.5
		Treatment and reuse	2.5
Environmental	Public and environmental safety	E&T	5
		Treatment and reuse	5
Technical	Ease of implementation of the business model	E&T	5
		Treatment and reuse	5
Social	Public acceptance and affordability	E&T	10
		Treatment and reuse	10
			100

TABLE 5 | Toilet typology in Kushtia municipality.

Type of toilet	Percentage of users in Kushtia
Environmentally safe toilet—improved toilet preventing the access to the feces, and human feces are contained in such a way that there is no pollution of surface or ground water	7.3%
Improved individual toilet (without access to flies)—human feces are contained in a toilet pit/tank with no access for human or animal contact or flies contact	75.6%
Improved individual toilet (with access to flies)—human feces are contained in a toilet pit/tank with no access for human or animal contact but is accessible to flies	7.1%
Shared toilet—toilet shared by one or more households	6.7%
Unimproved toilets—human feces are contained in a toilet pit/tank with access for human or animal contact or flies contact, or human feces are directly conveyed to the environment	2.8%
No toilet	0.4%

The study was formulated as per the Netherlands Code of Conduct for Research Integrity, 2018, and was supported by the Kushtia Municipality council. When this study was carried out, IHE Delft was in the process of establishing a research ethics committee, so no ethical approval was available. However, the authors are aware of the research ethics and all subjects involved in the study were informed about the purpose of the study and the consent was obtained from all participants of the study. The findings of the field study were shared with key stakeholders in JSM and later after completion of the study.

The study is limited to households in the study area and excludes financial flows from institutional and commercial holdings. The unavailability of some financial data has been adopted as suggested by stakeholders during JSMs.

RESULTS AND DISCUSSION

Existing FSM

Superstructure and Containment

In Kushtia municipality, more than 90% of the population have access to improved sanitation facilities (toilets), and their typology is presented in **Table 5** (Chowdhury, 2018). OSS was prevalently used with 52.1% septic tanks and 47% pit latrines of volumes 15.33 and 2.58 m^3, respectively (Al-Hafiz, 2017). Some low-income households are having toilets without containment, and excreta is directly discharged to nearby drains.

Emptying and Transport

Kushtia Municipality offers on demand FS emptying service through vacutug of capacities 1 m^3, 2 m^3, and 4 m^3 for a prescribed fee of 9.41 USD, 11.76 USD, and 14.12 USD, respectively. OSS are generally emptied in an interval of 4 years with some not emptied even in 12 years, which is similar to findings in Khulna, where OSS, having an average volume of 16.64 m^3 in a septic tank and 1.96 m^3 in a pit latrine, are generally emptied every 3 years and some even every 15 years (Singh et al., 2021). It was revealed that some OSS dispose liquid portion of FS into nearby open drains, which is a reason for holding FS for long and results in solidifying FS which is difficult to empty. One of the biggest challenges in FS emptying is difficulty in accessing mechanized emptying due to narrow roads which, in turn, leads to manual emptying. Emptied FS is transported to a

TABLE 6 | SWOT analysis of FSM stakeholders.

Stakeholder	Strength	Weakness	Opportunity	Threat
Households	Primary user of E&T services. Contributes to financial viability by paying for FSM services	Poor environmental and public health awareness. Some segments lack the capacity to pay for the FSM services	Could create demand for quality and regular FSM services. Could be engaged in the treatment and reuse component of the SVC	Inadequate and under quality FSM service could impact the SVC (both in quantity and finance). Improper FSM regulations and higher fees may disconnect them in the SVC. Unwilling to participate in the FSM service
Kushtia Municipality	Manages FSM services in the city by offering E&T service and generates revenue for OPEX of E&T services Mandated by the law in providing and regulating FSM services.	Lack of separate FSM department and inclusive services. Inadequate human resources for executing FSM operations	Could implement FSM regulations and improve the FSM institutional framework. Could encourage private sector participation in FSM services. Could form FSM unit	Change of local government can hamper smooth services. Subsidized E&T tariffs could cause fund diversion to other sectors causing financial challenges
Private entity	Responsible for treatment of FS. Zero transportation cost for the waste as it is executed by the municipality. Contributes to circular economy by selling the produced co-compos	Unavailability of space. Administrative delays in the municipality affect the efficiency	Could sensitize stakeholders on co-compost and FSM with assistance from community groups and other collaborators. Could establish stalls to expand co-compost market to the farmers	Change of local government may lead to changed priorities. Low socio-cultural acceptance toward FS-based co-compost in agriculture. Misconceptions toward co-compost and organic farming could create negative impact
Farmers	Being the end-user, farmers determine the co-compost demand. Improved quality produce and fertility of soil as a result of organic co-compost usage	Scarce awareness on co-compost usage, water management, and market for organic produce. Increased transportation costs	Could create a dedicated market for organic produce with increased prices. Could receive guidance from other stakeholders to improve yields and market awareness	Low market acceptance for produce from the FS-based co-compost. Insufficient institutional support for organic farmers

FSTP at Baradi, 5 km away from the city, and an average distance traveled by a vacutug is about 10 km per trip.

Treatment and Reuse

Collected FS is emptied into drying beds of capacity 9 m^3/day for dewatering and there are two units of drying beds. Percolate from the drying beds is pumped into a coco-pit filter for treatment and further treated in a pond. Dewatered sludge is co-composted with organic solid waste generated in the municipality. Co-compost contains a good amount of nutrients than chemical fertilizer, which is packaged and sold in fertilizer shops as well as procured by farmers directly. The co-compost is dried in open spaces due to the lack of space availability and the process of drying gets disrupted during rainy seasons. Similar to the co-composting facility in Devanahalli, India, segregation of municipal solid waste is the biggest problem faced in this FSTP, where plastic wastes are separated in the plant before the co-composting process (Rohini et al., 2019).

Major Stakeholders in FSM

Four major stakeholders were identified in FSM in Kushtia municipality: 1) households, 2) Kushtia municipality, 3) private entities, and 4) farmers. Households are responsible for the construction of OSS including plumbing systems for the proper functioning of OSS and its operation and maintenance. It is also the responsibility of households to pay for emptying fees to the E&T service provider. Kushtia Municipality provides E&T services by scheduling suitable vacutugs on request from households, operates and maintains vacutugs, and monitors the performance of FSTP. A single private entity operates and maintains FSTP and produces and markets co-compost. Farmers are end-users and purchase co-compost and apply in agricultural fields. The results of the SWOT analysis of stakeholders are illustrated in **Table 6**.

It is evident that households are significant stakeholders that initiate SVC and create demand for FSM services. FSM regulations should be favorable for households to ensure the proper working of FSM and sustainability of financial and business model as the main contribution of FSM business is through fees paid by households. Kushtia Municipality is the responsible authority to regulate FSM services and currently providing the sole E&T service and monitoring of FSTP. Due to the absence of a dedicated unit/wing for FSM in the municipality, a lack of planning in FSM services and management has been observed, which could cause public and environmental health risks. The municipality should utilize its authority to create a FSM unit for proper FSM planning and regularizing FSM services and to create an enabling environment for the private sector to engage in FSM services. It is also important to provide inclusive services to low-income households, which lack access to mechanized emptying due to narrow roads. The private entity's role in SVC is limited to treatment and reuse, which could potentially be included in E&T as well as to providing quality and timely FS E&T services. The efficiency of co-composting is affected as a result of limited space for drying co-compost in the FSTP. Although the private sector is collaborating with the Department of Agriculture and farmers, it seems that the current support is politically influenced and could have an impact in the case of a shift of power in politics. The smooth support from the

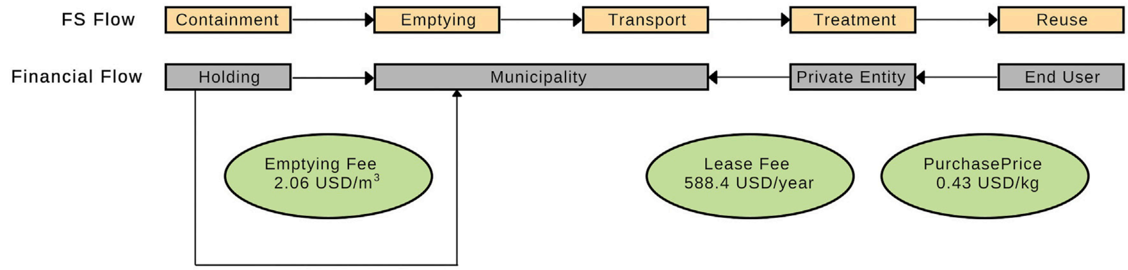

FIGURE 1 | Financial flows in the existing model.

department needs to be ensured together with increasing knowledge/awareness of the benefits of using co-compost and improved water management practices which could lead to a dedicated market for co-compost benefitting both private entities and farmers.

Financial Viability of Existing FFM

Existing FFM is a modification of the discrete collection and treatment model. The E&T service is provided by the municipality with an emptying fee (2.06 USD/m^3), and there is no discharge fee. Treatment and reuse is provided by a private entity which pays yearly lease fee (license fee) of 588.4 USD/year to the municipality to operate the FSTP and produces co-compost. Financially, the private entity operates with revenue generated from the sale of co-compost at a price of 0.43 USD/kg. The FS flow and the financial flow of the existing model are shown in **Figure 1**.

For financial analysis, a sanitation tax (tax collected by the municipality to provide FS emptying service) of 2.35 USD/containment/year for high- and middle-income households and 1.17 USD/containment/year for low-income households was adopted after analyzing the user willingness to pay through focus group discussions and JSMs. Several other cities such as Dumaguete, Philippines, charges the sanitation tax of 12 USD/family/year (Asian Development Bank Institute, 2018); Sinnar, India, charges 4.05 USD/property/year (CWAS, 2020); and Ouagadougou, Burkina Faso, charges 0.04 USD/m^3/year (Water and Sanitation for the Urban Poor–WSUP, 2012). A discharge incentive of 149 USD/year for emptying service provider has been adopted in this analysis is significantly less than 5 USD/truck/trip in Ouagadougou, Burkina Faso, to prevent the illegal discharge of FS (SANDEC, 2006). Sanitation tax and discharge incentives could be varied to provide equitable, inclusive, and safe sanitation to all citizens in the municipality. The introduction of sanitation tax is welcomed by the residents of Wai and Sinnar (Mehta et al., 2019), since it reduces the desludging cost paid by the residents to desludging operators.

Superstructure and Containment

Since the CAPEX and OPEX of superstructure and containment lie with households and no revenues are generated, this component is ignored in the financial analysis. The CAPEX of superstructure and containment is 82,704,020 USD and OPEX is 793,082 USD per year. Financially, it incurs a loss but it benefits users by providing comfort, safety, and privacy contributing to good health.

Emptying and Transport

Based on revenues of all vacutugs in Kushtia, an emptying fee of USD 2.06/m^3 is calculated, which is collected from households by the E&T service provider (municipality) in the existing FFM. An emptying fee of Kushtia Municipality is lower than other Bangladeshi cities such as Jashore and Jhenaidah (Sarwar, 2019). CAPEX for E&T was funded by a UN agency and OPEX for E&T is calculated as 18,689 USD per annum and it comprises the cost of maintenance of vacutugs, fuel cost, and human resources in E&T. The financial analysis shows that E&T incur a loss of 4,435 USD per year in existing FFMs as shown in **Table 7** and the loss is primarily due to low emptying fees. In contrast, globally E&T services are a profitable business in many cities due to higher emptying fees and higher trips, that is, Kigamboni, Tanzania (Masaninga, 2020); Jaipur, Delhi, Khulna, and Madurai (Chowdhry and Kone, 2012).

Treatment and Reuse

CAPEX was funded by a UN agency, and OPEX incurred by the private entity was 14,906 USD per year comprising lease fee, human resources, and maintenance of the FSTP. The financial analysis revealed that the treatment and reuse component of SVC has a profit of 534 USD per year in existing FFMs as shown in **Table 7**, which is similar to findings in Pokhara, Nepal (Furlong et al., 2020; Shrestha, 2018), whereas treatment plants in Jashore and Jhenaidah are not generating sufficient profit as they are not operating in full capacity (Sarwar, 2019).

Evaluation of FFMs/Business Models

In addition to the existing and five generalized FFMs described earlier, model 6 (**Figure 2**), which is a modified form of model 3 (Parallel Tax and Discharge Fee model), was adapted to the context of Kushtia. In this FFM, the municipality provides E&T service and households have to pay an emptying fee and yearly sanitation tax for the service. Treatment and reuse are provided by a private entity which operates primarily with revenue generated from the sale of end-product. The private entity pays a yearly lease fee (license fee) to the municipality to operate FSTP and produces co-compost, which is sold to the end-user. The biggest advantage of this FFMs is that the sanitation tax and lease fee is supportive for the municipality

TABLE 7 | Analysis of financial flow models (all figures in USD/year).

Part of SVC	Financial parameter	Existing model	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Emptying and transport	CAPEX	100,034	100,034	Emptying, transport and treatment	100,034	100,034	100,034	100,034
	OPEX	18,689	19,276		19,276	19,863	19,863	18,689
	Revenue	14,254	13,668		13,668	13,668	13,668	77,349
	Net profit/loss	−4,435	−5,608		−5,608	−6,195	−5,608	49,863
Treatment and reuse	CAPEX	292,379	292,379	392,413	292,379	292,379	292,379	292,379
	OPEX	14,906	14,318	33,006	14,318	14,318	14,467	14,906
	Revenue	15,534	15,534	29,202	79,216	79,216	79,216	15,534
	Net profit/loss	534	1,216	−3,805	55,164	55,164	54,665	1,533
Financial sustainability across the SVC								
Across the SVC	CAPEX	392,413	392,413	392,413	392,413	392,413	392,413	392,413
	OPEX	33,595	33,594	33,006	33,594	33,594	33,743	33,595
	Revenue	29,788	29,787	29,200	92,882	92,882	93,031	92,883
	Net profit/loss	−3,901	−4,392	−3,805	49,556	48,969	49,057	51,396

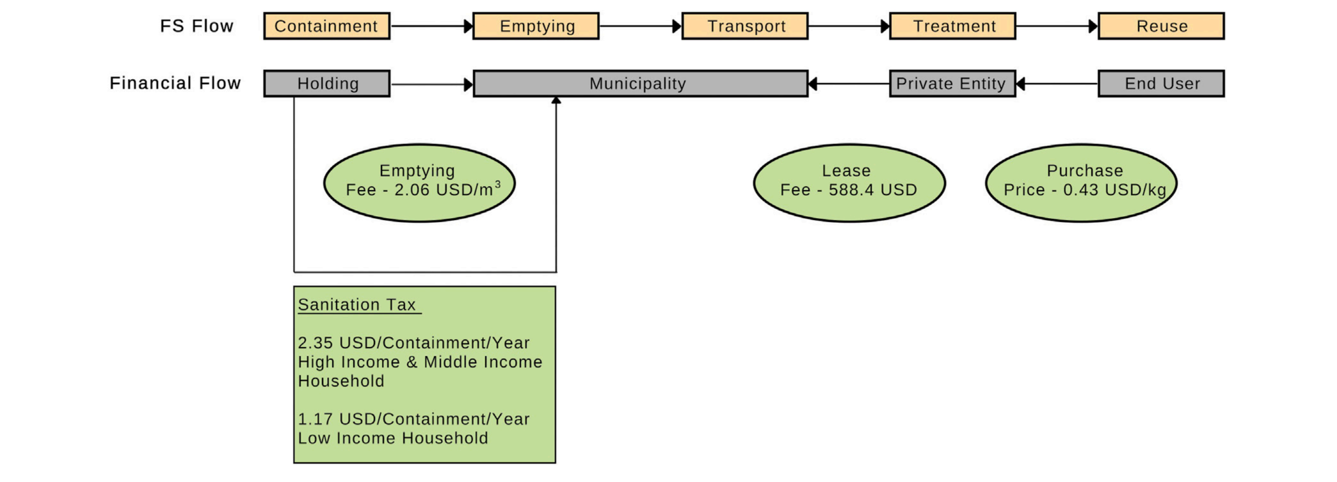

FIGURE 2 | Financial flows in the modified parallel tax and discharge fee model (model 6).

to sustain E&T service, whereas the biggest disadvantage is public might be reluctant to pay both emptying fee and sanitation tax. To overcome this disadvantage, the municipality has significantly reduced the E&T fee that households are currently paying.

From the financial analysis (**Table 7**), models 1, 3, 4, and 5 incur a loss in E&T as a result of lower E&T fees, whereas in financial analysis across SVC, models 3, 4, and 5 displayed a profit of 49,556 USD, 49,969 USD, and 49,861 USD, respectively, as a result of the combination of treatment and reuse revenue. The existing model and models 1 and 2 incurred a loss even after combining the revenue of E&T and treatment and reuse, which is due to the absence of sanitation tax. It is evident that model 6, which generated a net profit of 49,863 USD per year for E&T, 1,533 USD per year for treatment and reuse, and 50,439 USD for the entire SVC is the most profitable FFM for the municipality. Higher profit is due to the sanitation tax for E&T services in the municipality.

The FFMs were evaluated against FIETS criteria to determine a sustainable business model. The highest scoring model is the most sustainable model for the municipality. The description and weightage for each criterion were developed and finalized with inputs during JSM. All criteria were evaluated against 1) E&T and 2) treatment and reuse components. The models were rated between 0 and 100 for each of the FIETS criteria and converted to weighted scores as illustrated in **Table 8**.

Financial Aspect (50% Weightage)

The financial viability of FFMs was the only criterion to evaluate the financial aspect, which is scored against the amount of net profit generated by FFMs. The model with highest net profit scored full marks, that is, 25 each in E&T and treatment and reuse sub-criteria and other models have scored relative to the highest scoring model. For E&T, model 6 scored 25 and all other models did not score any since net profit is negative. For treatment and reuse, models 3 and 4

TABLE 8 | Multi-criteria analysis of FFMs (FIETS). Bold values are the total (sum) of values of the column i.e. weightage of each aspect totaling to 100%.

SN	Aspect	Criteria	Sub criteria	Weightage (%)	Rating							Weighted score						
					E	M1	M2	M3	M4	M5	M6	E	M1	M2	M3	M4	M5	M6
1	Financial	Financial viability	E&T	25	—	—	—	—	—	—	100							25
			Treatment and reuse	25	5	10	0	100	100	95	5	1.25	2.5	0	25	25	24	1.25
2	Institutional	Compatibility with existing regulations	E&T	2.5	100	0	100	0	0	0	100	2.5	0	2.5	0	0	0	2.5
			Treatment and reuse	2.5	100	100	100	0	0	0	100	2.5	2.5	2.5	0	0	0	2.5
		Institutional capacity	E&T	2.5	75	100	100	100	100	100	75	1.8	2.5	2.5	2.5	2.5	2.5	1.8
			Treatment and reuse	2.5	100	0	100	0	0	0	100	2.5	0	2.5	0	0	0	2.5
3	Environmental	Public and environmental safety	E&T	5	75	60	60	60	60	60	100	4	3	3	3	3	3	5
			Treatment and reuse	5	100	0	100	0	0	0	100	5	0	5	0	0	0	5
4	Technical	Ease of implementation of the business model	E&T	5	100	50	40	50	40	50	80	5	2.5	2	2.5	2	2.5	4
			Treatment and reuse	5	100	40	100	40	40	40	100	5	2	5	2	2	2	5
5	Social	Public acceptance and affordability	E&T	10	100	100	100	70	70	70	70	10	10	10	7	7	7	7
			Treatment and reuse	10	40	100	100	100	100	100	80	4	10	10	10	10	10	8
		Total		**100**	**895**	**560**	**900**	**520**	**510**	**515**	**930**	**45**	**35**	**45**	**52**	**51**	**51**	**70**

scored 25 as a result of profit generated by sanitation tax and the existing model and model 6 scored the least with a score of 1.25 as net profit generated is lower than other models. Model 2 has not scored since it incurs a negative profit albeit providing comprehensive FSM services covering the entire SVC.

Institutional Aspect (10% Weightage)

The institutional aspect is categorized into two criteria. The first criteria looked at "compatibility with existing regulations" (5% weightage), which examined the availability of supportive legal and regulatory framework for business model implementation. Without any legal and regulatory frameworks, it would be fairly difficult for institutions to implement a business model; hence models that have supportive legal and regulatory frameworks score high. For E&T, the existing models, models 2 and 6 scored 2.5 because of supportive regulations for the privatization of services and imposing sanitation tax up to 12% of holding tax. For treatment and reuse, all models except models 3, 4, and 5 scored 2.5 as there is no provision for imposing sanitation tax for treatment and reuse as it is handled by the private entity. Similarly, the discharge fee and discharge incentive are not being imposed for the same reason. The second criteria looked at "institutional capacity" (5% weightage), which assessed the availability of human resources and a dedicated unit for planning and management of FSM for the implementation of business model. For E&T, models 1, 2, 3, 4, and 5 scored 2.5 as the private sector is providing services with adequate capacity and making a profit. The existing model and model 6 scored less with a score of 1.8 due to inadequate capacity in planning FSM and the absence of FSM wing in the municipality. For treatment and reuse, models 1, 3, 4, and 5 scored 0 as there is no separate FSM department to operate the FSTP and the existing model, models 2 and 6 scored 2.5 as it has dedicated man-power to operate the FSTP and reuse.

Environmental Aspect (10% Weightage)

The environmental aspect was evaluated using the criterion of public and environmental safety, which assesses the impact of the business model on public and environmental safety. E&T evaluates safe hygiene practices that include use of personal protective equipment, provision of safe emptying services, and disposing of FS in FSTP. Models 1 to 5, where E&T is privately operated, provide prompt services being a profit-based entity. The lack of a monitoring agency and discharge incentive creates a high possibility of unsafe practices in E&T, and therefore these models scored 3. The existing model scored 4, higher than the former models as it is the public entity which provides services in a non-profit manner and it is monitored by the municipality. Models 1, 3, 4, and 5 scored 0 in terms of treatment and reuse as there is no FSM wing for operating FSTP. The private operated treatment and reuse will be environmentally safe as it is more profit-oriented; therefore, models 2 and 6 scored 5 in the environmental and public safety.

Technical Aspect (10% Weightage)

The criterion to evaluate this aspect was "ease of implementation of business model", which is assessed by any changes required in the existing behavior of the public or stakeholders and practical difficulties in implementing the business model. With regard to E&T, models 2 and 4 scored 2, because finding an entity to provide comprehensive FSM services which are in loss and finding an entity to pay for discharge license is difficult. Models 1, 3, and 5 scored slightly higher than previous models with a score of 2.5 as the municipality has to develop a plan for a discharge fee and dumping license. Model 6 scored 4 as there are provisions for imposing sanitation tax for emptying and transport operated by the municipality but achieving maximum collection efficiency will require some time. The existing model scored 5 as implementing the existing model is not complicated. The municipality handling treatment and reuse part is difficult as there is no separate department for FSM; therefore, models 1, 3, 4, and 5 scored 2. The existing models, models 2 and 6, scored 5 as there are no difficulties with the treatment and reuse part of these models.

Social Aspects (20% Weightage)

In the social aspect, the criterion of "public acceptance and affordability" of FSM services was used. People will accept the business model when it is affordable and it was observed that the public is more concerned about E&T and not much for treatment and reuse. For E&T, the existing model and models 1 and 2 scored 10, as these do not include any additional charge to public, whereas models 3, 4, 5, and 6 scored 7 as they add sanitation tax which is an additional expenditure for households. For treatment and reuse, all models scored 10 as it does not have a direct impact on the affordability for the public.

CONCLUSION

The financial flow simulator (eSOSView™) tool could be applied to determine financial viability of individual components as well as entire SVC. The financial analysis of existing FFMs in Kushtia revealed that it is financially unviable, incurring a loss of 3,901 USD per year. While exploring other FFMs, it showed that the modified parallel tax and discharge fee model generates the highest net profit of 51,396 USD per year considering the entire SVC (49,863 USD per year for E&T and 1,533 USD per year for treatment and reuse). It is evident that sanitation tax and discharge incentive aid service providers in attaining financial sustainability. The eSOSView™ tool could be tailored to determine financial viability of existing FFMs in addition to the generalized five FFMs. Financial viability is not adequate to determine a sustainable business model; hence, the FIETS sustainability approach was adapted to determine a sustainable FSM business model for Kushtia municipality. Criteria and weightage for each of the FIETS approaches could be developed and customized as per the existing situation and validated by relevant stakeholders. The study found out that the financial aspect remained the dominant criteria with 50% weightage, and due to this reason, the modified parallel tax and discharge fee model, which generated the highest net profit, turned out to be a sustainable business model for Kushtia.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at: https://ihedelftrepository.contentdm.oclc.org/digital/collection/masters1/id/315036/rec/1.

ETHICS STATEMENT

The ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

SA: conceptualization, methodology, validation, formal analysis, investigation, and writing—original draft. SS: conceptualization, methodology, formal analysis, writing—original draft, writing—review and editing, and supervision. TC: conceptualization, writing—review and editing, and supervision. DB: conceptualization, writing—review and editing, supervision, project administration, and funding acquisition.

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REFERENCES

Al-Hafiz, N. (2017). *Study on Faecal Sludge Management in Kushtia Municipality and its Future Development and Sustainability*. MSc thesis. Khulna, Bangladesh: Khulna University of Engineering & Technology.

Asian Development Bank Institute (2018). Spillover Effects from Fecal Sludge Management: Dumaguete City [Video]. YouTube. Available at: https://www.youtube.com/watch?v=XAIwcJvKEvs (Accessed at 11 16, 2021).

Baki, A. A. T. M. (2014). *Socio-Economic Impacts of Gorai River Bank Erosion on People: A Case Study of Kumarkhalli, Kushtia*. M.A Thesis Inst. Gov. Stud. (IGS). Dhaka, Bangladesh: BRAC University.

Capone, D., Chigwechokha, P., de Los Reyes, FL., Holm, RH., Risk, BB., and Tilley, E. (2021). Impact of Sampling Depth on Pathogen Detection in Pit Latrines. *PLOS Neglected Trop. Dis.* 15 (3), e0009176. doi:10.1371/journal.pntd.0009176

Center for Water and Sanitation (CWAS) - CEPT University (2020). Policy Brief - Financing and Business Models for Fecal Sludge and Septage Management for Urban India [Online]. Available at https://pas.org.in/Portal/document/UrbanSanitation/uploads/Policy_brief-Financing_and_business_models_FSSM_22.7.2019.pdf (Accessed at 11 07, 2021).

Chowdhry, S., and Kone, D. (2012). *Business Analysis of Fecal Sludge Management: Emptying and Transport Services in Africa and Asia*. Report. The United States of America: Bill and Melinda Gates Foundation.

Chowdhury, M. R. (2018). *An Endline Study to Assess Faecal Sludge Management of Residential Premises in Selected Southern Cities of Bangladesh*. Report. Bangladesh: SNV Netherlands Development Organization.

Dey, S., Patro, S. A., and Rathi, S. (2016). *Centre for Study of Science, Technology and Policy (CSTEP)*. Bengaluru, India:Sanitation Tool Compendium. Available at: https://www.cstep.in/drupal/sites/default/files/2019-01/CSTEP_RR_Technology_Options_for_the_Sanitation_Value_Chain_Compendium_2016.pdf(Accessed on 09 24, 2020).

Diener, S., Semiyaga, S., Niwagaba, B. C., Muspratt, A. M., Gning, J. B., Mbeguere, M., et al. (2014). A value proposition: Resource recovery from faecal sludge—Can it be the driver for improved sanitation?. *Resour. Conserv. Recycl.* 88, 32 38. doi:10.1016/j.resconrec.2014.04.005

Furlong, C., Singh, S., Shrestha, N., Sherpa, M. G., Lüthi, C., Zakaria, F., et al. (2020). Evaluating Financial Sustainability along the Sanitation Value Chain Using a Financial Flow Simulator (eSOSView™). *Water Sci. Technol.* 82 (11), 2220. doi:10.2166/wst.2020.456

Galli, G., Nothomb, C., and Baetings, E. (2014). *Towards Systemic Change in Urban Sanitation, Working Paper*. Netherlands: IRC WASH.

Islam, R., Saha, U. K., Mamun, A. A., Brosse, N., and Stevens, L. (2016). Implications of Inappropriate Containment on Urban Sanitation and Environment: a Study of Faridpur, Bangladesh. Paper presented at the 39th WEDC International Conference, Ghana 2016.

Kabir, A., and Salahuddin, M. (2014). *A Baseline Study to Assess Faecal Sludge Management of Residential Premises in Selected Southern Cities of Bangladesh*. Report. Bangladesh: SNV Netherlands Development Organization.

Kushtia Municipality (2019). *Municipality Citizen Charter*. Kushtia, Bangladesh: Kushtia Municipality.

Langergraber, G., and Weissenbacher, N. (2014). Introduction to CLARA. *Sustain. Sanit. Pract.* 19, 5–7.

Masaninga, B. M. (2020). *Development of a Sustainable Business Model for Faecal Sludge Management, A Case of Kigamboni District, Dar Es Salaam*. MSc thesis. Delft, Netherlands: IHE Delft Institute for Water Education.

Mehta, M., Mehta, D., and Yadav, U. (2019). Citywide Inclusive Sanitation through Scheduled Desludging Services: Emerging Experience from India. *Front. Environ. Sci.* 7, 188. doi:10.3389/fenvs.2019.00188

Opel, A. (2012). Absence of Faecal Sludge Management Shatters the Gains of Improved Sanitation Coverage in Bangladesh. *Sustain. Sanit. Pract.* 2012 (13), 4–10.

Rao, K. C., Kvarnström, E., Di Mario, L., and Drechsel, P. (2016). *Business Model for Faecal Sludge Management*. Colombo, SriLanka: International Water Management Institute (IWMI). CGIAR Research Program on Water, Land and Ecosystems WLE. 80p (Resource Recovery and Reuse Series 6).

Rohini, P., Gagana, S., and Girija, R. (2019). Findings from Cocomposting Operations at Fecal Sludge Treatment Plant (FSTP), Devanahalli, India, Proceedings of FSM 5–5th International Fecal Sludge Management Conference, Capetown, South Africa.

SANDEC (2006). Urban Excreta Management: Situation, Challenges, and Promising Solutions, Proceedings of the 1st International Fecal Sludge Management Policy Symposium and Workshop, . Dakar, Senegal.

Sarwar, R. M. (2019). *Funding Gaps & Barrier Analysis and Identification of Possible Financial Resources for Fecal Sludge Management (FSM) Services for SNV Netherlands Development Organisation*. Report. Dhaka, Bangladesh: SNV Netherlands Development Organisation.

Shabanova, L. B., Ismagilova, G. N., Salimov, L. N., and Akhmadeev, M. G. (2015). PEST- Analysis and SWOT- Analysis as the Most Important Tools to Strengthen the Competitive Advantages of Commercial Enterprises. *Mediterr. J. Soc. Sci.* 6 (3), 705–709. doi:10.5901/mjss.2015.v6n3p705

Shikun, C., Lei, Z., Mingyue, Z., Xue, B., Zifu, L., and Mang, H. (2017). Assessment of Two Fecal Sludge Treatment Plants in Urban Areas: Case Study in Beijing. *Int. J. Agric. Biol. Eng.* 10 (3), 237–245. doi:10.3965/j.ijabe.20171003.3067

Shrestha, N. (2018). *Optimisation of FSM Business Model in Pokhara, Nepal with an Emphasis on Fecal Sludge Entrepreneurs*. MSc Thesis. Delft, Netherlands: IHE Delft Institute for Water Education.

Singh, S., Gupta, A., Alamgir, M., and Brdjanovic, D. (2021). Exploring Private Sector Engagement for Faecal Sludge Emptying and Transport Business in Khulna, Bangladesh. *Int. J. Environ. Res. Public Health.* 18 (5), 2755. doi:10.3390/ijerph18052755

Strande, L., Ronteltap, M., and Brdjanovic, D. (2014). *Fecal Sludge Management: Systems Approach for Implementation and Operation*. London: IWA Publishing, The United Kingdom.

UN (2015). Transforming our world: the 2030 Agenda for Sustainable Development, United Nations, New York, USA. Available at: https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf (Accessed 16 May, 2020).

University of Leeds (2022). Climate and Costs. Available at: http://cactuscosting.com/(Accessed on 03 31, 2020).

Water and Sanitation for the Urban Poor – WSUP (2012). Sanitation Surcharges Collected through Water Bills: a Way Forward for Financing Pro-poor Sanitation? *Discuss. Pap.* Available at: https://www.wsup.com/content/uploads/2017/08/DP004-ENGLISH-Sanitation-Surcharges.pdf (Accessed on 03 31, 2022).

World bank (2022). CWIS Costing and Planning Tool. Available at: http://200.58.79.50/fmi/webd/CWIS%20Planning%20Tool%201_4 (Accessed on 03 31, 2020).

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Nutrient stocks, flows and balances for the Bolivian agri-food system: Can recycling human excreta close the nutrient circularity gap?

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Analysis of the current state of nutrient stocks, flows, and balances of a territory is necessary to inform strategies that can transition the agri-food sector to a circular economy model. In this study, we quantified the nitrogen and phosphorus budgets for the Bolivian agri-food system at national and regional scales by way of agro-ecological zoning. We performed nutrient balances to calculate indicators for *sufficiency* (extent of nutrient deficit/surplus) and *circularity* (proportion of nutrients recirculated). We also evaluated the potential of renewable stocks (human excreta and livestock manure) to meet nutrient deficits in the system. Our results showed that there are apparent deficits of 32 kt N and 8 kt P in the system that cannot be accounted for using available data. We estimate the real deficits required to bring yields of 45 crops grown in Bolivia to parity with those of neighbouring countries to be 110 kt N and 33 kt P. About 44% of nitrogen and 74% of phosphorus is currently recirculated in the system, with the major nutrient inputs being biological nitrogen fixation, livestock manure, and crop residues. However, nutrient recycling is likely to decrease in the future because the national strategy to address nutrient deficits is to increase domestic production of synthetic fertilisers. Our analysis also shows that there is a sufficient stock of nutrients already available in human excreta (39 kt N and 5 kt P) to cover 100% of the nitrogen deficit and 64% of the phosphorus deficit. The low-altitude zone of Chiquitania-Pantanal alone accounts for 65% of cultivation and 80% of the nutrient demand in the country. Here, export-oriented crops like soybean and sorghum are grown, but less than 25% of the nitrogen is recirculated. In contrast, there are nutrient surpluses of 41 kt N and 34 kt P in agro-ecological zones like the Valleys and Altiplano where traditional agriculture is practiced, and the majority of food is grown for local consumption. Overall, we find that recycling of human excreta, combined with transfer of regional nutrient surpluses, could be an effective strategy to reduce the overall nutrient deficit in the system.

KEYWORDS

circular economy, fertilizer, manure, nitrogen budget, phosphorus, soybean, sustainable food production, wastewater

1 Introduction

Nitrogen (N) and phosphorus (P) are the plant-essential macronutrients that most limit crop yields in agriculture. Therefore, an evaluation of food security at any geographical scale must consider whether there are sufficient stocks of these nutrients to support the production of food. Such evaluations are highly relevant today, as the global population is growing rapidly and the nutritional needs of an additional 2 billion people will need to be met by 2050 (UN, 2019). However, the agri-food system is already the largest contributor to anthropogenic transgression of several of the planetary boundaries, including the boundary for the biogeochemical flows of N and P (Steffen et al., 2015). To improve agricultural productivity, the application of synthetic fertilisers like urea and diammonium phosphate has increased over the years (Randive et al., 2021); however, so has eutrophication due to the linear flow of nutrients from soils to recipient watercourses (Farmer, 2018).

To reduce the environmental impact of agriculture and keep earth systems within their safe operating space, it is essential that we improve both nutrient use efficiency during cultivation and overall nutrient circularity in the food system (Elser and Bennett, 2011), for example, by changing to better fertiliser application methods or by recycling nutrients present in livestock manure (Mayer et al., 2016). However, to inform such circular economy initiatives, a good understanding and analysis of the current state of nutrient stocks, flows, and balances is necessary. While such analyses can be performed at various scales, analysis at the national and regional scales is most appropriate if the goal is to inform policymakers (Chowdhury et al., 2014). The literature on nutrient budgets at various scales is extensive (Senthilkumar et al., 2012; Chowdhury et al., 2014; Klinglmair et al., 2015; van der Wiel et al., 2019; Zhang et al., 2020), and there is a growing body of research (Mihelcic et al., 2011; Morée et al., 2013; Smit et al., 2015; Hanserud et al., 2016; Akram et al., 2019; van Puijenbroek et al., 2019) focusing on quantifying the potential of alternative sources to meet the nutrient demand in agriculture. We are, however, unaware of any such analysis performed at any scale for the Bolivian agri-food system.

The population of Bolivia has grown rapidly from 8.4 million in 2000 to 11.7 million in 2020 and is expected to peak at 17.7 million by 2083 (UN, 2019). About 70% of the population in the land-locked country lives in urban areas, where an estimated 72% of people have access to basic sanitation (MMAyA, 2020) but only 58% of the wastewater is treated (UN-WATER, 2021). The city of La Paz (the largest of Bolivia) has no wastewater treatment facility, and raw wastewater is directly discharged to rivers. As human excreta contain plant-essential macro- and micro-nutrients (Vinnerås et al., 2006), many initiatives have attempted to promote alternatives to conventional wastewater treatment in Bolivia, such as wastewater irrigation (Verbyla et al., 2016; Perez-Mercado et al., 2022) and ecological sanitation (Silveti and Andersson, 2019).

However, little is known about the nutrient stocks in excreta available for recycling. To address this gap, this study attempted to answer the following questions. Can human excreta-derived nutrients fill the nutrient gap in the Bolivian agri-food system? What proportion of fertiliser imports to the country can be substituted by excreta-derived nutrients? How close or far is the agri-food system in Bolivia from achieving nutrient circularity?

We conducted an evaluation of the current nutrient stocks, flows, and budgets for the Bolivian agri-food system at two geographical scales, national and regional. We quantified the current nutrient demand in terms of indicators for sufficiency (Guareschi et al., 2019) and circularity (Papangelou and Mathijs, 2021) and assessed the potential of renewable stocks (human excreta and livestock manure) to meet the nutrient deficit in the system. Our findings have implications for food and nutrition security policy in low- and middle-income countries.

2 Methodology

A mass balance for nitrogen and phosphorus was performed for the Bolivian agri-food system (i.e., crop cultivation and human consumption). Based on the results of the mass balance, indicators of nutrient sufficiency (Guareschi et al., 2019) and circularity (Papangelou and Mathijs, 2021) for crop cultivation were calculated. Subsequently, the potential of nutrients contained in human excreta to supply the nutrients required for crop cultivation was estimated. All analyses (mass balance and calculation of indicators and potential substitution of crop nutrients by excreta) were done at both national and regional levels.

2.1 The agri-food system

2.1.1 System components

The agri-food system comprises all of the processes required to provide food to the population living within the national boundary of Bolivia and the nutrient flows in and out of this system (Papangelou and Mathijs, 2021). The system includes the following eight processes: urea industry, cropland, crop residues, livestock production, grassland, forest, food industry, and human consumption (Figure 1A). However, we simplified the agri-food system (Figure 1B and Table 1) to include only the processes linked to crop cultivation (cropland and crop residues) and human consumption for the following reasons. First, data are not available for all the processes in Bolivia. For example, there is no literature on the composition of organic wastes or on the amount of phosphorus added to the system via cleaning agents. Second, for some processes, there is evidence of significant

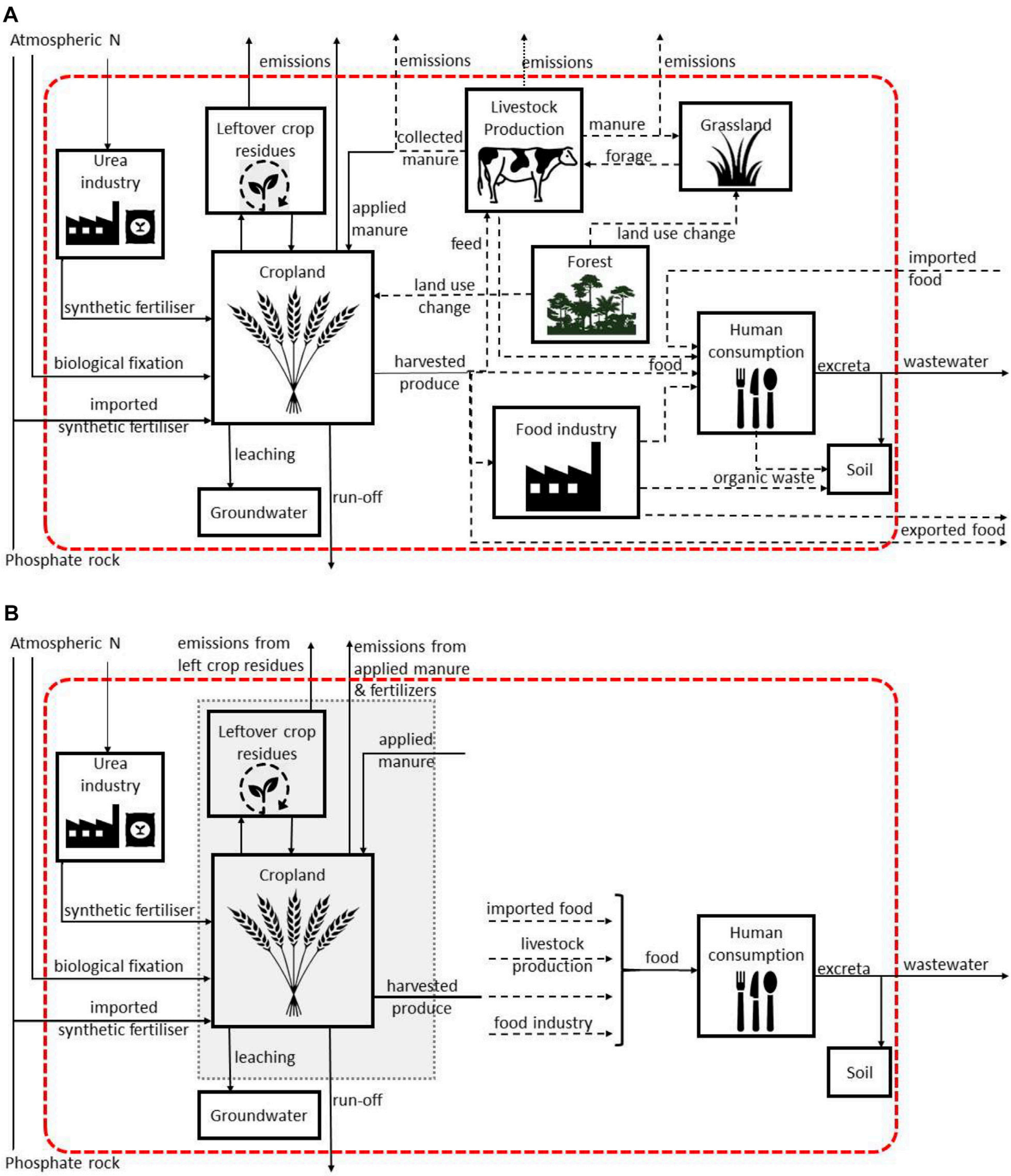

FIGURE 1
Processes (solid-line boxes), flows (arrows) and boundaries (dashed-line boxes) for **(A)** the complete Bolivian agri-food system and **(B)** the simplified system considered for the mass balance calculations for nitrogen and phosphorus. The national boundary is represented by a red dashed box and grey dashed boxes indicate processes linked to crop cultivation. The dashed arrows represent flows that were not included in the mass balance due to insufficient data.

TABLE 1 Processes and flows included in the nutrient mass balance, including how they were estimated or calculated. Data sources are indicated with superscript letters.

Process or flow	Description	Calculation method
Cropland	Process. N and P taken up by crops according to their needs until harvest	—
Imported and domestic synthetic fertiliser	Input flow. N and P in synthetic fertiliser applied to cropland in 2018	Calculated as mass of fertilisers applied[a] × N and P content for each fertiliser[a]
Biological fixation	Input flow. Atmospheric N fixed by microorganisms and taken up by crops	Calculated as crop yield[b] × proportion of N fixed by each crop[c]
Crop residues (outflow)	Output flow. N and P left over from crop residues that are incorporated into the soil	For N, data are published for each crop[b]. For P, calculated as N in leftover crop residues[b] ×ratio of N:P (for each crop's residues)[b,d,e,f]
Crop residues (inflow)	Input flow. N and P left over from crop residues that are incorporated into the soil and taken up by crops	For N, calculated as N in leftover crop residues incorporated into the soil[b] minus N in leftover crop residues incorporated into the soil that is emitted to the atmosphere[b]. P is the amount in leftover crop residues incorporated into the soil (no emissions were assumed)
Applied manure	Input flow. N and P in manure applied to cropland	For N, data are published for each type of manure[b] For P, calculated as N in manure[b] × ratio of N:P for each type of manure[g,h,i,j]
Emissions, leaching, and run-off from applied manure and fertilisers	Output flows. N in manure and synthetic fertilisers applied to cropland that is lost due to atmospheric emissions, leaching, and run-off	For manure, data are published for each type of manure[b]. For fertilisers, calculated as mass of N applied in fertilisers[a] × 0.3[c]
Harvested produce	Output flow. N and P taken up by crops during cultivation prior to harvest	Calculated as crop yield[b] × ratio of nutrient mass:yield mass (for each crop)[c,e,k,l,m,n,o,p,q,r,s]
Left crop residues	Process. N and P in crop residues left on soil are released	—
Emissions from leftover crop residues	Output flow. N from leftover crop residues that is emitted to atmosphere	Data published for each crop's residue[b]
Human consumption	Process. N and P in food is ingested by the population	—
Excreta	Output flow. N and P in human excreta ending up in untreated/ treated wastewater or in soil	Calculated for both nutrients according to Jönsson and Vinnerås (2003). For N, daily total protein consumption per capita[b] × 365 × population × 0.13[t]. For P, daily total protein consumption per capita[b] + daily vegetable protein consumption[b] × 365 × population × 0.011[t]
Food	Input flow. N and P in food ingested by the population	Assumed to be equal to the output flow[t]

a, INIAF, ANAPO, CIAB, (2019); b, FAO (2022); c, Guareschi et al. (2019); d, Torma et al. (2018); e, Roy et al. (2006); f, Lal (2009); g, Ali et al. (2019); h, Awodun et al. (2007); i, ASAE (2005); j, Brown (2013); k, Haifa-group (2021); l, de Sousa and Lobato (2004); m, Faquin (2004); n, Pires and Portela (2007); o, da Cunha et al. (2018); p, Halliday and Trenkel (1992); q, Crisóstomo and Naumov (2009); r, Alvar-Beltrán et al. (2021); s, Intrepid-potash (2021); t, Jönsson and Vinnerås (2003).

influence by "grey market" activities that make nutrient flow estimations unreliable even though data for the processes exist, e.g., smuggling of produce from abroad (Tito-Velarde and Wanderley, 2021) and unplanned change of land use, including conversion of forest land to pastures and cropland (Müller et al., 2012).

2.1.2 Flows

We studied the flows of nitrogen and phosphorus in and out of the crop cultivation (i.e., cropland and crop residues) and human consumption processes. Detailed information on the data used for estimating the mass flow of the elements, including data sources, is summarized in Table 1, and further information is available in the supplementary material (Supplementary Tables S1–S4).

2.1.3 National and regional level

We studied the Bolivian agri-food system at the national and regional levels. At the regional level, instead of the nine Bolivian administrative regions (or departments), we considered the seven agro-ecological zones. Agro-ecological zoning groups a territory based on landscape, climatic and soil characteristics, focusing on the requirements and management systems of crops (FAO, 1996). Such zoning is based on three inputs (i.e., land resource inventory, inventory of land utilization and crop requirements, and evaluation of land suitability), and its purpose is to inform decisions on development by identifying areas with similar potentials and constraints. In Bolivia, by law, agro-ecological zones are part of territorial planning at the departmental and municipal scales (Ministry for Planning of

TABLE 2 Main biophysical and productive characteristics of the Bolivian agri-food system and its seven agro-ecological zones.

Characteristic	Bolivia	Agro-ecological region						
		Altiplano	Amazonia	Chaco	Chiquitania-Pantanal	Llanuras	Valleys	Yungas-Chapare
Altitude[a] (metres above sea level)	NA	3,800–4,100	>400	250–950	<900	130–500	1,500–3,600	400–1900
Temperature[a] (mean min.-mean max., in °C)	NA	8–12	—	15–36	—	—	—	—
Annual rainfall[a] (mm)	NA	100–600	1500–2000	400–1,000	700–1500	700–2000	300–1,000	2000–4000
Population in 2018[b] (thousands [% of total country population])	11,347	2,456 (21.6)	398 (3.5)	378 (3.3)	2,993 (26.4)	244 (2.1)	4,313 (38.0)	561 (4.9)
Cultivated area[c] (thousand ha [% of the harvested area in the country])	3,741	207 (6)	101 (3)	359 (10)	2,455 (65)	95 (3)	361 (10)	160 (4)
Top 5 crops produced[c] (kt; % of the crop produced in country)	Sugarcane (9,616; 100)	Potatoes (396; 34)	Bananas (41; 13)	Groundnuts (20; 74)	Maize (516; 41)	Bananas (11; 4)	Maize (260; 21)	Bananas (226; 74)
	Soybean (2,942; 100)	Quinoa (68; 96)	Cassava (30; 15)	Maize (426; 34)	Rice (433; 80)	Cassava (30; 15)	Onions (71; 81)	Oranges (161; 85)
	Maize (1,260; 100)	Barley (20; 43)	Maize (17; 1)	Sorghum (280; 27)	Sorghum (741; 72)	Rice (60; 11)	Potatoes (704; 60)	Pineapples (81; 94)
	Potato (1,160; 100)	Carrots and turnips (15; 23)	Rice (11; 2)	Soybeans (108; 4)	Soybeans (2,842; 96)	Soybeans (10; 3)	Sugarcane (598; 6)	Plantains (468; 95)
	Sorghum (1,203; 100)	Broad beans (4; 32)	Sugarcane (76; 1)	Wheat (34; 11)	Sugarcane (8,886; 92)	Sugarcane (48; <1)	Tomatoes (60; 92)	Tangerines (101; 43)
Top 3 livestock species raised[c] (k LU; % of livestock in country)		Cattle (456; 5)	Cattle (741; 9)	Cattle (935; 11)	Cattle (2,827; 34)	Cattle (2,070; 25)	Chickens (16,728; 40)	Cattle (174; 2)
		Llamas (2,017; 80)	Chickens (590; 1)	Chickens (2,563; 6)	Chickens (18,955; 46)	Chicken (259; <1)	Goats (1,433; 76)	Chickens (2,120; 5)
		Sheep (3,202; 51)	Swine (77; 5)	Swine (262; 19)	Swine (357; 25)	Swine (57; 4)	Sheep (2,488; 40)	Sheep (303; 5)
Cultivated area fertilized with manure[d] (%)		44	<1	2	2	<1	43	5

[a]VDRA (2012).
[b]INE (2021).
[c]calculated by applying the proportions determined in the Bolivian Agricultural Census (2014) to the data from INIAF, ANAPO, CIAB, (2019).
[d]Bolivian Agricultural Census (2014). Further information can be found in the supplementary material (Supplementary Tables S2, S5).

Development, 2016) and are often used as criteria to establish associations of municipalities ("mancomunidades").

Agro-ecological zones are especially appropriate for estimating the potential for nutrient recycling in Bolivia because, besides grouping similar crop systems, they also express differences in altitude (agricultural production in Bolivia takes place between ~100 and ~4,000 m above sea level and slopes across the territory), which significantly increases the cost of transporting crops (Klein et al., 2017), biomass (Morato et al., 2019) and nutrients (Trimmer and Guest, 2018). The seven agro-ecological regions are briefly characterized in Table 2.

2.2 Mass balance

Mass balance calculations were done for the simplified agri-food system (Figure 1) at the national scale using data sourced from the literature and the FAOSTAT database for the year 2018 (Table 1). For the regional scale, we aggregated data sourced from the Bolivian Agricultural Census (2014) to calculate the nutrient flows for each agro-ecological, region as the census is performed at the municipality level. We assumed that the contribution of each region to the national nutrient budget remained constant until 2018. Detailed calculations can be found in the supplementary information.

2.2.1 Sufficiency

We calculated the *nutrient sufficiency* indicator to express the results of the mass and nutrient balance so that it can be related to the nutrient requirements of crops. As mass balance calculations compare nutrient inputs and outputs in the crop production system (Eq. 1), a negative value for the indicator implies that the amount of nutrient input to the system is not sufficient to meet the demand of the crops. In other words, there would be a *nutrient deficit*. Conversely, we interpreted a positive value for the indicator as nutrient inputs greater than the amount required by crops, or in other words, a *nutrient surplus*.

$$Sufficiency = \sum_{i=1}^{n} Input_i \times Efficiency_i - \sum_{j=1}^{45} Harvested.produce \quad (1)$$

Input is the amount of nutrient (nitrogen or phosphorus) applied to soil by the following input flows *i*: synthetic fertilizer, crop residues, animal manure, and (in the case of nitrogen only) biological fixation. *Efficiency* is the proportion of nutrient applied to soil by means of the input *i* that is available for and taken up by the crops. The efficiencies for each input were calculated by subtracting the amount of nutrients lost to emissions, leaching, and run-off according to the coefficients and data from Guareschi et al. (2019) for synthetic fertilizer and nitrogen biological fixation and from the FAO (FAO, 2022) for crop resides and animal manure (Table 1).

Harvested.produce (crop requirements) is the mass of nutrient taken up by the crop *j* (where *j* is one of the 45 highest-yield crops in Bolivia according to FAOSTAT). It was calculated by means of published ratios that link crop yield with the amount of nutrient taken up by crops for a given yield (Table 1). Since the current yields for most crops in Bolivian agriculture are considered low, especially in comparison with yields for the same crops in neighbouring countries (Guareschi et al., 2019; INIAF, ANAPO, CIAB, 2019), we calculated the *sufficiency* indicators using the following two approaches derived from Eq. 1. In the first approach (Eq. 2), crop nutrient requirements were calculated based on data for the latest crop yields available to us, i.e., for the year 2018 (*current sufficiency*). If the calculated value of the *current sufficiency* indicator was negative, we interpreted it as an *apparent nutrient deficit* since the value should be zero if all inputs and outputs have been considered in the mass balance. In the second approach (Eq. 3), crop nutrient requirements were calculated based on data for yields obtained in neighbouring countries for the same crops (*optimum sufficiency*) taken from FAOSTAT (FAO, 2022) and available in the supplementary material (Supplementary Table S2). If the calculated value of the *optimum sufficiency* indicator was negative, we interpreted it as a *real nutrient deficit*, since it represents the deficit in nutrient inputs necessary to obtain optimal crop yields.

$$Curent.sufficiency = \sum_{i=1}^{n} Input_i \times Efficiency_i - \sum_{j=1}^{45} Harvested.produce.actual \quad (2)$$

$$Optimum.sufficiency = \sum_{i=1}^{n} Input_i \times Efficiency_i - \sum_{j=1}^{45} Harvested.produce.optimum \quad (3)$$

2.2.2 Circularity

Circularity can be defined as the extent to which a system reduces (or even eliminates) waste by recirculating it as a product or raw material for other processes (Antikainen et al., 2018). Therefore, we evaluated the circularity of the nutrients in the studied system by calculating the share of nutrient inputs that are recirculated (i.e., that originated from secondary resources) (Eq. 4), following the work of Papangelou and Mathijs (2021).

$$Circularity = \frac{\sum recirculated.Input}{\sum Input} \quad (4)$$

recirculated.Input is the amount of nutrients in the recirculated inputs that are applied to soil for crop cultivation. In this study, the inputs deemed recirculated were leftover crop residues and collected manure, while synthetic fertilizers and biological fixation of nitrogen were not considered circular inputs (Table 1).

2.2.3 Replacement potential of excreta

The potential of human excreta to replace current nutrient demand for crop cultivation (*R.potential*) was calculated by dividing the amount of nutrients available in excreta by the amount of nutrients required for crop cultivation. In the case of nitrogen (*N.R.potential*), the proportion of nitrogen biologically fixed (*B.Fixation*) from atmosphere by microorganisms associated with some of the crops was subtracted from the amount of nitrogen taken up by the crops ($Harvested.produce_N$) (Eq. 5).

$$N.R.potential = \frac{Excreta_N}{\sum_{j=1}^{45} Harvested.produce_N - B.Fixation} \quad (5)$$

$Excreta_N$ is the amount of nitrogen in human excreta and *B. Fixation* is the amount of atmospheric nitrogen fixed by microorganisms and taken up by crops. For phosphorus, the replacement potential of excreta (*P.R.potential*) was calculated as for nitrogen except for biological fixation, which does not take place for phosphorus (Eq. 6).

$$P.R.potential = \frac{Excreta_P}{\sum_{j=1}^{45} Harvested.produce_P} \quad (6)$$

In this case, $Excreta_P$ is the amount of phosphorus in human excreta and $Harvested.\ produce_P$ is the amount of phosphorus

TABLE 3 Summary of parameters resulting from the mass balance for nitrogen and phosphorus in the agri-food system of Bolivia and its seven agro-ecological regions, with crop yields for 2018.

Parameter	Bolivia	Agro-ecological region						
		Altiplano	Amazonia	Chaco	Chiquitania-Pantanal	Llanuras	Valleys	Yungas-Chapare
Top 5 crops demanding N (crop yields in kt)	Soybean (47,074)	Quinoa (1,385)	Bananas (261)	Maize (10,744)	Soybean (45,190)	Rice (1,502)	Maize (6,555)	Coffee (2,107)
	Maize (31,775)	Potatoes (1,424)	Maize (495)	Sorghum (8,406)	Sorghum (22,229)	Maize (299)	Potatoes (2,425)	Bananas (1,435)
	Sorghum (30,699)	Barley (506)	Rice (275)	Soybean (1,730)	Maize (13,016)	Cassava (161)	Onions (2,131)	Oranges (945)
	Rice (13,528)	Carrots and turnips (383)	Cassava (162)	Wheat (1,185)	Rice (10,834)	Soybean (153)	Wheat (1,490)	Plantains (889)
	Wheat (10,559)	Onions (382)	Brazil nuts (132)	Beans (742)	Sugarcane (9,241)	Bananas (71)	Beans (1,402)	Rice (644)
Top 5 crops demanding P (crop yields in kt)	Soybean (38,247)	Quinoa (190)	Bananas (54)	Maize (1,743)	Soybean (36,717)	Rice (300)	Maize (1,063)	Oranges (693)
	Maize (5,156)	Potatoes (153)	Maize (72)	Sorghum (1,681)	Sorghum (4,445)	Soybean (124)	Potatoes (273)	Bananas (296)
	Sorghum (6,139)	Barley (81)	Rice (55)	Soybean (1,405)	Rice (2,166)	Maize (48)	Wheat (255)	Tangerine (181)
	Rice (2,705)	Broad beans (46)	Cassava (25)	Wheat (203)	Maize (2,112)	Cassava (24)	Beans (246)	Coffee (138)
	Wheat (1,810)	Carrots and turnips (46)	Oranges (22)	Groundnuts (199)	Sunflower (1,332)	Bananas (14)	Onions (213)	Rice (129)
N required (tonnes)	395,220	4,826	1,676	35,229	315,575	3,027	24,843	8,114
N required (%)	100	1	<1	9	80	<1	6	2
P required (tonnes)	63,564	619	284	5,605	51,259	538	3,137	1,790
P required (%)	100	1	<1	9	80	1	5	3
N balance (tonnes) Excess +, deficit -	−32,159	+6,760	−1,137	−15,460	−50,748	−705	+34,274	−3,426
P balance (tonnes) (+, excess; −, deficit)	−7,793	+3,719	−206	−3,135	−37,486	−357	+29,839	+158
Main N input (%)	BNF (56)	Manure (78)	Crop residues (57)	BNF (51)	BNF (72)	Crop residues (45)	Manure (65)	Manure (62)
Main P input (%)	Manure (53)	Manure (90)	Crop residues (81)	Crop residues (78)	Crop residues (57)	Crop residues (99) (69)	Manure (77)	Manure
N circularity (%)	44	98	57	49	24	42	82	81
P circularity (%)	74	97	98	83	67	99	72	83
N environmental loss (%)	—	195	5	2	7	12	246	42
Area with manure (%)	8	44	<1	2	2	<1	43	5
Main manure source (%)	—	Swine (75–50%) and cattle (13–20%)	Cattle (97–98%)	Cattle (39–56%) and swine (53–34%	Chicken (63–81%) and swine (36–18%)	Cattle (99%)	Chicken (57–71%) and swine (29–14%)	Chicken (49–69%) and swine (46–25%)
Main manure source (no. Of heads/ cultivated ha)	—	—	—	—	Chicken (6.4)	—	Chicken (38)	Chicken (11)
	—	Cattle (1.8)	Cattle (6)	Cattle (2.1)	—	Cattle (18)	—	—
	—	Swine (0.4)	—	Swine (0.6)	Swine (0.1)	—	Swine (1.1)	Swine (0.4)

TABLE 4 Summary of parameters resulting from the mass balance for nitrogen and phosphorus in the agri-food system of Bolivia and its seven agro-ecological regions, with optimised crop yields (average yields in neighbouring countries) for 2018.

Parameter	Bolivia	Agro-ecological region						
		Altiplano	Amazonia	Chaco	Chiquitania-Pantanal	Llanuras	Valleys	Yungas-Chapare
Top 5 crops demanding N (crop yields in kt)	Maize (76,870)	Quinoa (2,841)	Maize (1,079)	Maize (25,994)	Soybean (62,802)	Rice (2,827)	Maize (15,858)	Coffee (3,515)
	Soybean (65,420)	Potatoes (3,327)	Rice (517)	Sorghum (8,918)	Maize (31,488)	Maize (724)	Potatoes (5,920)	Bananas (1,890)
	Sorghum (32,569)	Barley (869)	Bananas (344)	Soybean (2,404)	Sorghum (23,583)	Cassava (329)	Wheat (3,056)	Oranges (1,719)
	Rice (25,466)	Carrots and turnips (678)	Cassava (332)	Wheat (2,431)	Rice (20,394)	Soybean (213)	Onions (2,747)	Maize (1,371)
	Wheat (21,653)	Onions (493)	Watermelon (197)	Seed cotton (1,509)	Wheat (15,931)	Watermelon (120)	Carrots and turnips (2,115)	Rice (1,213)
Top 5 crops demanding P (crop yields in kt)	Soybean (53,154)	Quinoa (390)	Maize (175)	Maize (4,218)	Soybean (51,026)	Rice (565)	Maize (2,573)	Oranges (1,261)
	Maize (12,474)	Potatoes (358)	Rice (103)	Soybean (1,953)	Maize (5,109)	Soybean (173)	Potatoes (638)	Tangerine (391)
	Sorghum (6,513)	Barley (139)	Bananas (71)	Sorghum (1,783)	Sorghum (4,716)	Maize (117)	Wheat (523)	Bananas (390)
	Rice (5,093)	Broad beans (68)	Cassava (51)	Wheat (416)	Rice (4,078)	Cassava (50)	Beans (280)	Rice (242)
	Wheat (3,711)	Carrots and turnips (81)	Oranges (41)	Groundnuts (283)	Wheat (2,731)	Bananas (19)	Onions (274)	Coffee (230)
N required (tonnes)	605,790	9,436	2,955	60,147	460,292	5,532	48,170	13,858
N required (%)	100	1	<1	10	76	<1	8	2
P required (tonnes)	96,823	1,202	505	9,284	74,499	977	6,234	3,141
P required (%)	100	1	<1	9	77	1	6	3
N balance (tonnes) (+, excess; −, deficit)	−109,415	+4,880	−1,975	−28,427	−90,072	−1,933	+21,364	−8,147
P balance (tonnes) (+, excess; −, deficit)	−33,019	+3,441	−352	−5,330	−56,248	−630	+28,124	−1,049
Main N input (%)	BNF (58)	Manure (63)	Crop residues (67)	BFN (50)	BNF (71)	Crop residues (55)	Manure (55)	Manure (50)
Main P input (%)	Manure (46)	Manure (84)	Crop residues (90)	Crop residues (86)	Crop residues (67)	Crop residues (99)	Manure (66)	Manure (71)
N circularity (%)	43	98	67	52	26	52	82	81
P circularity (%)	77	97	99	89	75	99	73	84

taken up by crops. The results of the replacement potential of excreta are expressed as percentages for both nutrients. We assumed that there were no losses during treatment, storage, transportation, and application.

2.3 GIS mapping

Data calculated in the mass balance were processed with the PostGIS extension for PostgreSQL and then plotted as choropleth maps with QGIS.

3 Results

3.1 Nutrient sufficiency

At the national level, the total nutrient requirements in relation to crop yields obtained in the year 2018 (i.e., current crop yield; see Section 2.2.1) were 395 and 63 kt for N and P, respectively. The total nutrient inputs to the agri-food systems after accounting for nutrient losses during application amounted to 363 kt for N and 55 kt for P. This suggests that there are apparent deficits of 32 kt of N (8% of total crop requirement after accounting for biological fixation) and

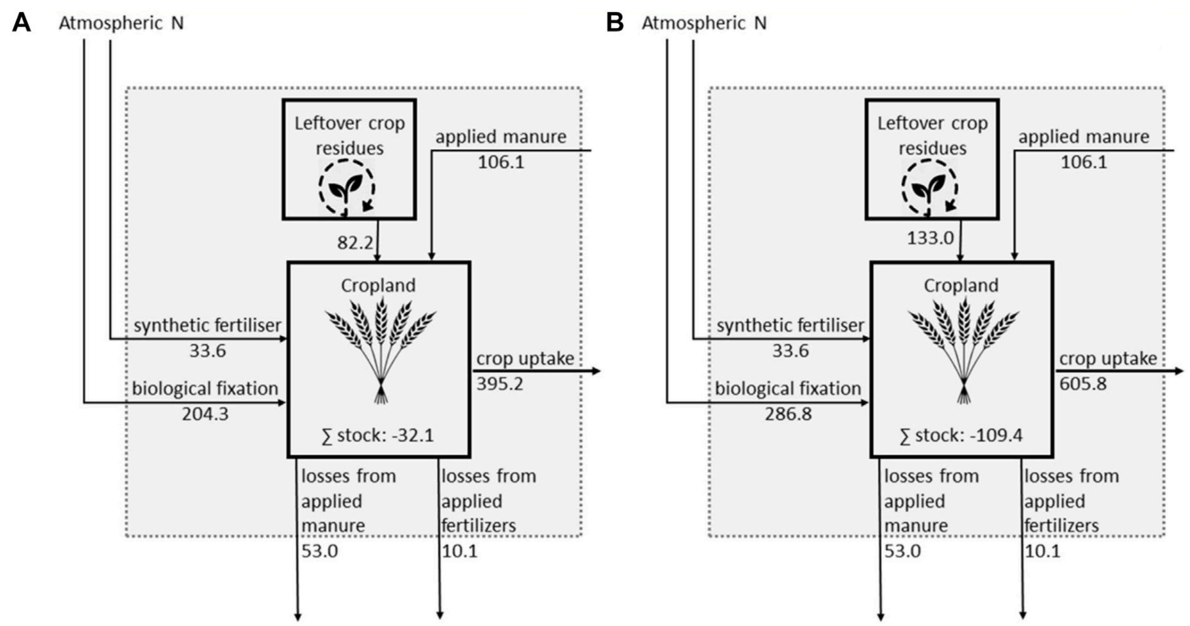

FIGURE 2
Mass balance for nitrogen in the agri-food system of Bolivia calculated using **(A)** crop yield data sourced from FAOSTAT database for the year 2018 (*harvest.produce.actual*) and **(B)** yield for the same crops in neighbouring countries (*harvest.produce.optimum*). The calculations show an apparent nitrogen deficit of 32 kt and a real nitrogen deficit of 110 kt in the agri-food system.

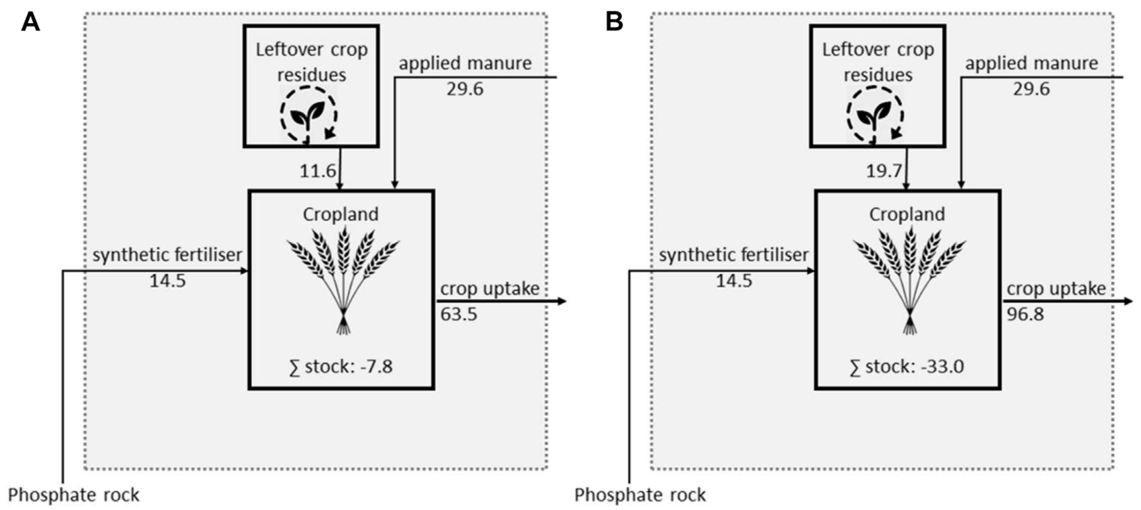

FIGURE 3
Mass balance for phosphorus in the agri-food system of Bolivia calculated using **(A)** crop yield data sourced from FAOSTAT database for the year 2018 (*harvest.produce.actual*) and **(B)** yield for the same crops in neighbouring countries (*harvest.produce.optimum*). The calculations show an apparent phosphorus deficit of 7.8 kt and a real phosphorus deficit of 33 kt in the agri-food system.

7.7 kt of P (12% of total crop requirement) (Table 3). However, if all crops received optimal nutrient inputs so that their yields were maximised (i.e., optimum crop yield; see Section 2.2.1), then 605 kt of N and 97 kt of P would be required (Table 4). This means that the real nutrient deficit was much larger, 110 kt of N and 33 kt of P (Figure 2, Figure 3).

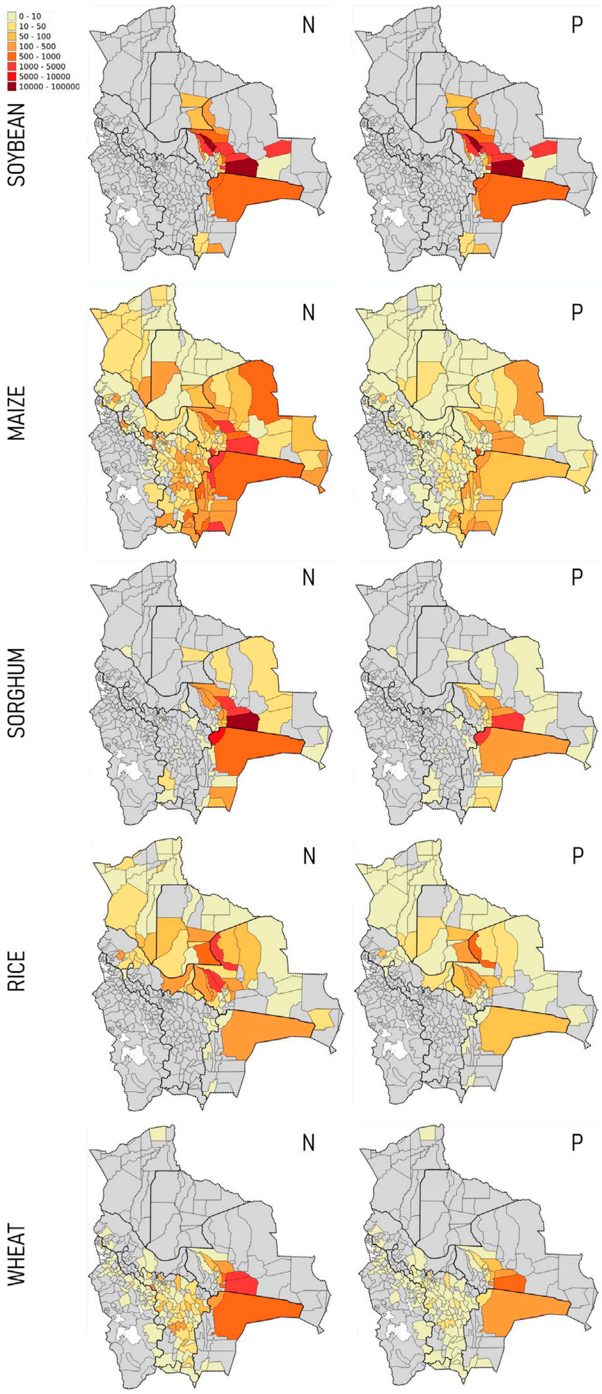

FIGURE 4
Nutrient requirements (kg) from the top five crops with highest nutrient demands produced in Bolivia in 2018, determined by mass balance. For nitrogen, the requirements shown resulted from subtracting the biologically fixed amount from the total demand. Requirements are shown at the municipality level. The seven agro-ecological regions are delimited with thicker lines.

Although the top five crops in total yield (i.e., in tonnes) were sugarcane, soybean, maize, potato, and sorghum (Table 2), the five crops that demanded the largest N and P inputs were soybean, maize, sorghum, rice, and wheat (47, 31, 30, 13, and 10 kt for N, and 38, 5, 6, 2.7, and 1.8 kt for P, after accounting for biological nitrogen fixation and losses during application; see Table 3). The differences between the nutrient input required for maximising crop yields (Table 4) and the nutrient input received by crops in year 2018 (Table 3) were smallest for sorghum (6%) and soybean (28%), both of which are processed mainly to produce animal feed, but much larger (52% on average) for the staple crops wheat, rice, and maize.

Three agro-ecological regions (Chiquitania-Pantanal, Chaco, and the Valleys) accounted for nearly 90% of the nutrient demand (Table 3). About 65% of the cultivated area in Bolivia is found in the Chiquitania-Pantanal region (Table 2), which alone accounts for 80% of the nitrogen and phosphorus demand of the country (Table 3). This is because soybean, sorghum, and rice (three out of the five most cultivated and most nutrient-demanding crops grown) can only be cultivated in low-altitude agro-ecological regions (Figure 4). In contrast to Chiquitania-Pantanal, the Valleys region accounts for 10% of cultivated area but only 6 and 5% of the N and P demands of the country, respectively.

In five out of the seven regions (excluding Altiplano and the Valleys), there are deficits of both the nutrients. The deficit is largest in Chiquitania-Pantanal, where there is a shortfall of 50 kt N and 37 kt P, followed by Chaco (15 kt N and 3.1 kt P) and Yungas-Chapare (deficit of 3.4 kt N but surplus of 0.1 kt P). In both the Valleys and the Altiplano, there are nutrient surpluses of approximately 41 kt of N and 33.5 kt of P.

According to the mass balance at the regional scale, there is discrepancy between the demand for nutrients and the nutrients harvested for some crops. For example, sugarcane is one of the five most cultivated crops in Amazonia, Chiquitania-Pantanal, and Llanuras, but is not among the top five nutrient-demanding crops, and it is the fifth largest crop in terms of nitrogen demand in Chiquitania-Pantanal (Table 3). This is also the case for tomato cultivation in the Valleys and for pineapple cultivation in Yungas-Chapare. Soybeans accounted for about 17% of the total nitrogen applied in Chiquitania-Pantanal, where almost all the country's soybean crop is cultivated. Although it is a common approach when calculating nutrient demand (INIAF, ANAPO, CIAB, 2019) to focus on crops with the highest harvests, our findings suggest that this can be inaccurate in countries and regions where crops with high water content and low nutrient demand are produced at large scale.

3.2 Circularity

The main nitrogen input at national level was biological nitrogen fixation (204 kt, accounting for 47% of the total input) followed by manure (25%), crop residues (19%), and synthetic fertilizer (8%). For phosphorus, the main input was manure (29 kt, accounting for 53% of total input), followed by synthetic fertilizers (26%) and crop residues (21%). Therefore, the nutrient circularity of the Bolivian agri-food system (i.e., the proportion of nutrients recirculated to the nutrient inputs added during crop cultivation; see Eq. 4) was estimated to be 44% for nitrogen and 74% for phosphorus (Table 3).

In the two regions where there is surplus of both nutrients, the main nutrient input was animal manure (swine in the Altiplano and chicken in the Valleys), accounting for >65% of the total input (Table 3). In the two regions with the largest nutrient deficits (Chiquitania-Pantanal and Chaco), soybean was the most nutrient-demanding crop but also the main source of nitrogen input to the soil because of biological fixation (72 and 51% of the nitrogen inputs for Chiquitania-Pantanal and Chaco, respectively), while the crop residues left over after harvest were the main source of phosphorus (57 and 78% for Chiquitania-Pantanal and Chaco, respectively) (Table 3).

In regions with nutrient surpluses, the proportion of nutrients recirculated back to the food system was high, >95% in the Altiplano and >71% in the Valleys, respectively. This is likely because of the wider availability of manure across both these agro-ecological regions in comparison to that in the other five regions (Figure 5). In contrast, the estimated nutrient circularity in the two regions with the largest nutrient deficits was low, 24–67% for Chiquitania-Pantanal and 49–83% for Chaco.

3.3 Replacement potential of human excreta

In Bolivia, about 39 kt of nitrogen and 5 kt of phosphorus are available in human excreta (Figure 6). If all of the excreta were to be collected and recycled back to cropland, 100% of the nitrogen deficit and 64% of the phosphorus deficit of the current system (Table 3) could be met. Overall, the nutrients in excreta are equivalent to 20% of the nitrogen demand and 8% of the phosphorus demand of the agri-food system (Table 5). At the regional level, the replacement potential of excreta is higher in regions with large populations and low crop production. For example, 60% of the country's population lives in the Altiplano and the Valleys, where only 16% of crop production occurs, so recycling either animal manure alone (the current practice; see Table 3) or human excreta alone in these regions can meet the majority of the nutrient demand (Table 5). Outside the Altiplano region, excreta would not be enough to meet nitrogen or phosphorus requirements. In Chiquitania-Pantanal, less than 10% of nutrient requirements could be met by recycling excreta.

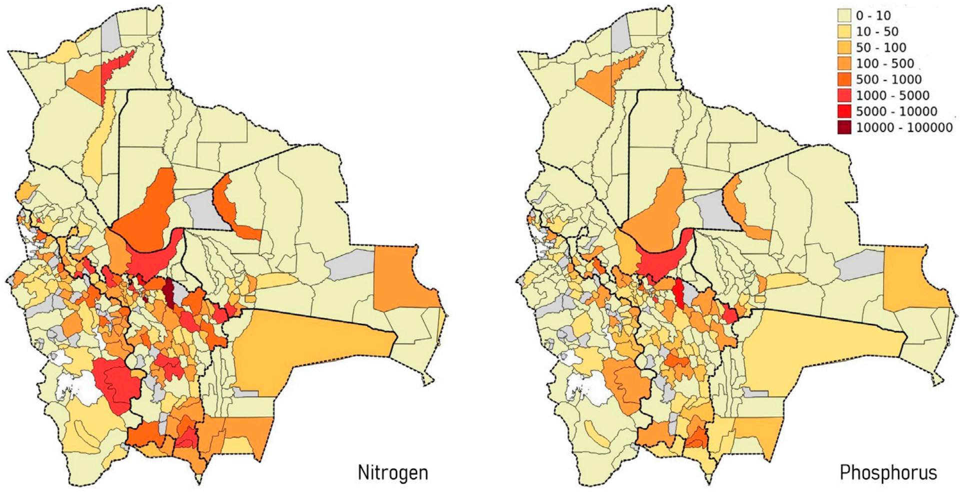

FIGURE 5
Availability of nutrients (kg) from manure in Bolivia in 2018, determined by mass balance. The seven agro-ecological zones are delimited with thicker lines.

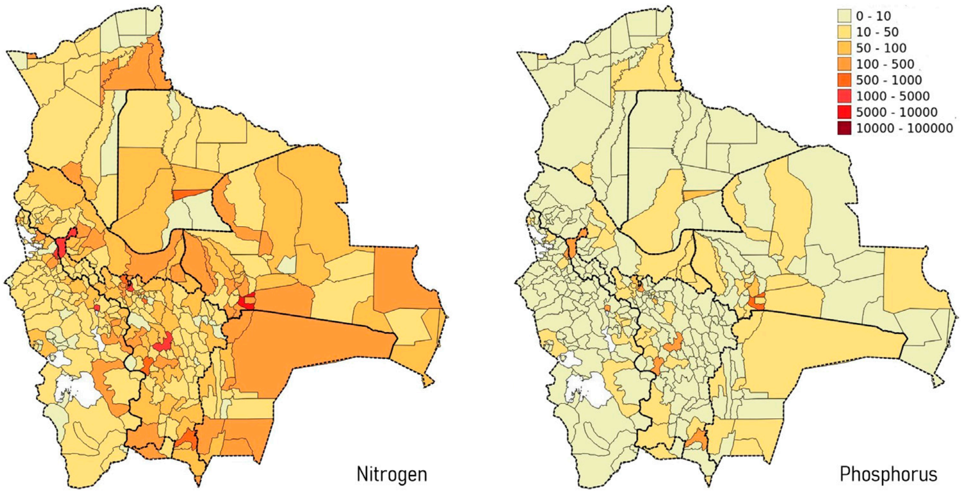

FIGURE 6
Availability of nutrients from human excreta in Bolivia in 2018, determined by mass balance. The seven agro-ecological zones are delimited with thicker lines.

4 Discussion

4.1 Nutrient demand and sufficiency in the bolivian agri-food system

The findings of this study suggest that 395 kt N and 65 kt P were required to support crop production in Bolivia for the year 2018. According to our mass balance calculations, there was an apparent deficit of 32 kt N and 8 kt P in crop production, which we cannot account for from the available data. The starting point of our calculations was the FAOSTAT (FAO, 2022) database where Bolivia reports the total yields of 45 different crops grown in the country. Thus, the total amounts of N and P in agricultural harvests are known, as are the total nutrient inputs to the food system in the form of biological fixation, manure, and synthetic fertiliser application. Therefore, it is unclear why the mass balance shows a nutrient deficit and/or how that deficit is being met.

There are several possible reasons for this deficit. First, the deficit may have been met with nutrient stocks in soil that

TABLE 5 Replacement potential of human excreta for nutrient requirements for agriculture in Bolivia in 2018. Net requirement of nitrogen refers to the requirement after subtracting the biologically fixed nitrogen.

Parameter	Agro-ecological region							
	Altiplano	Amazonia	Chaco	Chiquitania-Pantanal	Llanuras	Valleys	Yungas-Chapare	Bolivia
Excreta/net requirement N (%)[a]	186	87	5	8	36	70	24	20
Excreta/requirement P (%)[a]	176	62	2	3	20	61	14	8
Total potential for N circularity (%)[b]	337	64	40	54	63	249	57	81
Total potential for P circularity (%)[b]	818	76	39	20	50	810	102	71

[a]Recovery and efficiency of 100% was assumed for excreta.
[b]recovery and efficiency of 50% (current efficiency for manure) was assumed for excreta and for applied manure, while 98% (current efficiency) was considered for crop residues.

become available during land use change (planned or unplanned conversion of forest land to agricultural land). There is evidence of deforestation in Bolivia linked to large-scale farming of industrial crops in agro-ecological zones where agriculture is practiced in close proximity to forest land (i.e., Amazonia, Chaco, and Chiquitania-Pantanal) (Müller et al., 2012; Ormachea, 2018). Second, the deficit could have been met through traditional agricultural practices (e.g., crop rotation, fallowing, etc.) for which there are no data, and which thus could not be accounted for. If these explanations hold, it would mean that the agri-food system is operating at a deficit that will ultimately result in depletion of soil nutrient stocks.

We also estimated that the true deficit in the Bolivian agri-food system is much higher than what the mass balance suggests, given the following two aspects. Firstly, if all crops received optimal nutrient application rates that maximised their yields, an additional 220 kt N and 32 kt P would be required. Secondly, the mass balance at the national level assumes that in regions that have nutrients in excess of the local demand, the surplus is collected and applied in regions that have a net deficit. If this is not the case, then there is an additional deficit of 53 kt N and 40 kt P. In the Chiquitania-Pantanal and Chaco regions alone, where 75% of the crop production occurs, the local deficit is approximately 15% for nitrogen but 70% for phosphorus. Addressing this deficit is vital because according to projections by Rivero Lobo and Aliaga Lordermann (2014), the production of proteins, fruits, and vegetables in Bolivia for 2018 could only meet 60–70% of the nutritional requirements of its population.

4.2 Nutrient recycling and circularity in the bolivian agri-food system

We found that less than half of the nitrogen applied or fixed in the cropland was recirculated in the food system, whereas three-quarters of the phosphorus was recirculated. However, there is great variation in nutrient circularity between the different agro-ecological zones. In zones where animal manure is the main nutrient input and livestock density is high, the circularity is also high (>0.9). This does not mean that all of the available nutrients are recycled, as there are surpluses of 41 kt N and 34 kt P in these zones, primarily in the Valleys (Table 3). Even if the surplus nutrients were to be recycled locally to optimise crop yields, there would still be excesses of 21 kt N and 28 kt P (Table 4). The surplus nutrients are equivalent to 40% of the N deficit and 75% of the P deficit in Chiquitania-Pantanal. Therefore, recycling nutrients from regions with a net surplus to regions with a net deficit could be one way to reduce the overall deficit, as well as to improve nutrient circularity and crop yields.

As in other developing countries that aim to increase food production, the agricultural strategy in Bolivia has focused on improving the access of farmers to synthetic fertilisers (INIAF, ANAPO, CIAB, (2019); Mnthambala et al., 2021). In 2017, a state-owned petrochemical plant was inaugurated in Bolivia to produce urea and ammonia. In 2022, the plant is expected to produce 600 kt of urea, of which about 7% will be sold locally and the rest exported to other Latin American countries (McNelly, 2020; BNAmericas, 2021). However, considering the true national N deficit (110 kt; see Table 4), urea fertiliser at the current application rate can only meet 20% of the N required to obtain optimal crop yields. About 40% of the industrial urea production would need to be sold domestically to have zero nitrogen deficit in the agri-food system. As of today, there is no domestic production of synthetic phosphate fertiliser in Bolivia, but the petrochemical plant intends to also produce monoammonium phosphate and diammonium phosphate.

4.3 Potential of human excreta-derived nutrients

Despite the domestic sale of urea, there are still total N and P deficits of 109 kt and 33 kt, respectively, in the agri-food system. If all the human excreta in Bolivia were to be collected and returned to cropland, the deficits can be reduced to 70 kt N and

28 kt P. This would significantly increase circularity, as excreta is a renewable source of nutrients. It would also improve the resilience in the food system against global events, e.g., disruptions in fertiliser supply chains seen during the COVID-19 pandemic (Amjath-Babu et al., 2020) and rise of fertiliser prices against a backdrop of rising natural gas prices (Hebebrand and Laborde, 2022).

Since >70% of the population in Bolivia lives in cities and urban areas, it could be possible to collect the majority of the nutrients available in excreta. For example, the population density in La Paz and El Alto is > 9,000 inhabitants/km^2 (Parés-Ramos et al., 2013). However, much of the economic feasibility of transporting these nutrients to croplands surrounding the cities will depend on how excreta are collected, treated, stored, and applied (Simha et al., 2020). The feasibility of this increases if water is removed from excreta to concentrate the nutrients (Trimmer and Guest, 2018). A wide range of technologies are available to convert human excreta (Harder et al., 2019) or source-separated fractions like human urine (Vasiljev et al., 2022) and faeces (Musazura and Odindo, 2022) to concentrated fertilisers.

In this study, we assumed that 100% of the human excreta-derived nutrients can be recovered and returned to cropland. In practice, the recovery efficiency would be likely lower, especially depending on the choice of technology used to treat excreta or source-separated excreta fractions (Harder et al., 2019). Many technologies like alkaline dehydration are currently being optimised to recover >98% of the nitrogen and phosphorus contained within human urine (Vasiljev et al., 2022). However, our findings showed that even if excreta-derived nutrients are applied at current manure-like efficiencies (*i.e.* 50%), they would significantly improve the nutrient circularity of the agri-food system (Table 5).

5 Conclusions

Our calculations suggest that the Bolivian agri-food system is currently running on a nutrient deficit. It is likely that the nutrient stocks in soil (e.g., conversion of forests to cropland) are being used to cover the nutrient deficit in crop production, which is not sustainable long term. The real nutrient deficit is at least three-fold greater if we consider the nutrient demand required to optimize crop yields to be in line with those of neighbouring countries.

Around 44% of N and 74% of P are currently recirculated in the agri-food system, with livestock manure and crop residues being the major sources of the recirculated nutrients. As the national strategy to address the nutrient deficit is to increase the domestic production and application of synthetic fertilizers, nutrient circularity in the food system will likely decrease in the future.

We also found that both nutrient deficits and circularity differed considerably between the different agro-ecological zones. Recycling nutrients from regions with nutrient surpluses to regions with nutrient deficits could be a way to reduce overall deficits and increase overall circularity.

Based on the current crop yields, nutrients available in human excreta could meet 100 and 70% of the N and P apparent deficits, respectively. This suggests that excreta recycling could be one of the strategies to prevent deforestation and depletion of nutrient stocks in forests. Recycling excreta-derived nutrients would also contribute to increasing nutrient circularity and crop yields.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

LP-M and PS conceptualized the study. LP-M did the mass balance calculations with inputs from PS. CP-M developed the GIS maps. BV provided resources and acquired funding. LP-M and PS wrote the first draft of the manuscript. All authors contributed to manuscript revision, read and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.956325/full#supplementary-material

References

Akram, U., Quttineh, N.-H., Wennergren, U., Tonderski, K., and Metson, G. S. (2019). Enhancing nutrient recycling from excreta to meet crop nutrient needs in Sweden–a spatial analysis. *Sci. Rep.* 9, 10264. doi:10.1038/s41598-019-46706-7

Ali, Q., Ashraf, S., Kamran, M., Ijaz, M., Rehman, A., Tahir, M., et al. (2019). "Organic manuring for agronomic crops," in *Agronomic crops* (Springer), 163

Alvar-Beltrán, J., Napoli, M., Dao, A., Ouattara, A., Verdi, L., Orlandini, S., et al. (2021). *Nitrogen, phosphorus and potassium mass balances in an irrigated quinoa field*. Italian Journal of Agronomy.

Amjath-Babu, T. S., Krupnik, T. J., Thilsted, S. H., and McDonald, A. J. (2020). Key indicators for monitoring food system disruptions caused by the COVID-19 pandemic: insights from Bangladesh towards effective response. *Food Secur.* 12, 761–768. doi:10.1007/s12571-020-01083-2

Antikainen, R., Lazarevic, D., and Seppälä, J. (2018). "Circular economy: origins and future orientations," in *Factor X* (Springer), 115–129.

ASAE (2005). *Manure production and characteristics*. St. Joseph, Michigan, USA: American Society of Agricultural Engineers ASAE.

Awodun, M. A., Omonijo, L. I., and Ojeniyi, S. O. (2007). Effect of goat dung and NPK fertilizer on soil and leaf nutrient content, growth and yield of pepper. *Int. J. Soil Sci.* 2, 142–147. doi:10.3923/ijss.2007.142.147

BNAmericas (2021). *Restart of PAU operations in Bolivia projects income of up to $ 22 million per month from the sale of urea*. [WWW Document]. BNAmericas. URL https://www.bnamericas.com/en/news/restart-of-pau-operations-in-bolivia-projects-income-of-up-to–22-million-per-month-from-the-sale-of-urea (accessed 23 2, 22).

Brown, C. (2013). *Available nutrients and value for manure from various livestock types*. Ontario Ministry of Agriculture, Food and Rural Affairs, Ontario, Canada. https://fieldcropnews.com/wp-content/uploads/2015/03/Nutrient-Value-of-Manure.pdf.

Chowdhury, R. B., Moore, G. A., Weatherley, A. J., and Arora, M. (2014). A review of recent substance flow analyses of phosphorus to identify priority management areas at different geographical scales. *Resour. Conservation Recycl.* 83, 213–228. doi:10.1016/j.resconrec.2013.10.014

Crisóstomo, L. A., and Naumov, A. (2009). *Adubando para alta produtividade e qualidade: Fruteiras tropicais do brasil*. Fortaleza, Brazil: Embrapa Agroindústria Tropical-Livro científico ALICE. Available at: https://www.alice.cnptia.embrapa.br/bitstream/doc/658334/1/LV09002.pdf.

da Cunha, J. F., Bohac, E. A., and Prochnow, L. I. (2018). Balanco de nutrientes na agricultura brasileira no periodo de 2013 a 2016. *Inf. Agron.*, 3.

de Sousa, D. M. G., and Lobato, E. (2004). *Cerrado: correção do solo e adubaçãoEmbrapa Informação Tecnológica; Embrapa Cerrados, Brasilia DF, Brazil.* 2nd ed.

Elser, J., and Bennett, E. (2011). A broken biogeochemical cycle. *Nature* 478, 29–31. doi:10.1038/478029a

FAO (1996). *Agro-ecological zoning: Guidelines*. Rome, Italy: Food & Agriculture Organization of the United Nations FAO.

FAO (2022). *Faostat*. Food and Agriculture Organization. License: CC BY-NC-SA 3.0 IGO [WWW Document]. Available at: https://www.fao.org/faostat/en/#data (accessed 21 2, 22).

Faquin, V. (2004). Nutrição mineral e diagnose do estado nutricional das hortaliças. Universidade Federal de Lavras (UFLA) - FAEPE (Fundacao de apoio ao ensino, pesquisa e extensao), Lavras, Minas Gerais. Brazil Available at: https://dcs.ufla.br/images/imagens_dcs/pdf/Prof_Faquin/Nutricao_mineral_diagnose_hortalicas2_ed.pdf.

Farmer, A. M. (2018). *Phosphate pollution: A global overview of the problem*. Phosphorus: Polluter and Resource of The Future—Removal and Recovery From WastewaterSchaum, C., 35–55.

Guareschi, R. F., Boddey, R. M., Alves, B. J. R., Sarkis, L. F., Martins, M., dos, R., et al. (2019). Balanço de nitrogênio, fósforo e potássio na agricultura da américa latina e o caribe. *Terra* 37, 105. doi:10.28940/terra.v37i2.423

Haifa-group (2021). Crop guide. [WWW Document]. Available at: https://haifa-group.com/ (accessed 20 4, 21).

Halliday, D. J., and Trenkel, M. E. (1992). *IFA world fertilizer use manual*. International fertilizer industry association Paris.

Hanserud, O. S., Brod, E., Øgaard, A. F., Müller, D. B., and Brattebø, H. (2016). A multi-regional soil phosphorus balance for exploring secondary fertilizer potential: The case of Norway. *Nutr. Cycl. Agroecosyst.* 104, 307–320. doi:10.1007/s10705-015-9721-6

Harder, R., Wielemaker, R., Larsen, T. A., Zeeman, G., and Öberg, G. (2019). Recycling nutrients contained in human excreta to agriculture: Pathways, processes, and products. *Crit. Rev. Environ. Sci. Technol.* 49, 695–743. doi:10.1080/10643389.2018.1558889

Hebebrand, C., and Laborde, D. (2022). High fertilizer prices contribute to rising global food security concerns [WWW Document]. URL https://www.ifpri.org/blog/high-fertilizer-prices-contribute-rising-global-food-security-concerns#:~:text=High%20prices%20of%20both%20ammonia,in%202021%20and%20into%202022 (accessed 27 4, 21).

INIAF, ANAPO, CIAB (2019). *Plan nacional de fertilización y nutrición vegetal 2019-2025*. La Paz, Bolivia: Instituto nacional de innovación agrícola y forestal INIAF.

Intrepid-potash (2021). *Naturally balanced nutrition for tobacco*. [WWW Document]. Availabel at: www.intrepidpotash.com/tobacco/ (accessed 20 4, 21).

Jönsson, H., and Vinnerås, B. (2003). "Adapting the nutrient content of urine and faeces in different countries using FAO and Swedish data," in *Proceedings from the 2nd international symposium on ecological sanitation* (Luebeck, Germany.

Klein, K., Torrico Albino, J. C., and Schlueter, S. (2017). Insights into the potato value chain of Bolivia-Market potentials for integrating native varieties in the context of Food Security. *CienciAgro* 7 , 69–76.

Klinglmair, M., Lemming, C., Jensen, L. S., Rechberger, H., Astrup, T. F., Scheutz, C., et al. (2015). Phosphorus in Denmark: National and regional anthropogenic flows. *Resour. Conservation Recycl.* 105, 311–324. doi:10.1016/j.resconrec.2015.09.019

Lal, R. (2009). "Use of crop residues in the production of biofuel," in *Handbook of waste management and Co-product recovery in food processing* (Elsevier), 455.

Mayer, B. K., Baker, L. A., Boyer, T. H., Drechsel, P., Gifford, M., Hanjra, M. A., et al. (2016). total value of phosphorus recovery. *Environ. Sci. Technol.* 50, 6606–6620. doi:10.1021/acs.est.6b01239

McNelly, A. (2020). Neostructuralism and its class character in the political economy of bolivia under evo morales. *New Polit. Econ.* 25, 419–438. doi:10.1080/13563467.2019.1598962

Mihelcic, J. R., Fry, L. M., and Shaw, R. (2011). Global potential of phosphorus recovery from human urine and feces. *Chemosphere* 84, 832–839. doi:10.1016/j.chemosphere.2011.02.046

Ministry for planning of development, B. (2016). *Lineamientos metodológicos para la formulación de planes de gestión territorial comunitaria*. La Paz, Bolivia: Ministry for Planning of Development.

MMAyA (2020). *Estrategia nacional de tratamiento de aguas residuales*. La Paz, Bolivia: Ministerio de medio ambiente y agua.

Mnthambala, F., Tilley, E., Tyrrel, S., and Sakrabani, R. (2021). Phosphorus flow analysis for Malawi: Identifying potential sources of renewable phosphorus recovery. *Resour. Conservation Recycl.* 173, 105744. doi:10.1016/j.resconrec.2021.105744

Morato, T., Vaezi, M., and Kumar, A. (2019). Developing a framework to optimally locate biomass collection points to improve the biomass-based energy facilities locating procedure–a case study for Bolivia. *Renew. Sustain. Energy Rev.* 107, 183–199. doi:10.1016/j.rser.2019.03.004

Morée, A. L., Beusen, A. H. W., Bouwman, A. F., and Willems, W. J. (2013). Exploring global nitrogen and phosphorus flows in urban wastes during the twentieth century. *Glob. Biogeochem. Cycles* 27, 836–846. doi:10.1002/gbc.20072

Müller, R., Müller, D., Schierhorn, F., Gerold, G., and Pacheco, P. (2012). Proximate causes of deforestation in the Bolivian lowlands: an analysis of spatial dynamics. *Reg. Environ. Change* 12, 445–459. doi:10.1007/s10113-011-0259-0

Musazura, W., and Odindo, A. O. (2022). Characterisation of selected human excreta-derived fertilisers for agricultural use: a scoping review. *J. Clean. Prod.* 339, 130516. doi:10.1016/j.jclepro.2022.130516

Ormachea, E. (2018). *Tierras y producción agrícola: A 13 años del gobierno del mas*. La Paz, Bolivia: CEDLA.

Papangelou, A., and Mathijs, E. (2021). Assessing agro-food system circularity using nutrient flows and budgets. *J. Environ. Manag.* 288, 112383. doi:10.1016/j.jenvman.2021.112383

Parés-Ramos, I. K., Álvarez-Berríos, N. L., and Aide, T. M. (2013). Mapping urbanization dynamics in major cities of colombia, ecuador, perú, and bolivia using night-time satellite imagery. *Land (Basel)* 2, 37–59. doi:10.3390/land2010037

Perez-Mercado, L. F., Lalander, C., Joel, A., Ottoson, J., Iriarte, M., Vinnerås, B., et al. (2022). Managing microbial risks in informal wastewater-irrigated agriculture through irrigation water substitution. *Agric. Water Manag.* 269, 107733. doi:10.1016/j.agwat.2022.107733

Pires, A. L., and Portela, E. (2007). Assessment of nutrient outputs in chestnut groves: fruit and pruned biomass. *Acta Hortic.* 815, 75–82. doi:10.17660/actahortic.2009.815.10

Randive, K., Raut, T., and Jawadand, S. (2021). An overview of the global fertilizer trends and India's position in 2020. *Min. Econ.* 34, 371–384. doi:10.1007/s13563-020-00246-z

Rivero Lobo, B., and Aliaga Lordermann, J. (2014).*Disponibilidad, consumo y utilización biológica de alimentos en Bolivia: análisis y perspectivas (1990-2030).* Revista Latinoamericana de Desarrollo Económico 161–198.

Roy, R. N., Finck, A., Blair, G. J., and Tandon, H. L. S. (2006). Plant nutrition for food security. a guide for integrated nutrient management. *FAO Fertilizer Plant Nutr. Bull.* 16, 368.

Senthilkumar, K., Nesme, T., Mollier, A., and Pellerin, S. (2012). Regional-scale phosphorus flows and budgets within France: the importance of agricultural production systems. *Nutr. Cycl. Agroecosyst.* 92, 145–159. doi:10.1007/s10705-011-9478-5

Silveti, D., and Andersson, K. (2019). Challenges of governing off-grid "Productive" sanitation in peri-urban areas: Comparison of case studies in Bolivia and south africa. *Sustainability* 11, 3468. doi:10.3390/su11123468

Simha, P., Senecal, J., Gustavsson, D. J. I., and Vinnerås, B. (2020). "Resource recovery from wastewater: A new approach with alkaline dehydration of urine at source," in *Current developments in biotechnology and bioengineering* (Elsevier), 205–221.

Smit, A. L., Van Middelkoop, J. C., Van Dijk, W., and Van Reuler, H. (2015). A substance flow analysis of phosphorus in the food production, processing and consumption system of the Netherlands. *Nutr. Cycl. Agroecosyst.* 103 (1), 1–13. doi:10.1007/s10705-015-9709-2

Steffen, W., Richardson, K., Rockström, J., Cornell, E., Fetzer, I., Bennett, E., et al. (2015). Sustainability. Planetary boundaries: guiding human development on a changing planet. *Science* 347, 1259855. doi:10.1126/science.1259855

Tito-Velarde, C., and Wanderley, F. (2021). *Contribución de la agricultura familiar campesina e indígena a la producción y consumo de alimentos en Bolivia*. La Paz, Bolivia: Cuadernos de Investigación. CIPCA; IISEC-UCB.

Torma, S., Vilček, J., Lošák, T., Kužel, S., and Martensson, A. (2018). Residual plant nutrients in crop residues–an important resource. *Acta Agric. Scand. Sect. B —. Soil & Plant Sci.* 68, 358–366. doi:10.1080/09064710.2017.1406134

Trimmer, J. T., and Guest, J. S. (2018). Recirculation of human-derived nutrients from cities to agriculture across six continents. *Nat. Sustain.* 1, 427–435. doi:10.1038/s41893-018-0118-9

UN (2019). *World population prospects [WWW Document]*. United Nations Department of Economics and Population Affairs–Population Dynamics. URLAvailable at: https://population.un.org/wpp/ (accessed 27 2, 22).

Un-Water (2021). *Summary Progress Update 2021 – SDG 6 – water and sanitation for all*. Geneva, Switzerland: United Nations Water.

van der Wiel, B. Z., Weijma, J., van Middelaar, C. E., Kleinke, M., Buisman, C. J. N., Wichern, F., et al. (2019). Restoring nutrient circularity: a review of nutrient stock and flow analyses of local agro-food-waste systems. *Resour. Conservation Recycl. X* 3, 100014. doi:10.1016/j.rcrx.2019.100014

van Puijenbroek, P., Beusen, A. H. W., and Bouwman, A. F. (2019). Global nitrogen and phosphorus in urban waste water based on the Shared Socio-economic pathways. *J. Environ. Manag.* 231, 446–456. doi:10.1016/j.jenvman.2018.10.048

Vasiljev, A., Simha, P., Demisse, N., Karlsson, C., Randall, D. G., Vinnerås, B., et al. (2022). Drying fresh human urine in magnesium-doped alkaline substrates: Capture of free ammonia, inhibition of enzymatic urea hydrolysis & minimisation of chemical urea hydrolysis. *Chem. Eng. J.* 428, 131026. doi:10.1016/j.cej.2021.131026

Verbyla, M. E., Symonds, E. M., Kafle, R. C., Cairns, M. R., Iriarte, M., Mercado Guzmán, A., et al. (2016). Managing microbial risks from indirect wastewater reuse for irrigation in urbanizing watersheds. *Environ. Sci. Technol.* 50, 6803–6813. doi:10.1021/acs.est.5b05398

Vinnerås, B., Palmquist, H., Balmér, P., and Jönsson, H. (2006). The characteristics of household wastewater and biodegradable solid waste—a proposal for new swedish design values. *Urban Water J.* 3, 3–11. doi:10.1080/15730620600578629

Zhang, X., Davidson, E. A., Zou, T., Lassaletta, L., Quan, Z., Li, T., et al. (2020). Quantifying nutrient budgets for sustainable nutrient management. *Glob. Biogeochem. Cycles* 34, e2018GB006060. doi:10.1029/2018gb006060

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Water and nutrient recovery from stored urine by forward osmosis with an ammonium bicarbonate draw solution

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Forward osmosis with an ammonium bicarbonate draw solution was investigated as a low energy non-sewered sanitation solution, to recover nutrients and water from source separated urine. Stored urine collected from Urine Diversion Dry Toilets in the eThekwini Municipality (Durban), South Africa was used as the feed solution. Water recoveries of up to 45.9% with water fluxes up to 6.0 L m^{-2} h^{-1} were achieved using undiluted stored urine over an 8-h operating period with a 2.5 M draw solution. Rejections of up to 95% for phosphates, 85% for nitrogen and chlorides, and 75% for potassium and sodium were achieved. Low fouling of the membrane was observed after multiple runs and cleaning the membrane by circulation of deionized water or by osmotic backwash was sufficient to recover >95% of the original water flux. Little irreversible fouling was detected, assumed to be caused by carbonate calcium scaling from SEM-EDX analysis. This study suggests that forward osmosis with an ammonium bicarbonate solution could be integrated as a closed loop nutrient recycling technology for source separated urine with the prospect of clean water and draw solution recovery that could use waste heat from, for example, fecal sludge combustion.

KEYWORDS

fouling, membrane, non-sewered sanitation, rejections, resource recovery, water recovery

1 Introduction

The United Nations estimates that 46% of the global population lack safely managed sanitation (United Nations, 2020), due to the economic unfeasibility of a sewered wastewater treatment infrastructure in low-income countries where sewerage accounts for up to 84% of capital costs (Jung et al., 2018). In this circumstance, non-sewered sanitation alternatives exist, which act as containment for feces, urine and wash water. Eventually, this waste requires additional costly services such as emptying, transport and treatment for safe disposal and hence only 22% has been reported to be safely managed in the urban setting (Blackett et al., 2014). Such waste is rich in nutrients, organics and water, which provides direct opportunity for fertilizer, energy or water recovery, which could thereby present local prospects for an affordable sanitation chain (Onabanjo et al., 2016; Eshetu Moges et al., 2018; Larsen et al., 2021a).

With a world population estimated to reach 9.8 billion by 2030 (United Nations, 2017), demand for resources will increase proportionally. Particularly, fertilizers containing the macronutrients nitrogen, phosphorus and potassium (N, P, K respectively), will need to increase to ensure food security (Xie et al., 2016). Urine is a source for these nutrients and provides an alternative to synthesized nitrogenous fertilizer compounds from the Haber-Bosch process, potash from rock salt deposits geographically constrained to the Northern Hemisphere and phosphates from finite rock deposits of increasingly lower grade (Skorina and Allanore, 2015; Randall and Naidoo, 2018). Urine contains 80% and 50% of the polluting nutrients, nitrogen and phosphorus, in domestic wastewater, while contributing only 1% of volumetric flow (Larsen and Gujer, 1996). By containing urine's abundant source of nutrients at 10–12 g/L nitrogen, 0.1–0.5 g/L phosphorous and 1.0–2.0 g/L potassium (Patel et al., 2020) through passive separation from feces at the toilet interface (source separation), the nutrient polluting potential of wastewater is reduced and contained in a smaller volume for potential recovery opportunities. In addition, solid-liquid separation is achieved which reduces dewatering requirements in the solids fraction and immediate fecal separation mitigates pathogenic risk for water recovery in the liquid fraction. As such, source separated urine has been identified to contribute to multiple Sustainable Development Goals (SDGs), including zero hunger (SDG 2), water and sanitation for all (SDG 6), and nutrient pollution mitigation (SDG 14) (Larsen et al., 2021a).

The recovery of nutrients from urine has been demonstrated by a range of physical, chemical, and biological processes (Larsen et al., 2021b). Although effective, such processes either possess are limited selectivity to one or two nutrients (precipitation, adsorption, ammonia stripping, membrane distillation, microbial fuel cells, microbial electrolysis cells); or are energetically demanding (reverse osmosis, nanofiltration); require a large footprint (algal growth); are limited by concentration factor (electrodialysis) or do not provide prospects for water recovery (ion exchange, heat drying, freeze drying) (Patel et al., 2020; Larsen et al., 2021b).

An alternative technology for concentrating multiple nutrients in urine is forward osmosis (FO) membrane filtration, which also provides prospects for water recovery, using analogous semipermeable reverse osmosis membranes, applied for potable water reuse from wastewater (Pype et al., 2016; Davey, Thomas and McAdam., 2022). The osmotic pressure differential between the feed solution (FS) and draw solution (DS) provides the driving force for separation, thus reducing energy requirements when compared to reverse osmosis. This also allows for a more fouling resilient process, as water transport occurs by diffusion instead of advection (Siddiqui et al., 2018).

Previous studies have investigated the use of FO for urine volume reduction, to decrease transport costs and protect nutrient sensitive environments such as caves during exploration (Nikiema et al., 2017; Engelhardt et al., 2020), or to recover nutrients such as ammonium (Engelhardt et al., 2019; Ray et al., 2020), urea (Engelhardt et al., 2019), nitrogen (Zhang et al., 2014; Nikiema et al., 2017; Volpin et al., 2018; Volpin et al., 2019a), phosphorus (Zhang et al., 2014; Volpin et al., 2018; Volpin et al., 2019b), and potassium (Zhang et al., 2014). Despite promising nutrient concentration and water flux results, previous studies have employed a DS where permeated water separation from the DS is challenging for clean water recovery (i.e. sodium chloride, glucose, fertilizer blend or brine). Instead, researchers have investigated the prospect of FO integrated with thermally driven MD, whereby the MD process reconcentrates the DS and generates clean water from low grade heat (Liu et al., 2016; Volpin et al., 2019a; Ray et al., 2019). Ammoniacal nitrogen co-transport from urine can however be a challenge for MD permeate quality as ammonia is highly volatile (vapour pressure of 7,500 mmHg compared to 24 mmHg of water at 25°C), and therefore at reduced permeate vapour pressures and high feed temperatures used for thermally driven processes, its transport is encouraged over water (El-Bourawi et al., 2007). Additional measures such as feed acidification to convert ammonia to non-volatile ammonium, thicker membranes and feed dilutions are then required to mitigate its transport (Volpin et al., 2019a; Ray et al., 2019). Ammonium bicarbonate as a DS could represent an alternative water recovery method without the need of a downstream membrane process, as it can be decomposed into ammonia and carbon dioxide by moderate heating (<60°C). Hence, a scenario could be depicted where urine is treated for nutrient and water recovery by FO and the ammonium bicarbonate DS is subsequently decomposed and recaptured to regenerate the DS for further urine filtration This is advantageous over conventional distillation and evaporation/alkaline dehydration with condensation processes as: 1) the FO membrane provides a selective barrier for water recovery, able to reject urine micropollutants and achieve compliance in high strength wastewaters (e.g., blackwater) (Valladares Linares et al., 2011; Davey, Thomas and McAdam, 2022) and 2) Heating is targeted at volatile gas decomposition, rather than water vapour recovery through evaporation and therefore requires less heat energy than the latent heat of vaporization. However, FO could also be integrated with such volume reducing thermal processes as a pre-treatment, to enhance water quality. Ammonium bicarbonate provides a cheaper solute than sodium chloride at a similar osmotic pressure (Johnson et al., 2018) and has been explored for seawater desalination (Feng et al., 2018), acid mine drainage treatment (Vital et al., 2018), textile wastewater treatment (Wang et al., 2020), among other possible applications. However, to the best of the authors' knowledge the use of ammonium bicarbonate as a DS has not been reported for urine treatment.

TABLE 1 Composition of the stored urine used in this study.

Parameter	Units	Range	Mean
pH		7.8–10	8
Conductivity	(mS cm−1)	25–33	29
Total Phosphates (TP)	mg L−1	1770–1800	1773
Potassium (K+)	mg L−1	1,478–1,500	1,488
Total Nitrogen (TN)	mg L−1	4,830–4,980	4,870
Magnesium (Mg2+)	mg L−1	24–25	24.5
Calcium (Ca2+)	mg L−1	9–11	10
Chloride (Cl–)	mg L−1	3,100–3,300	3,200
Sulfate (SO42-)	mg L−1	1,500	—
Total Suspended Solids (TSS)	mg L−1	318–328	323
Chemical Oxygen Demand (COD)	mg L−1	6,000	—

South Africa provides an ideal case study for trialing FO with an ammonium bicarbonate DS. Firstly, source separation has been implemented as Urine Diversion Dry Toilets (UDDTs) in the communities without sewered sanitation access (Durban municipality). Secondly, during the storage of urine in UDDTs, urea hydrolysis occurs Eq (1) facilitated by the urease enzyme (Hellström et al., 1999). This results in ammonium being formed Eq (2) and a pH increase to > pH 8, thus converting ammonium to volatile free ammonia (pKa = 9.24).

$$CO(NH_2)_2 + 3H_2O \rightarrow 2NH_4^+ + HCO_3^- + OH^- \quad (1)$$

$$NH_4^+ + OH^- \leftrightarrow NH_{3(aq)} + H_2O \quad (2)$$

Although nutrient concentrations are slightly lower in hydrolyzed urine compared to fresh (Larsen et al., 2021b), the removal of urea and free ammonia is beneficial for FO rejection capabilities. Both compounds are low molecular weight uncharged compounds which bypass the electrostatic repulsion mechanism of the membrane (Lee and Lueptow, 2001). Thirdly, South Africa persistently experiences low crop yields (i.e., maize) due to geographic constraints of nutrient limited soils and water scarcity (Choruma et al., 2021).

This study aims to assess the suitability of ammonium bicarbonate as an alternative FO DS for the recovery of water and nutrients from source separated urine from UDDTs in South Africa with the specific objectives: 1) to identify the optimum DS and FS concentrations for water flux; 2) to evaluate the rejection of key macronutrients (P, K, N) and 3) to determine fouling propensity and reversibility.

2 Materials and methods

2.1 Feed and draw solutions

Stored hydrolyzed urine (Table 1) collected from Urine Diverting Dry Toilet (UDDT) in the eThekwini Municipality in Durban, South Africa, was used in this study as the feedstock (ethical clearance: BREC/00002684/2021). Urine was also diluted to simulate typical flushing scenarios from urine diversion toilets where flush volumes range between 0.5 and 2 L (von Münch and Winker, 2011). Assuming a urine volume of ~300 ml (Haylen et al., 1989), dilution factors of 3 and 6 were prepared accordingly using deionized water.

Ammonium bicarbonate DS were prepared for each test run using distilled water and analytical grade ammonium bicarbonate. Draw solution concentrations of 0.6, 1.0, 2.0, 2.2, and 2.5 M ammonium bicarbonate solution were used in this study.

2.2 Forward osmosis experimental setup

Thin film composite (TFC) membranes (*OsMem™* TFC-ES, Hydration Technology Innovations) comprised of a polyamide active layer placed on the top of a thick microporous polysulfone support layer were employed in this study, due to their reported higher water fluxes and lower reverse solute flux (Kedwell et al., 2018; Almoalimi and Liu, 2022). The membrane supports a maximum operating temperature of 71°C and a maximum transmembrane pressure of 70 kPa. The pH of the solutions should be in the range of 2–11 and this high pH tolerance justified use of the TFC membrane for stored urine. Membrane sheets were immersed in deionized water before experiments as recommended by the membrane manufacturer. The membrane was supported in a *SEPA* crossflow membrane cell which allowed for tangential flow of both solutions (draw and feed) across the membrane. The cell was characterized by an effective filtration area of 140 cm^2, and a channel width and depth of 95.25 mm and 1.91 mm, respectively.

The membranes were operated in the AL-FS (Active Layer facing Feed Solution) orientation as this configuration minimized reverse solute flux in comparison to AL-DS (Active Layer facing Draw Solution), according to a baseline test using a 0.36 M sodium chloride solution FS with a 2 M ammonium bicarbonate DS over a period of 4 h. The measurements indicated a reverse solute flux of 4 ± 0.3 and 7.1 ± 0.1 g of ammonium bicarbonate per L of permeated water across the membrane in the AL-FS and AL-DS mode, respectively.

Feed and DS (1 L starting volume) were circulated at a cross flow velocity of 0.05 m s^{-1} (Figure 1). The solutions were maintained at 22°C ± 0.1°C using a *Grant* TC120 thermostatic bath and continuously mixed with magnetic stirrers whilst sealed to ensure no loss of NH_4-N as NH_3 gas. The pH and conductivity of the FS as well as the pH of the DS were continuously measured through a probe *Hach MM150*, whilst the mass of both the feed and DS were measured on a *Kern* precision balance connected to a computer to log the data every two hours. Samples (5 ml) were taken every two hours during 8 h runs for chemical analysis. All FO runs were carried out in triplicate with new membranes for each run to evaluate the reproducibility of the results.

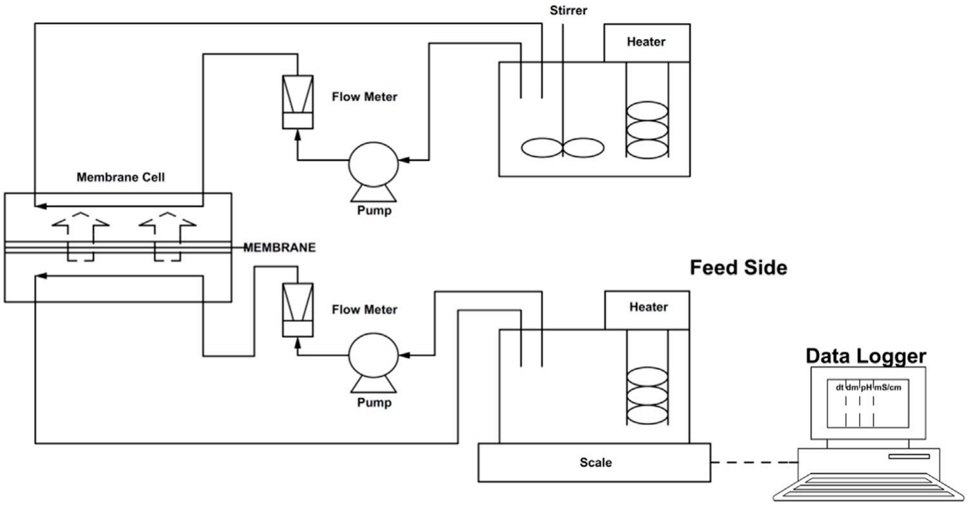

FIGURE 1
Forward osmosis experimental setup.

2.3 Chemical analysis

The following parameters were tracked during the FO runs: sodium (Na^+), calcium (Ca_2^+), magnesium (Mg_2^+), potassium (K^+), chloride (Cl^-), sulfates (SO_4^{2-}) total nitrogen (TN) and total phosphates (TP). Sodium and chloride concentrations allowed for the initial characterization of the membrane rejections during the baseline runs. Potassium, total phosphates and total nitrogen concentrations were monitored due to their significance as agricultural supplements, while calcium, magnesium and sulfates gave an indication of precipitation that would have occurred during hydrolysis of urine. The feed and draw solutions were analyzed by concentrations and volume over time to calculate a mass balance and evaluate membrane rejections. The ions concentration (Ca^+, Na^+, Mg^{2+}, K^+) were determined using an Agilent 4,200 Microwave-Plasma Atomic Emission Spectroscopy, whilst the total phosphates total nitrogen, ammonical nitrogen and sulfates were determined using a Merck Pharo 300 Spectroquant. Chloride analysis was carried out using a Sherwood Scientific 926 chloride analyzer.

2.4 Water flux, solute rejection, and osmotic pressure calculations

Water flux was calculated from the mass change of the FS over time, considering the density of water and area of the membrane Eq. (3):

$$J_w = \frac{\Delta W}{\rho\, A\, \Delta t} \tag{3}$$

Where J_w represents the water flux ($L{\cdot}m^{-2}{\cdot}h^{-1}$), ΔW is the mass change in FS (kg), ρ is the water density ($kg{\cdot}L^{-1}$), A is the membrane area (m^2) and Δt is the time interval between measurements (h). Overall permeate recovery R to the DS was calculated as a volume percentage at the end of each run according to Eq (4):

$$R = \frac{V_p}{V_f} \times 100\% \tag{4}$$

Where V_p is the permeate volume (L) and V_f is the initial FS volume (L). Solute rejections were determined through Eq (5) based on the chemical analysis of the samples taken every two hours from the feed and DS.

$$R(t_i) = \left[1 - \frac{C_{s(t_i)}}{C_{f(t_i)}}\right] \tag{5}$$

Where $R(t_i)$ represents solute rejection at the time t_i (-), $C_{f(t_i)}$ is the solute concentration in the FS at t_i ($mg{\cdot}L^{-1}$), and $C_{s(t)}$ is the solute concentration in the permeate at t_i ($mg{\cdot}L^{-1}$). The solute concentration in the permeate was calculated through a mass balance by Eq (6) (Abousnina and Nghiem, 2014):

$$C_{s(t_i)} = \frac{C_{ds(t_i)}V_{ds(t_i)} - C_{ds(t_{i-1})}V_{ds(t_{i-1})}}{V_{w(t_i)}} \tag{6}$$

Where $C_{ds(t_i)}$ is the solute concentration in the DS at time t_i ($mg{\cdot}L^{-1}$), $C_{ds(t_{i-1})}$ is the solute concentration in the DS at time t_{i-1} ($mg{\cdot}L^{-1}$), $V_{w(t_i)}$ is the permeate volume of water to the DS at time t_i (L), $V_{ds(t_i)}$ is the volume of DS at time t_i (L) and $V_{ds(t_{i-1})}$ is the volume of DS at time t_{i-1} (L).

Osmotic pressure of the feed and DS were determined from the measured concentrations of ionic species using PHREEQC™

software, which is a program based on the calculation of equilibrium chemistry of aqueous solutions.

2.5 Membrane cleaning and fouling evaluation

Comparison of the water flux through the virgin membrane, fouled membrane (after several FO runs with undiluted stored urine accumulating to 48 h and a processed flux of 108.6 L m^{-2}) and cleaned membrane can be used to evaluate the fouling and flux recovery through cleaning. Two cleaning methods were evaluated to test the fouling reversibility of the membranes after a run: the circulation of deionized water at higher flow rates, and the utilization of an osmotic backwash.

The first method involved cleaning the used membrane by circulation of deionized water on both sides of the FO rig for 30 min. Osmotic backwashing was also conducted on fouled membranes, whereby ammonium bicarbonate was circulated on FS side and distilled water on the DS side. This configuration leads to the inverse of the osmotic pressure gradient across the membrane, leading to a water flow in opposite direction compared to the forward osmosis runs. This is expected to remove the foulant material deposited on the membrane surface. Osmotic backwashes were conducted with 1 and 2 M ammonium bicarbonate solutions for 30 and 60 min in each case (Kim et al., 2012). Prior to osmotic backwashing, all the feed and DS trapped within the system were drained to minimize the influence of residual salts on the osmotic pressure differential across the membrane. Care was taken to not disturb the membrane prior to the backwashing. On completion of the osmotic backwashing, the flux recovery was measured, to have an indication of the flux recovered and to compare with deionized water operation.

Virgin and cleaned membranes were observed using scanning electron microscopy (SEM) with a maximum resolution of 50 nm, to determine the deposition of foulants on the membrane after cleaning. This analysis was coupled with energy-dispersive X-ray spectroscopy (EDX) to perform chemical analyses on selected areas from the virgin and cleaned used membranes. Prior to the SEM observations, the membranes were dried at room temperature and then coated with a thin layer of platinum using a sputter coater (SC7620, Emitech, United Kingdom).

3 Results and discussion

3.1 Impact of draw and feed solutions on water flux

Feed and DS concentrations were investigated to identify conditions which improved water flux, for increased FS volume reduction and water recovery prospects. Ammonium bicarbonate DS ranging from 0.6 M to 2.5 M resulted in increasing water fluxes from 1.4 to 4.7 L m^{-2} h^{-1} (Figure 2), driven by a greater osmotic gradient between the feed and DS. It would be expected that this relationship increases linearly, however at 2 M the line gradient decreases from 2 to 0.7. This suggests that at DS concentration gradients greater than ~2 M, the onset of internal dilutive concentration polarization (ICP) occurs, whereby water accumulates within the support layer of an asymmetric membrane which in turn reduces the draw solute concentration at the membrane (Johnson et al., 2018). Several authors have reported this phenomenon in literature (McCutcheon et al., 2006; Le and Nunes, 2016). Therefore, 2 M was considered as the optimum DS concentration to be taken forward for further assessment. This concentration is also similar to Liu et al. (2016) who reported a water flux of 5.2 L m^{-2} h^{-1} using 2 M sodium chloride compared to 4.6 L m^{-2} h^{-1} with ammonium bicarbonate in this study.

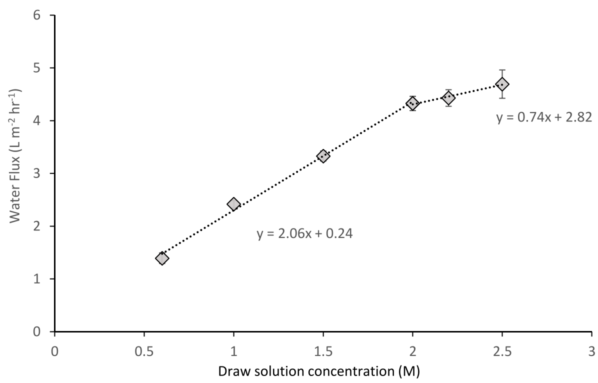

FIGURE 2
Influence of ammonium bicarbonate draw solution concentration on water flux using stored urine as a feed solution. Operated for 2 h at 22°C and a 0.05 m s^{-1} crossflow velocity. Error bars represent the standard deviation of a triplicated experiment.

As the experiments were operated in batch mode using 1 L draw and FS, water transport into the DS impacted the temporal water flux, due to the decline in osmotic gradient over time. Over an 8-h run using 2 M ammonium bicarbonate and stored urine, the transmembrane osmotic pressure decreased from 51.41 to 9.61 bar, which corresponded to water fluxes of 4.6 to 2.1 L m^{-2} h^{-1} (Figure 3). This decrease in the osmotic pressure gradient followed a logarithmic pattern, illustrating the declining rate in driving force and consequent water transport which is to be expected as the solutions verge towards equilibrium. Increasing the initial DS volume would prolong the solutions reaching equilibrium, thereby maintaining a higher osmotic pressure gradient/water flux and concentrating the FS at a faster rate. This attenuation of water flux decline by mitigating DS dilution was demonstrated by Xue et al. (2015), using a 2:1 DS:FS volume

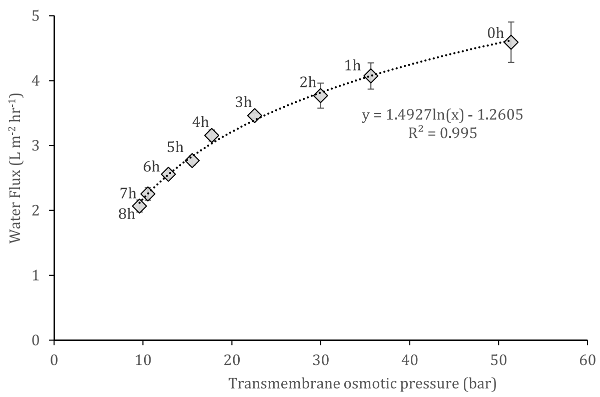

FIGURE 3
Temporal change in transmembrane osmotic pressure and its influence on water flux. Operated for 8 h at 22°C and a 0.05 m s^{-1} crossflow velocity. Feed and draw solutions are stored urine and 2 M ammonium bicarbonate respectively. Error bars represent the standard deviation of a triplicated experiment.

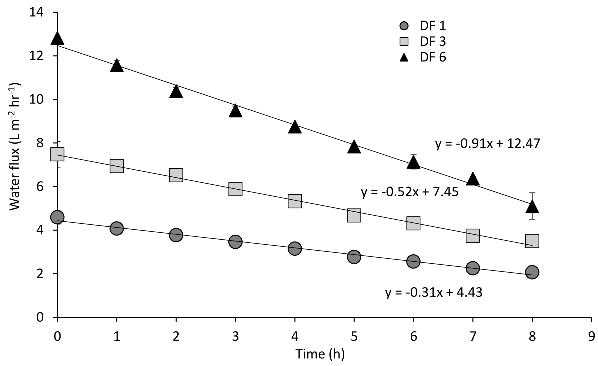

FIGURE 4
Impact of urine feed dilution on water flux over time. Urine was either undiluted (DF 1) or diluted by a factor of 3 (DF 3) or 6 (DF 6). Operated for 8 h at 22°C and a 0.05 m s^{-1} crossflow velocity. Feed and draw solutions are stored urine and 2 M ammonium bicarbonate respectively. Error bars represent the standard deviation of a triplicated experiment.

ratio with seawater and wastewater, achieving a 93% water reduction and a 10 fold concentration factor.

The implications of urine FS dilution with flush water were assessed in Figure 4. Greater dilution factors (DF) decrease urine osmolality, leading to an increase in transmembrane osmotic pressure. This results in a greater water flux where a DF of 6 reached 12.8 L m^{-2} h^{-1} compared to 4.6 L m^{-2} h^{-1} of undiluted urine, at the start of the run. Temporally, the water flux declines faster with increasing DF factors (linear gradients of −0.91, −0.51 and −0.31 for DF 6, DF 3 and DF 1 respectively, Figure 4). These results suggest that flush water is advantageous for FO favoring water recovery, however limits volume reduction and nutrient concentration due to the increased operational times required (Volpin et al., 2019b). In addition, a higher amount of energy will be required in the regeneration step of the draw solution. Indeed, a higher volume of water on the draw solution side will need more thermal energy for its heating to the temperatures where the ammonium bicarbonate decomposes into carbon dioxide and ammonium (<60°C).

3.2 Rejection of key nutrients

The impact of water flux on key nutrient rejection was assessed on undiluted urine to understand the potential of combined water and nutrient recovery (Figure 5). Within an 8-h operating period, the membrane demonstrated high rejections of total phosphates (TP, 84%–94%), total nitrogen (TN, 72%–85%) and chloride (Cl^-, 70%–85%), followed by potassium (K^+, 39%–71%) and sodium (Na^+, 32%–68 %). It is also important to note that the less critical ions Ca^{2+} and SO_4^{2+} and CO_3^{2-} were completely rejected during the run. The observed high rejections for TP and Cl^- could be attributed to their ability to retard the reverse permeation of the negatively charged bicarbonate ions from the DS, resulting in electrostatic repulsion as also reported by Zhang et al. (2014), Liu et al. (2016), and Volpin et al. (2018). The PO_4^{3-} ion was particularly retained due to its larger size (molecular weight of 95 g mol-1 compared to 35 g mol-1 of Cl^-) aiding to steric hindrance associated to reduced membrane permeability (Zhang et al., 2014).

The membrane exhibited lower rejections of Na^+ and K^+, compared to Cl^-, TN, and TP. A possible explanation for the low rejections of Na^+ and K^+ might be the fact that the membrane might have assumed a more negative charge as the pH of the urine feed stock increased during the FO process. The increase in pH (pH 7.5–8.4) could be attributed to the back diffusion of the ammonium bicarbonate draw solutes. The baseline tests (0.36 M NaCl FS and 2 M NH_4HCO_3 DS) indicated an average reverse solute flux of 4 ± 0.3 g of ammonium bicarbonate per litre of permeated water. The assumed negative charge would have attracted more positive ions towards the membrane (higher partitioning) resulting in higher permeation rates towards the DS as also observed by Zhang et al. (2014). Potassium also has a high permeability due to a smaller hydrated radius than PO_4^{3-}, which has prevented high rejection in literature (Zhang et al., 2014; Ray et al., 2020). For the same reason, the small solute size of sodium has proven to be problematic as a NaCl DS, resulting in large reverse solute fluxes (Johnson et al., 2018).

Total nitrogen exists predominantly as ammonium ions in the stored hydrolyzed urine as the mean pH of the hydrolysed urine was pH 8 (Table 1), leading to only 4.39% ammonia because of a pKa of 9.34 at 22°C

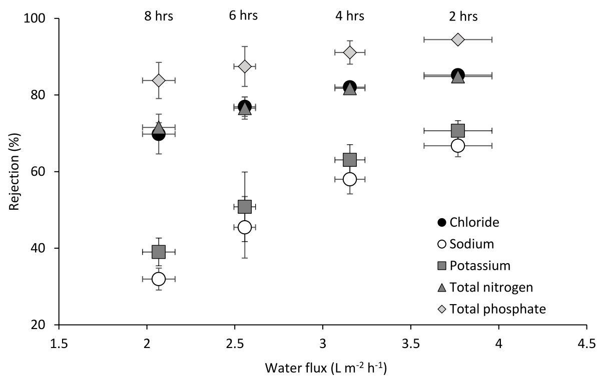

FIGURE 5
Relationship between water flux and nutrient rejection using stored urine and 2 M ammonium bicarbonate as the feed and draw solutions respectively. Operated for 8 h at 22°C and a 0.05 m s^{-1} crossflow velocity. Error bars represent the standard deviation of a triplicated experiment.

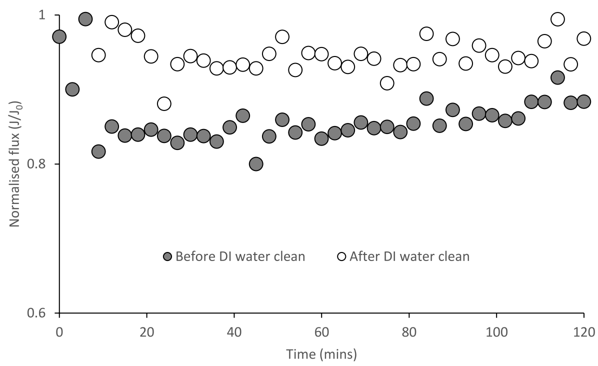

FIGURE 6
Normalised water flux with a virgin membrane (J_0) with respect to a used membrane (J) before and after membrane cleaning with deionized water. Operated for 2 h at 22°C and a 0.05 m s^{-1} crossflow velocity. Feed and draw solutions are deionized water and 2 M ammonium bicarbonate respectively.

(Emerson et al., 1975). Therefore, following the explanations for the observed high rejections for negative ions and low rejections for positive ions, coupled with being the smallest ion (molecular weight = 18 g mol^{-1}), we could expect the TN rejections to be low. However, the rejections are higher than that of K^+ and Na^+. This could be attributed to the reduced mass transfer gradient that exists between the feed and DS with respect to the ammonium. The DS (ammonium bicarbonate) contains more ammonium ions than the stored urine, resulting in a reduced mass transfer force for ammonium diffusion from the feed to the DS, hence the observed higher rejections compared to the other positively charged ions. This phenomenon explains why Na+, Cl^- and K^+ rejections are higher in other studies using NaCl and KH_2PO_4 as respective DS (Ray et al., 2020). Back diffusion could also be contributing to the enhanced TN FS concentrations (4 ± 0.3 g of ammonium bicarbonate per litre of permeated water). Therefore, the use of ammonium bicarbonate as a DS is particularly advantageous as a method for enhanced TN nutrient recovery, where TN is usually problematic to retain (Patel et al., 2020).

Generally, the rejections of nutrients declined with the water flux which decreased over time. This can be accounted for by the classical solution-diffusion theory, whereby the solute concentration gradient governs mass transfer. In the case of AL-FS FO, an increased co-transport of water dilutes the concentration of nutrients at the membrane interface (active layer and porous support) which results in a higher nutrient rejection (Zhang et al., 2014). The Na^+ and K^+ rejections decline the fastest with decreasing the water flux, which could be linked to the effect of their positive charge enhancing solute permeability compared to the negatively charged solutes.

3.3 Membrane fouling characterization and mitigation

Two *in situ* cleaning methods were evaluated for cleaning membranes to restore water flux after the same membrane sample was exposed to several forward osmosis runs with undiluted stored urine accumulating to 48 h and a processed flux of 108.6 L m^{-2}: deionized water circulation (Figure 6) and osmotic backwashing (Figure 7). The fluxes were determined over 2 h with deionized water and 2 M ammonium bicarbonate as the FS and DS respectively. After circulating deionized water for 30 min, a fouled membrane with a flux reduced to ~83% could be recovered to ~95% of the flux using a virgin membrane (Figure 6).

For the osmotic backwash cleaning method which is particularly effective in controlling particulate and organic fouling (Kim et al., 2012), the duration and DS concentration were evaluated. The flux recovery improved by increasing the osmotic gradient between the feed and DS (i.e., by increasing ammonium bicarbonate concentration), and by increasing the duration of the osmotic backwash (only at 1 M DS concentration). An increase in the osmotic gradient results in a greater reverse water flux that removes foulants from the membrane which achieved ~98% flux recovery at 2 M for 30 min. However, an unexpected decline in flux recovery during the fourth osmotic backwash after increasing the backwashing time to 60 min and ammonium bicarbonate concentration to 2 M was observed. This limit was also documented by Daly and Semiao (2020), who reported adhesive forces acting between the fouling layer and DS at high concentrations.

The foulants which could not be removed from DI water circulation and osmotic backwashing cleaning methods were examined using SEM and EDX analysis (Figure 8). The virgin

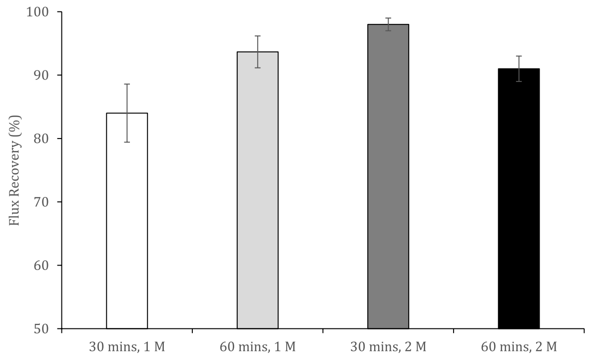

FIGURE 7
Flux recoveries observed after osmotic backwashing for 30 and 60 min, with 1 and 2 M ammonium bicarbonate as the feed solution and deionized water as the draw solution. Operated for 2 h at 22°C and a 0.05 m s^{-1} crossflow velocity. Error bars represent the standard deviation of a triplicated experiment.

membrane (Figures 8A,B) exhibited peaks of carbon, sulphur, and oxygen, which are the constituent elements of the membrane. Carbon has the highest content as it forms the backbone of the membrane structure. The membrane is composed of a TFC polyamide on polysulfone with an embedded polyester screen, which explains the O and S peaks. Through SEM observations, it was noted that some particulates remained linked to the membrane surface after cleaning (Figure 8C). Achilli et al. (2010), emphasized that the probability of mineral scale occurring on the membrane surface is enhanced when the FS is concentrated above the solubility limits of various water-soluble minerals. The FS for this work contained scale precursors such as magnesium, calcium, sulfate and bicarbonate ions. EDX analysis of the fouled membrane (Figure 8D) exhibited prevalent peaks of calcium, suggesting irreversible fouling by the deposition of bicarbonate on the membrane. In addition, sulfate fouling could occur, as this compound was completely rejected by the membrane and therefore prone to exceeding the solubility limits, causing scaling. However, the impact of irreversible foulants on the membrane was negligible for flux reduction during this study (3%–5% irreversible decline in flux), illustrating the low fouling propensity of the FO membranes and the ease of *in situ* membrane cleaning, which can significantly reduce the operating costs of the process.

4 Outlook—Prospects of draw solution regeneration and water recovery

The decomposition of ammonium bicarbonate solution upon moderate heating (<60°C) to yield ammonia and carbon dioxide gases and a water product can be summarized by the following equation:

$$NH_4HCO_3(aq) \rightleftharpoons NH_4^+(aq) + HCO_3^-(aq) \rightleftharpoons NH_3(g) + CO_2(g) + H_2O(\text{l}). \quad (7)$$

The use of a distillation column to initiate volatile compound separation and the diluted DS to reabsorb the gases downstream is a simple and proven method for the removal and recovery of volatile DS for seawater desalination applications (Kim et al., 2015). Pilot scale results from a desalination plant that utilized ammonium bicarbonate as a DS indicated that 265–300 kWh of thermal energy was needed to produce 1000 L of water (McGinnis et al., 2013; Kim et al., 2015). In the case of urine treatment, a low-grade heat source will be therefore enough to provide the thermal energy required to decompose ammonium bicarbonate in the draw solution. Different low-cost energy source options could provide the energy for the draw solution regeneration. One alternative could be using the faecal sludge from UDDTs (solid fraction) as biofuel.

Based on an individual's average daily defecation and urination (Rose et al., 2015), the faecal sludge and urine production rates in a UDDT would be 128 g wet solid $user^{-1}$ day^{-1} (or 32 g dry solid $user^{-1}$ day^{-1} considering the average moisture content of faeces of 75% and 1.4 L $user^{-1}$ day^{-1}, respectively (Rose et al., 2015). Assuming that the UDDT serves one individual, the annual faecal sludge and urine production will be around 12 kg dry solid and 500 L, respectively. Considering that the urine will be treated by a forward osmosis process with a water recovery of 50% (as observed after an 8-h run with the 2.5 M ammonium bicarbonate draw solution), an energy amount of 240–270 MJ would be required to regenerate the draw solution (based on the estimated thermal energy required to produce 1,000 L of water). Considering a calorific value of around 15 MJ kg^{-1} dry solids (Getahun, et al., 2020), combusting the UDDT sludge generated will liberate 175 MJ, which could cover part of the energy required for the regeneration of the draw solution.

Therefore, the solid fraction from source-separated toilets can be utilized as a fuel to decompose ammonium bicarbonate and ensure a closed loop in the recycling of the DS, which allows for an economically feasible process. However, additional energy may be required to fully regenerate the ammonium bicarbonate, which could be brought by adding other types of biomass or organic wastes to the sludge or by solar thermal energy. For example, co-incinerating the faecal sludge with 4 kg of food waste with a calorific value of approximately 23 MJ/kg (Ouadi et al., 2019), or adding a 0.1 m^2 solar water heater (typically yielding 450 kWh/m^2 of thermal energy (Zukowski et al., 2021)), to the system could suffice to provide the energy to decompose the ammonium carbonate in the draw solution and generate 250 L of reuse water per year and per person in the studied scenario.

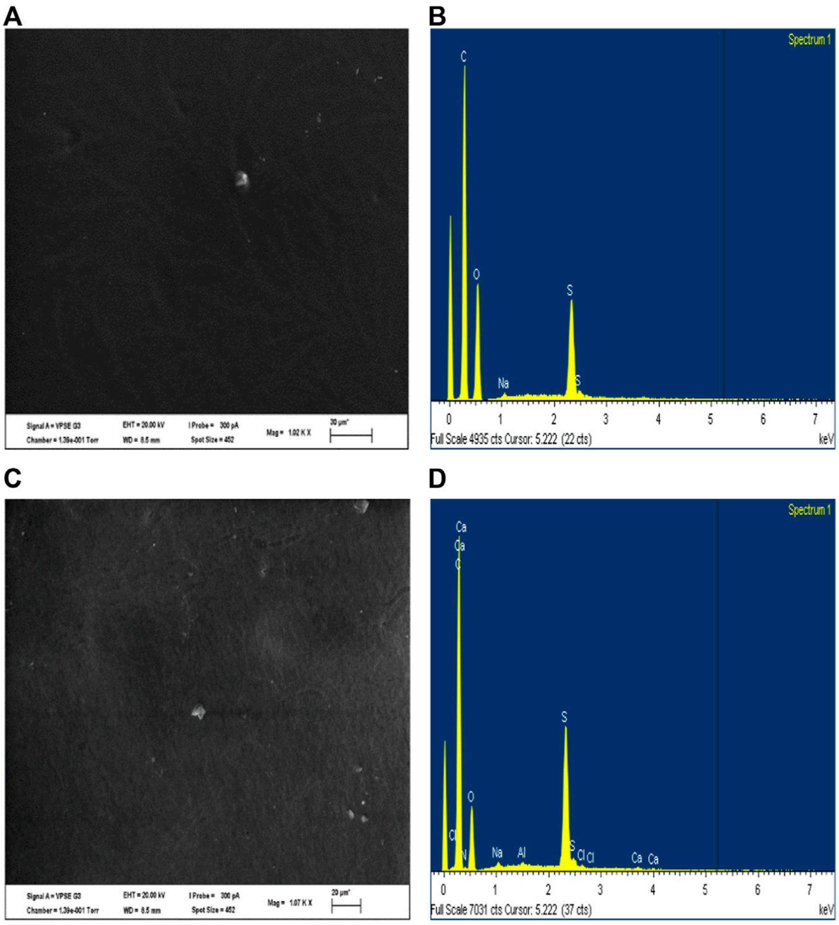

FIGURE 8
SEM observation and EDX analysis of the **(A,B)** virgin membrane and **(C,D)** fouled membrane after cleaning.

When comparing forward osmosis with an ammonium bicarbonate DS to other urine volume reducing processes, the energy consumption of the forward osmosis is lower than direct urine evaporation. For example, the evaporation of 250 L of water from urine will require a theoretical energy consumption of 565 MJ, which is distinctly higher than the energy required to recover the same amount of water from the forward osmosis process. FO also provides an additional passive selective barrier process for enhanced water quality. Reverse osmosis has a notably lower specific energy consumption for seawater desalination (2.5–4.0 kWh per 1000 L of produced water (Kim et al., 2019)) than forward osmosis. Nonetheless, reverse osmosis consumes energy in the form of electricity, requiring grid connection or a renewable power source (photovoltaic cells, wind turbines). In contrast, most of the energy consumption in the case of a forward osmosis setup would be in the form of heat, with a minimal need for electricity to run low-pressure pumps. The thermal energy requirements in a forward osmosis process could be easily supplied by the incineration of waste, allowing for the integration of a waste management component to urine treatment, and by solar thermal collectors, which are simpler to implement and lower cost than photovoltaic systems. Another advantage of forward osmosis is its robustness to fouling, as it would not necessitate urine pre-treatment and can handle higher salinity levels. Therefore, forward osmosis could be more suitable than reverse osmosis (particularly in South African where electricity interruptions are frequent), which is currently the desalination gold standard process.

With regards to water quality for recovered water (Table 2), the permeate already meets compliance to key chemical parameters (TP, TN and pH) stated in the ISO 30500 standard for non-sewered sanitation systems (International Organization for Standardization, 2018).

TABLE 2 Permeate water quality.

Parameter	Units	Mean ± SD	Range	ISO 30500 (2018) criteria
Na+	mg L^{-1}	203 ± 5		—
Cl−	mg L^{-1}	226 ± 12		—
TP	mg L^{-1}	60 ± 22		—
TP	% reduction		84–94	≤80 % reduction
TN	mg L^{-1}	346 ± 13		—
TN	% reduction		72–85	≤70 % reduction
K+	mg L^{-1}	203 ± 17		—
Conductivity	mS cm^{-1}	83 ± 6		—
pH		8.3 ± 0.1		6–9

Although not measured in this study, it can also be assumed that organics and faecal coliforms (also included in the standard), would be sufficiently rejected by FO due to the proven rejection of urine organics in literature (>97% rejection of total organic carbon, Liu et al., 2016), and dense membrane providing an absolute barrier to pathogens in a naturally sterile liquid.

5 Conclusion

This study evaluated the use of a novel volatile DS (ammonium bicarbonate) for the sustainable treatment of source separated urine with prospects of nutrient, water and DS regeneration. Ammonium bicarbonate as a DS for FO evidenced comparable water fluxes to literature using conventional NaCl (Liu et al., 2016). Up to 6 L m^{-2} h^{-1} was achieved with a FS of stored urine and a DS of 2.5 M ammonium bicarbonate, representing water recoveries of up to 46% by volume after 8 h. This allows for a significant volume reduction in the treated urine and the potential for recovery of reuse water through further processing of the DS. The water flux increased with urine DF or increased DS concentrations, due to greater osmotic pressure gradients. Internal concentration polarization was observed at DS concentrations >2 M, therefore operation using 2 M is advised to maximize water recovery efficiency.

Rejections of up to 95% of total phosphates, 85% of total nitrogen and chloride, and 70% of potassium and sodium were achieved. This would allow generating a concentrated FS rich in nutrients that could be used as fertilizer. The rejections were influenced by temporally reducing water fluxes. However, this could be controlled through increasing the DS volume in batch mode, thereby prolonging the osmotic gradient from reaching equilibrium. Ammonium in the DS also acted to retard the mass transfer of ammonium in the urine feed by reversing the concentration gradient, thereby enhancing rejection of the typically problematic nitrogenous compounds.

Forward osmosis exhibited a low fouling propensity with a water flux decrease of approximately 20% after a few uses. *In situ* membrane cleaning through circulation of deionized water on both the feed and draw sides could restore up to 95 % of the water flux for a fouled membrane, whilst osmotic backwashing of the membrane could achieve up to 98% flux recovery, with calcium, bicarbonate and sulfate detected as the causes of irreversible fouling.

This study has evidenced that an ammonium bicarbonate DS provides similar results to other well researched DS, for the treatment of stored urine using FO. However, its use provides additional benefits such as enhanced TN rejection and the prospect of closed loop nutrient recovery, water recovery and DS regeneration using low grade heat from fecal sludge combustion. Further research is required to develop a closed loop system which assesses recovered water quality against ISO 30500 (International Organization for Standardization, 2018) and integrates fecal combustion for DS regeneration. Long term trials are also warranted to assess the impacts of the organic and inorganic fractions of urine.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Biomedical Research Ethics Committee: BREC/00002684/2021. The patients/participants provided their written informed consent to participate in this study.

Author contributions

PJ, VK, SS and BA contributed to conception and design of the study. MA conducted the experiments. MA and ME performed data analysis. MA wrote the first draft of the manuscript. PJ, ME, VK, SS, and BA wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Abousnina, R. M., and Nghiem, L. D. (2014). Removal of dissolved organics from produced water by forward osmosis. *Desalination Water Treat.* 52 (4–6), 570–579. doi:10.1080/19443994.2013.827292

Achilli, A., Cath, T. Y., and Childress, A. E. (2010). Selection of inorganic-based draw solutions for forward osmosis applications. *J. Memb. Sci.* 364 (1), 233–241. doi:10.1016/j.memsci.2010.08.010

Almoalimi, K., and Liu, Y. Q. (2022). Enhancing ammonium rejection in forward osmosis for wastewater treatment by minimizing cation exchange. *J. Memb. Sci.* 648, 120365. doi:10.1016/J.MEMSCI.2022.120365

Blackett, I., Hawkins, P., and Heymans, C. (2014). *The missing link in sanitation service delivery: a review of faecal sludge management in 12 cities*. Washington D.C: World Bank Group.

Choruma, D. J., Balkovic, J., Pietsch, S. A., and Odume, O. N. (2021). Using EPIC to simulate the effects of different irrigation and fertilizer levels on maize yield in the Eastern Cape, South Africa. *Agric. Water Manag.* 254, 106974. doi:10.1016/j.agwat.2021.106974

Daly, S., and Semiao, A. J. C. (2020). Mechanisms involved in osmotic backwashing of fouled forward osmosis (FO) membranes. *J. Membr. Sci. Res.* 6 (2), 158–167. doi:10.22079/jmsr.2020.118843.1315

Davey, C. J., Thomas, N., and McAdam, E. J. (2022). Downscaling reverse osmosis for single-household wastewater reuse: towards low-cost decentralised sanitation through a batch open-loop configuration. *J. Water Reuse Desalination* 12, 191–205. doi:10.2166/wrd.2022.084

El-Bourawi, M. S., Khayet, M., Ma, R., Ding, Z., Li, Z., Zhang, X., et al. (2007). Application of vacuum membrane distillation for ammonia removal. *J. Membr. Sci.* 301 (1–2), 200–209. doi:10.1016/j.memsci.2007.06.021

Emerson, K., Russo, R. C., Lund, R. E., and Thurston, R. V. (1975). Aqueous ammonia equilibrium calculations: effect of pH and temperature. *J. Fish. Res. Bd. Can.* 32 (12), 2379–2383. doi:10.1139/f75-274

Engelhardt, S., Bender, K., Vogel, J., Duirk, S., Moore, F., and Barton, H. (2020). Urine volume reduction during long-duration cave exploration by a light-weight and portable forward osmosis system. *Int. J. Speleol.* 49, 229–234. doi:10.5038/1827-806X.49.3.2336

Engelhardt, S., Vogel, J., Duirk, S. E., Moore, F. B., and Barton, H. A. (2019). Urea and ammonium rejection by an aquaporin-based hollow fiber membrane. *J. Water Process Eng.* 32, 100903. doi:10.1016/j.jwpe.2019.100903

Eshetu Moges, M., Todt, D., and Heistad, A. (2018). Treatment of source-separated blackwater: a decentralized strategy for nutrient recovery towards a circular economy. *Water* 104, 463. doi:10.3390/w10040463

Feng, L., Xie, L., Suo, G., Shao, X., and Dong, T. (2018). Influence of temperature on the performance of forward osmosis using ammonium bicarbonate as draw solute. *Trans. Tianjin Univ.* 24 (6), 571–579. doi:10.1007/s12209-018-0159-1

Getahun, S., Septien, S., Mata, J., Somorin, T., Mabbett, I., Buckley, C., et al. (2020). Drying characteristics of faecal sludge from different on-site sanitation facilities. *J. Environ. Manage.* 261, 110267. doi:10.1016/j.jenvman.2020.110267

Haylen, B. T., Ashby, D., Sutherst, J. R., Frazer, M. I., and West, C. R. (1989). Maximum and average urine flow rates in normal male and female populations-the liverposl nomograms. *Br. J. Urol.* 64, 30–38. doi:10.1111/j.1464-410x.1989.tb05518.x

Hellström, D., Johansson, E., and Grennberg, K. (1999). Storage of human urine: acidification as a method to inhibit decomposition of urea. *Ecol. Eng.* 12 (3), 253–269. doi:10.1016/S0925-8574(98)00074-3

International Organization for Standardization (2018). Non–sewered sanitation systems–Prefabricated integrated treatment units–General safety and performance requirements for design and testing (ISO 30500: 2018 (E)). Available at: https://www.iso.org/standard/72523.html.

Johnson, D. J., Suwaileh, W. A., Mohammed, A. W., and Hilal, N. (2018). Osmotic's potential: an overview of draw solutes for forward osmosis. *Desalination* 434, 100–120. doi:10.1016/j.desal.2017.09.017

Jung, Y. T., Narayanan, N. C., and Cheng, Y.-L. (2018). Cost comparison of centralized and decentralized wastewater management systems using optimization model. *J. Environ. Manage.* 213, 90–97. doi:10.1016/j.jenvman.2018.01.081

Kedwell, K. C., Quist-Jensen, C., Giannakikis, G., and Christensen, M. L. (2018). Forward osmosis with high-performing TFC membranes for concentration of digester centrate prior to phosphorus recovery. *Sep. Purif. Technol.* 197, 449–456. doi:10.1016/j.seppur.2018.01.034

Kim, C., Lee, S., and Hong, S. (2012). Application of osmotic backwashing in forward osmosis: mechanisms and factors involved. *Desalination Water Treat.* 43 (1–3), 314–322. doi:10.1080/19443994.2012.672215

Kim, J., Park, K., Yang, D. R., and Hong, S. (2019). A comprehensive review of energy consumption of seawater reverse osmosis desalination plants. *Appl. Energy* 254, 113652. doi:10.1016/j.apenergy.2019.113652

Kim, Y., Lee, J. H., Kim, Y. C., Lee, K. H., Park, I. S., Park, S.-J., et al. (2015). Operation and simulation of pilot-scale forward osmosis desalination with ammonium bicarbonate. *Chem. Eng. Res. Des.* 94, 390–395. doi:10.1016/j.cherd.2014.08.015

Larsen, T. A., Gruendl, H., and Binz, C. (2021a). The potential contribution of urine source separation to the SDG agenda – A review of the progress so far and future development options. *Environ. Sci. Water Res. Technol.* 7 (7), 1161–1176. doi:10.1039/D0EW01064B

Larsen, T. A., Riechmann, M. E., and Udert, K. M. (2021b). State of the art of urine treatment technologies: a critical review. *Water Res. X* 13, 100114. doi:10.1016/j.wroa.2021.100114

Larsen, T., and Gujer, W. (1996). Separate management of anthropogenic nutrient solutions (human urine). *Water Sci. Technol.* 34 (3–4), 87–94. doi:10.2166/wst.1996.0420

Le, N. L., and Nunes, S. P. (2016). Materials and membrane technologies for water and energy sustainability. *Sustain. Mater. Technol.* 7, 1–28. doi:10.1016/j.susmat.2016.02.001

Lee, S., and Lueptow, R. M. (2001). Membrane rejection of nitrogen compounds. *Environ. Sci. Technol.* 35, 3008–3018. doi:10.1021/es0018724

Liu, Q., Liu, C., Zhao, L., Ma, W., Liu, H., Ma, J., et al. (2016). Integrated forward osmosis-membrane distillation process for human urine treatment. *Water Res.* 91, 45–54. doi:10.1016/j.watres.2015.12.045

McCutcheon, J. R., McGinnis, R. L., and Elimelech, M. (2006). Desalination by ammonia–carbon dioxide forward osmosis: influence of draw and feed solution concentrations on process performance. *J. Memb. Sci.* 278 (1), 114–123. doi:10.1016/j.memsci.2005.10.048

McGinnis, R. L., Hancock, N. T., Nowosielski-Slepowron, M. S., and Mcgurgan, G. (2013). Pilot demonstration of the NH_3/CO_2 forward osmosis desalination process on high salinity brines. *Desalination* 312, 67–74. doi:10.1016/j.desal.2012.11.032

Nikiema, B. C. W.-Y., Ito, R., Guizani, M., and Funamizu, N. (2017). Estimation of water flux and solute movement during the concentration process of hydrolysed urine by forward osmosis. *J. Water Environ. Technol.* 15 (5), 163–173. doi:10.2965/jwet.16-074

Onabanjo, T., Kolios, A. J., Patchigolla, K., Wagland, S. T., Fidalgo, B., Jurado, N., et al. (2016). An experimental investigation of the combustion performance of human faeces. *Fuel* 184, 780–791. doi:10.1016/j.fuel.2016.07.077

Ouadi, M., Bashir, M. A., Speranza, L. G., Jahangiri, H., and Hornung, A. (2019). Food and market waste–a pathway to sustainable fuels and waste valorization. *Energy fuels.* 33 (10), 9843–9850. doi:10.1021/acs.energyfuels.9b01650

Patel, A., Mungray, A. A., and Mungray, A. K. (2020). Technologies for the recovery of nutrients, water and energy from human urine: a review. *Chemosphere* 259, 127372. doi:10.1016/j.chemosphere.2020.127372

Pype, M. L., Lawrence, M. G., Keller, J., and Gernjak, W. (2016). Reverse osmosis integrity monitoring in water reuse: the challenge to verify virus removal – a review. *Water Res.* 98, 384–395. doi:10.1016/J.WATRES.2016.04.040

Randall, D. G., and Naidoo, V. (2018). Urine: the liquid gold of wastewater. *J. Environ. Chem. Eng.* 6 (2), 2627–2635. doi:10.1016/j.jece.2018.04.012

Ray, H., Perreault, F., and Boyer, T. H. (2020). Ammonia recovery from hydrolyzed human urine by forward osmosis with acidified draw solution. *Environ. Sci. Technol.* 54 (18), 11556–11565. doi:10.1021/acs.est.0c02751

Ray, H., Perreault, F., and Boyer, T. H. (2019). Urea recovery from fresh human urine by forward osmosis and membrane distillation (FO–MD). *Environ. Sci. Water Res. Technol.* 5 (11), 1993–2003. doi:10.1039/C9EW00720B

Rose, C., Parker, A., Jefferson, B., and Cartmell, E. (2015). The characterization of feces and urine: a review of the literature to inform advanced treatment technology. *Crit. Rev. Environ. Sci. Technol.* 45 (17), 1827–1879. doi:10.1080/10643389.2014.1000761

Siddiqui, F. A., She, Q., Fane, A. G., and Field, R. W. (2018). Exploring the differences between forward osmosis and reverse osmosis fouling. *J. Memb. Sci.* 565, 241–253. doi:10.1016/j.memsci.2018.08.034

Skorina, T., and Allanore, A. (2015). Aqueous alteration of potassium-bearing aluminosilicate minerals: from mechanism to processing. *Green Chem.* 17 (4), 2123–2136. doi:10.1039/C4GC02084G

United Nations (2020). SDG 6 overview. Available at: https://sdgs.un.org/goals/goal6 (Accessed November 10, 2021).

United Nations (2017). *World population prospects: the 2017 revision, key findings and advance tables*. New York: United Nations.

Valladares Linares, R., Yangali-Quintanilla, V., Li, Z., and Amy, G. (2011). Rejection of micropollutants by clean and fouled forward osmosis membrane. *Water Res.* 45 (20), 6737–6744. doi:10.1016/j.watres.2011.10.037

Vital, B., Bartacek, J., Ortega-Bravo, J. C., and Jeison, D. (2018). Treatment of acid mine drainage by forward osmosis: heavy metal rejection and reverse flux of draw solution constituents. *Chem. Eng. J.* 332, 85–91. doi:10.1016/j.cej.2017.09.034

Volpin, F., Chekli, L., Phuntsho, S., Cho, J., Ghaffour, N., Vrouwenvelder, J. S., et al. (2018). Simultaneous phosphorous and nitrogen recovery from source-separated urine: a novel application for fertiliser drawn forward osmosis. *Chemosphere* 203, 482–489. doi:10.1016/j.chemosphere.2018.03.193

Volpin, F., Chekli, L., Phuntsho, S., Ghaffour, N., Vrouwenvelder, J. S., Shon, H. K., et al. (2019a). Optimisation of a forward osmosis and membrane distillation hybrid system for the treatment of source-separated urine. *Sep. Purif. Technol.* 212, 368–375. doi:10.1016/j.seppur.2018.11.003

Volpin, F., Heo, H., Hasan Johir, M. A., Cho, J., Phuntsho, S., Shon, H. K., et al. (2019b). Techno-economic feasibility of recovering phosphorus, nitrogen and water from dilute human urine via forward osmosis. *Water Res.* 150, 47–55. doi:10.1016/j.watres.2018.11.056

von Münch, E., and Winker, M. (2011). *Technology review of urine diversion components*. Editor E. von Münch (Eschborn, Germany: Postfach: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH). Available at: http://www.susana.org/_resources/documents/default/2-875-giz2011-en-technology-review-urine-diversion.pdf (Accessed June 15, 2022).

Wang, S.-Y., Chen, Y.-F., Zhou, H., Xu, X.-H., and Cheng, L.-H. (2020). Calcium carbonate scaling in forward osmosis for textile reverse osmosis concentrate treatment. *J. Water Process Eng.* 35, 101181. doi:10.1016/j.jwpe.2020.101181

Xie, M., Shon, H. K., Gray, S. R., and Elimelech, M. (2016). Membrane-based processes for wastewater nutrient recovery: technology, challenges, and future direction. *Water Res.* 89, 210–221. doi:10.1016/j.watres.2015.11.045

Xue, W., Tobino, T., Nakajima, F., and Yamamoto, K. (2015). Seawater-driven forward osmosis for enriching nitrogen and phosphorous in treated municipal wastewater: effect of membrane properties and feed solution chemistry. *Water Res.* 69, 120–130. doi:10.1016/j.watres.2014.11.007

Zhang, J., She, Q., Chang, V. W. C., Tang, C. Y., and Webster, R. D. (2014). Mining nutrients (N, K, P) from urban source-separated urine by forward osmosis dewatering. *Environ. Sci. Technol.* 48 (6), 3386–3394. doi:10.1021/es405266d

Zukowski, M., Kosior-Kazberuk, M., and Blaszczynski, T. (2021). Energy and environmental performance of solar thermal collectors and PV panel system in renovated historical building. *Energies* 14, 217158. doi:10.3390/en14217158

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Health Benefits of Improved Latrine in Rural China

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Proper sanitation facilities promote health because they allow people to dispose of their waste appropriately. Since the founding of the People's Republic of China, the Chinese government has been committed to improving water and sanitation. The coverage of sanitary latrines in rural China reached more than 70.0% in 2022. Using published literature, open data, and national statistics, this study evaluated the health effects of improved latrines in China. A search strategy aimed at collecting all latrine improvement-related community intervention research in China from 1990 to 2021 was designed and implemented. Incidences of three diseases—schistosomiasis, diarrheal disease, and soil-transmitted helminths (STH)—were used as indicators of health benefits. The relationship between adjusted relative risk (RR) and coverage of sanitary latrines in the study area was examined using a log-linear model. Overall, 411 incidences of the three diseases before and after community intervention were extracted from 74 qualified articles. The results demonstrated the importance of promoting access to sanitary latrines in disease prevention and control in China. The overall estimates revealed mean reductions of 60% for diarrhea risk, 42% for schistosomiasis risk, and 65% for STH risk compared to no intervention. In addition, increasing sanitary latrine coverage was negatively correlated with RR in China, indicating that populations with high sanitary latrine coverage were less likely to be affected with water, sanitation, and hygiene-related diseases.

Keywords: latrine improvement, schistosomiasis, diarrheal, soil-transmitted helminth, meta-analysis

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1 INTRODUCTION

Poor excreta disposal is associated with cholera, typhoid, paratyphoid fevers, schistosomiasis, and hookworm disease, whereas proper sanitation facilities promote health because they allow people to dispose of their waste appropriately. Inadequate sanitation combined with contaminated water and poor hygiene is the leading cause of morbidity and mortality in low-income countries (WHO, 2021). In 2020, nearly half of the world's population lacked safely managed sanitation and 494 million people still defecated in the open (WHO/UNIFC, 2021). Moreover, 80% of infectious diseases, such as children's diarrhea and schistosomiasis, are caused by fecal pollution and unsafe drinking water, and environments with high fecal contamination put people at risk of long-term exposure to intestinal pathogens. Therefore, improvement of basic sanitation facilities is an important development goal in low- and middle-income countries (Deshpande et al., 2020).

Sanitation, especially sanitary latrines, can decrease the transmission of a variety of diseases (Reese et al., 2019). Indeed, improved latrines and sanitation can effectively stop most fecal–oral transmitted diseases (Pickering and Davis, 2012; Odagiri et al., 2016). Because human excreta may contain many types of pathogens and these pathogens can remain infectious for long periods when introduced into the environment, these pathogens can be transmitted to new victims in a number of ways and can therefore present a potential threat to human health (Wagner and Lanoix, 1958). Therefore, effective excreta management at the household and community levels plays important roles in protecting water resources and the food supply from fecal contamination (Fewtrell and Bartram, 2001). Related studies have shown that the popularization of sanitary latrines can directly and effectively prevent and control the incidence of some kinds of intestinal infectious diseases (Chen and Kallawicha, 2021). Moreover, increased sanitation latrine coverage can reduce the risk of exposure to fecal pathogens and can provide health benefits. Furthermore, associations between increased latrine coverage and reduced incidences of related diseases have been observed at the ecological level (Lin et al., 2020).

Improved sanitation facilities are defined as those that ensure hygienic separation of human excreta from human contact (UNICEF, 2018). For most countries, rural access to improved sanitation facilities typically lags behind urban areas (Hannah and Max, 2021; Wu et al., 2022). Goal 6 of the United Nations' proposed 2030 Sustainable Development Goals (SDGs) is to achieve access to adequate and equitable sanitation and hygiene for all and to end open defecation (UN, 2016). For most countries, open defecation in urban areas is typically below 20% of the population, but in rural areas, this can range from 20 to 90% (Hannah and Max, 2021). Therefore, there is an urgent need to further reduce gaps in access to improved drinking water and sanitation between rural and urban areas. At the global level, a series of programs have been designed to improve sanitation and hygiene with a focus on the needs of rural residents, women, girls, and school students. These programs focus on latrine construction, sanitation science and technology, community-led health education, and policy advocacy (Tumwine et al., 2003; Fewtrell et al., 2005; Banke et al., 2006; Strunz et al., 2014; Du et al., 2019; Patel et al., 2019; Rheinländer et al., 2019; Als et al., 2020; Darmstadt et al., 2020; Morse et al., 2020).

As one of the largest developing agricultural countries in the world, China has been continuously implementing measures to improve sanitation coverage (Li et al., 2022). Latrines were regarded as obscure and dirty things in Chinese culture because of the association with human excreta, although human excrement had always been the most common fertilizer in China's rural areas. After the establishment of the People's Republic of China (PRC) in the 1950's, the Patriotic Health Campaign (PHC) was launched to reduce disease and improve health conditions (Yang, 2004; Chen and Kallawicha, 2021). As one of the most important parts of the PHC, rural latrine improvement, which consists of measures aimed at providing sanitary latrines for households in China, has been continuously promoted by a series of policies, projects, and investments in the PHC. Now, "latrine improvement" has been updated to "latrine revolution," with the additional goal of creating sanitation infrastructure and public services that work for everyone while turning waste into a value product (Cheng et al., 2018) (Tao, 2019).

In the 1990s, the Chinese government listed coverage of rural sanitary latrines as China's primary health care index for measurement of attaining the goal of a minimum standard of health care for all residents by the year 2000 (WHO, 1981). In 2005, the government put forward the concept of "Building a New Socialist Countryside," which emphasized improvement of water and latrines and used the construction of biogas digesters to promote changes in latrines in rural areas (Feng et al., 2012). The portion of the population with improved environmental sanitation facilities in China increased from 48% in 1990 to 76% in 2015 (WHO/UNIFC, 2021), and China achieved the water and sanitation goals outlined in the Millennium Development Goals (MDGs) by 2015. According to Health China 2030 Program Planning, the goal of China's rural latrine revolution is to achieve 100% sanitary latrine coverage by 2030 (Dong et al., 2020).

Both latrine improvement and the latrine revolution have produced huge social, economic, and health benefits. In China, many epidemiological studies have focused on the health benefits of improved sanitation since the 1990's, especially those from improved latrines. At the national level, such benefits could be summarized based on the reduction of specific diseases (Esrey, 1996; Clasen et al., 2010; Chen and Kallawicha, 2021). The mortality of WASH-related diseases varies in different countries, and significant differences in the burden of disease (BOD) have been observed between countries. For example, the mortality of children under 5 years old caused by diarrheal diseases in Chad (499 deaths per 100,000) was much higher than that in some areas such as the United States (4 deaths per 100,000) in 2016 (GBD, 2018). Moreover, it is likely that the health benefits of WASH intervention vary in different countries. For example, a study in Tanzania (Young et al., 2007) revealed that improved sanitation could reduce the risk of *Ascaris lumbricoides* infection by 67%, while only reducing the risk by 32% in Nigeria (Asaolu et al., 2002). No such assessments have been conducted in China, despite its long-term rural toilet improvement plan.

We designed this system review to evaluate the health benefits of latrine improvement in China and obtain evidence-based results. Because there are many sanitation-related diseases, we selected three typical diseases, namely, schistosomiasis, diarrhea, and STH. These diseases were selected for the following reasons: 1) they were widely prevalent in the early days in China; 2) there were sufficient research articles associated with these diseases in China to conduct reviews; and 3) they are related to poor sanitation, including the lack of a sanitary latrine in households.

2 METHODS

2.1 Search Strategy

A search strategy was designed and implemented to collect all published and available literature on latrine improvement intervention and its effects on these three diseases in both Chinese and English. Preferred Reporting Items for Systematic

Reviews and Meta-Analyses (PRISMA) (Liberati et al., 2009) guidelines were followed when these systematic review and meta-analysis were conducted. A systematic database search of MEDLINE, Embase, and the Web of Science was conducted to identify potentially relevant English literature. At the same time, the China National Knowledge Infrastructure (CNKI), WanFang Data E-Resources, and VIP Journal Integration Platform were also searched for Chinese-language records. We defined two groups of key search terms: one including the three targeted diseases, "schistosomiasis," "bilharziasis," "diarrhea," "soil-transmitted helminth" (STH, including ascariasis, trichuriasis, hookworm [*Ancylostoma duodenale* and *Necator americanus*], and *Strongyloides stercoralis*) and their synonyms, and another including intervention information such as "latrine," "sanitation," "intervene," and their synonyms. Search terms and their synonyms were combined using the Boolean operator to capture as many documents as possible. The Boolean operator "or" was used to connect the keywords in the group, whereas "and" was used to connect the keywords between groups. The retrieved literature was limited to publication dates between 1990 and 2021.

2.2 Study Inclusion and Exclusion Criteria

We first filtered the articles according to title and abstract to ensure that they were not obviously beyond the scope of the review, after which we went to the next step of screening. We used the defined criteria to assess the eligibility of each retained article and extract data. The inclusion criteria were as follows: 1) the definition of the specific intervention measures and these measures, including the improved latrines. 2) The outcome indicators were measured by the occurrence of schistosomiasis, diarrhea, and STH. 3) The study design was required to consist of cross-sectional or community intervention experiments. The exclusion criteria were as follows: 1) latrine improvement was not included as an intervention measure; 2) studies were conducted in an outbreak background; and 3) control group data were not available.

Three researchers reviewed and screened all available titles and abstracts to identify potentially eligible records for full-text review. In the initial screening, only titles and abstracts were examined to avoid unintentional bias when looking at author names, publication types, and journal titles. On the basis of the content of the title and/or abstract, records of any latrine-related infection agent interventions that may have involved schistosomiasis, diarrhea, and STH were kept to exclude studies that did not meet the requirements of this step. In addition, two researchers reviewed all potentially eligible full-text records in accordance with the defined inclusion and exclusion criteria to determine eligibility for data extraction. If there was disagreement about the eligibility of the study at this stage, a third investigator was consulted and included in the discussion until a consensus was reached.

2.3 Data Extraction

Qualified studies were used for data extraction. A spreadsheet data entry table was designed to store data.

The major categories of the items coded included 1) study characteristics (such as author, year, language, and journal), 2) research object characteristics (such as age, quantity, crowd field, and region), 3) intervention characteristics (such as mode, starting year, ending year, and duration), and 4) outcome characteristics (such as disease types, diagnostic method, cases, and incidence).

All data were extracted from the original article independently by two researchers. Two researchers checked the completeness and accuracy of the extracted data, and if there was disagreement, another researcher participated in the discussion and made a decision. After the initial data extraction, one investigator performed a data cleanup and two researchers re-examined all of the final extracted data.

2.4 Data Processing

Relative risk (RR) was used to measure the effect size for each included study. RR, which was the incidence rate of the intervention group divided by the incidence rate of the control group (**Eq. 1**), indicated the relative risk of the intervention group and control group for a given disease. An RR value of less than 1 suggests that the intervention being considered is associated with a reduction in risk. Moreover, the lower the RR value is, the larger is the effect value (Massad et al., 2009). The Mantel–Haenszel method was then used to pool the effect sizes (Higgins et al., 2019). Inconsistency (i.e., heterogeneity) was assessed with Moran's I-squared before calculating the pooling effect sizes (Als et al., 2020). When the I-squared statistic was below 50%, the data were considered to have good heterogeneity and a fixed-effects model (FEM) was used; otherwise, a random-effects model (REM) was used (Coory, 2010). The 95% CI was calculated using the natural logarithm of RR and SE of RR (**Eq. 2**), and the SE was calculated based on the incidence in the intervention group and control group, as well as the n of the two groups (**Eq. 3**).

$$RR = (a/n_1)/(b/n_2) \tag{1}$$

$$95\%\,CI = \exp[\ln(RR) \pm 1.96 \times SE(lnRR)] \tag{2}$$

$$SE(lnRR) = sqrt(1/a + 1/b - 1/n_1 - 1/n_2) \tag{3}$$

In **Eq. 3**, a is the incidence in the intervention group, b is the incidence in the control group, n_1 is the total number of the intervention group, and n_2 is the total number of the control group. For this systematic review, latrine improvement was the primary sanitation exposure. This was defined as the use of any type of sanitary latrine, not a specific type. Moreover, because multiple intervention measures rather than individual measures such as latrine improvement were usually implemented to control schistosomiasis, our study compared the effects of different interventions. To accomplish this, the interventions were divided into five types from the perspective of ecology (**Table 1**). Latrine improvement and the combination of latrine improvement and these five types of interventions were compared using subgroup analysis. To reduce heterogeneity and avoid the impact of the already implemented interventions on the baseline, only studies from no intervention to the first year of intervention were included in the meta-analysis.

A linear model was used to examine the relationship between the sanitary latrine coverage rate and pooled RR. Because the coverage rate may change with the long duration of the included studies, this study focused on the incremental coverage, which was defined as the difference between the coverage rate at the end of the study and that at the beginning. Because not all coverage data of the included studies were available, provincial-level data were replaced when such coverage rates for the study area were not available (NHFPC, 2012; NHFPC, 2017). Egger's test and the visual inspection of funnel plots were used to assess possible publication bias in this systematic review. A $p > 0.05$ for Egger's test indicated that there was no significant publication bias; otherwise, publication bias existed. An inverted funnel that tends to be symmetrical indicates a smaller publication bias, and an asymmetrical funnel plot indicates a need to investigate the possible causes of the bias (Liu, 2011).

3 RESULTS

3.1 Retrieved Studies

A total of 17,233 articles were retrieved from CNKI (n = 2,936), WanFang (n = 12,058), VIP (n = 2,200), Web of Science (n = 7), PubMed (n = 26), and Embase (n = 6). The detailed search results of each database are shown in **Supplementary Tables S1–S8**. After removing duplicates, 15,427 articles were identified. Following the review of the titles and abstracts, 15,225 articles were excluded according to the inclusion and exclusion criteria. A full-text review was then conducted to further screen the rest of the articles. On the basis of the exclusion criteria, there were no set control group in 69 articles, no latrine improvement interventions in 33 articles, and no specific disease incidence data in 24 articles. Furthermore, 76 articles met the criteria, including 64 on schistosomiasis, 6 on diarrhea, and 6 on STH. There were few intervention studies on diarrhea and STH possibly because most intervention studies focused on other measures, such as improved water supply, health education, and hygiene, rather than improved latrines. The PRISMA flow diagram is summarized in **Figure 1**.

3.2 Characteristics of Extracted Qualified Data

Of the 76 eligible articles, 411 reported results (i.e., potential sample sizes varied with data from different sources or duration of intervention). There were more studies on schistosomiasis than on diarrhea and STH. Overall, there were 376 (91.5%) reports of schistosomiasis, 8 (1.9%) reports of diarrhea, and 27 (6.6%) reports of STH. Among the qualified data, there were 376 (91.5%) community intervention studies that were frequently used for public health. Few were cross-sectional studies, and only 35 (8.5%) studies were conducted. Some other general features of the extracted data by study disease classification are shown in **Table 2**. When categorized by location, studies covered a total of 13 provinces and cities in the middle and lower reaches of the Yangtze River in China and areas south of the Yangtze River basin. A map of the frequency of eligible studies by province and city in China is provided in **Figure 2**. The extracted studies were

TABLE 1 | Classification of interventions.

No.	Category	Description of the Main Content
I	Population-level disease control	• Crowd inspection and treatment: preventive check of the community of people, infected patients with corresponding treatment • Health education: organization of systematic education activities, establishment of health awareness, inducing people to consciously adopt healthy behaviors and lifestyles, eliminating or reducing risk factors affecting health • Chemotherapy: community use of praziquantel for medical treatment
II	Animal reservoirs control	• Replacing cattle with machines: replacing cattle farming with machine farming to reduce the chance of cattle spreading disease • Captive livestock: measures such as concentrated breeding of livestock with enclosures, reducing the spread of diseases such as occur in livestock excrement while moving • Banning grazing: prohibit grazing in endemic areas to reduce the amount of fecal worm eggs entering the land and spreading the disease
III	Water supply improvement	• Water improvement: physical chemical and biological methods to improve drinking water quality and prevent the spread of disease by the water
IV	Agricultural and forestry measures	• Planting forests to control snails: afforestation to reduce parasitic egg survival in the environment • Ditch hardening: hardening irrigation channels to reduce contamination of surrounding land by the spread of pathogens along channels • Land leveling: building settling basins for Oncomelania snails, dredging ditches to improve ecology
V	Other comprehensive environmental improvement measures	• Build biogas digester: fermentable raw materials, such as human and animal dung, are treated by closed fermentation to reduce environmental pollution caused by pathogens • Living environment renovation: implementing treatment of household garbage, sewage and other comprehensive treatments • Environmental extermination of snails: checking and eliminating Oncomelania snails from the environment to reduce the parasitic route of pathogens

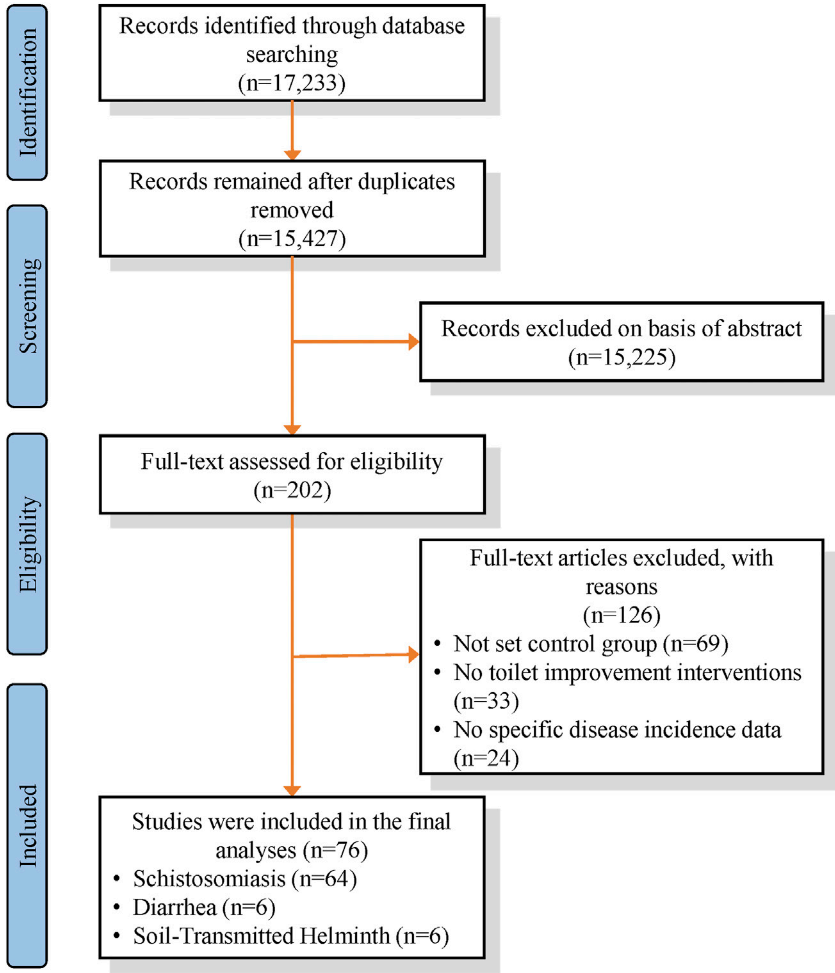

FIGURE 1 | Overview of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses strategy used for the selection of articles.

mostly concentrated in the southern region of China and distributed along the Yangtze River valley. Most studies were conducted in Hubei province ($n = 156$), followed by Anhui ($n = 90$) and Jiangxi ($n = 89$). The distribution of the extracted studies was similar to that of schistosomiasis in China, which may have been due to the large proportion of studies of schistosomiasis in the extracted literature.

3.3 Latrine Improvement Effects on the Three Investigated Diseases

A total of 114 studies were included in the meta-analysis, among which 82 investigated schistosomiasis, 8 investigated diarrhea, and 24 investigated STH. Of the 82 studies investigating latrine improvement effects on schistosomiasis, 74 showed an infection rate in the intervention group that was significantly lower than that in the control group, 7 showed the opposite results, and 1 revealed no significant difference between groups. All eight diarrheal intervention studies revealed significantly fewer instances of diarrhea in the intervention group than in the control group. Among the 24 STH intervention studies, 20 showed a significantly lower infection rate in the intervention group than in the control group, 3 showed the opposite results, and 1 showed no significant difference.

High heterogeneity was observed for each of the three diseases with an I-squared value of 98% for schistosomiasis, 81% for diarrhea, and 97% for STH. Therefore, a random-effects model was used to pool the effect size. The results revealed that the pooled RR values were less than 1 for all three diseases, and the reduction of the infection rates of schistosomiasis (RR = 0.58, 95% CI: 0.54–0.62), diarrhea (RR = 0.40, 95% CI: 0.28–0.57), and STH (RR = 0.35, 95% CI: 0.25–0.50) was related to the studied interventions. The pooled relative risk for the latrine improvement group and 95% CI for controlling schistosomiasis, diarrheal disease, and STH are summarized in **Figure 3**.

The funnel plot of the schistosomiasis studies indicated that there was some potential publication bias (**Supplementary Figure S1**), as did Egger's test ($p = 0.001$). Egger's test of diarrheal studies did not show significant publication bias ($p =$

TABLE 2 | Overview of eligible records with extractable data.

	Schistosomiasis (*n* = 376)		Diarrheal (*n* = 8)		STH (*n* = 27)		Total (*n* = 411)	
	N	%	N	%	N	%	N	%
Language								
Chinese	364	96.8	8	100.0	27	100.0	399	97.1
English	12	3.2	-	-	-	-	12	2.9
Type of Intervention	-	-	-	-	-	-	-	-
Latrine improvement	5	1.3	5	62.5	15	55.6	25	6.1
Latrine Improvement +I	3	0.8	3	37.5	-	-	6	1.5
Latrine Improvement +I II III	30	8.0	-	-	-	-	30	7.3
Latrine Improvement +I II III IV V	147	39.1	-	-	-	-	147	35.8
Latrine Improvement +I II III V	119	31.6	-	-	-	-	119	29.0
Latrine Improvement +I II V	38	10.1	-	-	-	-	38	9.2
Latrine Improvement +I III	-	-	-	-	1	3.7	1	0.2
Latrine Improvement +I III IV	4	1.1	-	-	-	-	4	1.0
Latrine Improvement + I III IV V	9	2.4	-	-	-	-	9	2.2
Latrine Improvement +I III V	9	2.4	-	-	11	40.7	20	4.9
Latrine Improvement +II	1	0.3	-	-	-	-	1	0.2
Latrine Improvement +II III V	11	2.9	-	-	-	-	11	2.7
Study Population	-	-	-	-	-	-	-	-
Adult	367	97.6	8	100.0	27	100.0	402	97.8
Students	9	2.4		-	-	-	-	-
Initial Study Time	-	-	-	-	-	-	-	-
≤ 1999	24	6.4	-	-	-	-	24	5.8
2000–2005	195	51.9	-	-	3	11.1	198	48.2
≥ 2006	153	40.7	-	-	24	88.9	177	43.1
Unreported	4	1.1	8	100.0	-	-	12	2.9

Notes: I–V correspond to the code of the intervention classification shown in ***Table 1****. I refers to population-level disease control, II refers to animal reservoir control, III refers to water supply improvements, IV refers to agricultural and forestry measures, and V refers to other comprehensive environmental improvement measures.*

0.314), which is the funnel plot in **Supplementary Figure S2**. Egger's test also did not indicate significant publication bias for STH articles (p = 0.398), which is the funnel plot in **Supplementary Figure S3**.

3.4 Subgroup Analysis of Different Intervention Combinations

Because latrine improvements are often combined with other interventions, the results of RR and 95% CI for these various combinations were consolidated (**Figure 4**). Based on the definition of intervention types in **Table 3**, a total of 10 combinations of intervention measures were obtained, and 6 combinations were obtained for schistosomiasis, 2 for diarrhea, and 2 for STH. The results confirmed that latrine improvement intervention alone could decrease the incidence of schistosomiasis (RR = 0.53, 95% CI: 0.50–0.55), diarrhea (RR = 0.46, 95% CI: 0.33–0.63), and STH (RR = 0.68, 95% CI: 0.53–0.87). For schistosomiasis, when combining latrine improvement interventions and other intervention measures, all combinations were associated with a reduction in the incidence rate of the disease, except the combination of latrine improvement and animal reservoir control and other comprehensive environmental improvement measures (II V) (RR = 0.98, 95% CI: 0.65–1.47). The lowest RR (0.63, 95% CI: 0.56–0.70) was observed in the group containing a combination of all interventions (I II III IV V), indicating that this had the best intervention effect. For diarrhea, when water improvement measures (III) were combined with latrine improvement measures, there was a lower RR value (RR = 0.28, 95% CI: 0.08–0.95), indicating a better intervention effect. For STH, when latrine improvement was combined with population-level disease control and water supply improvement measures (I III), there was a higher RR value (RR = 0.20, 95% CI: 0.13–0.29) than was observed for pure latrine improvement (RR = 0.68, 95% CI: 0.53–0.87).

The I-squared values of the heterogeneity tests and the Egger's test information pertaining to publication bias are shown in **Table 3**. Owing to the limitations of the community intervention experiment, only the I-squared value of the latrine improvement interventions of the schistosomiasis group (I-squared: 0%, 95% CI: 0.0–13.9) was less than 50%. Therefore, the fixed-effects model was adopted. The remaining interventions had large heterogeneity and I-squared values greater than 50%. Therefore, the random-effects model was adopted. Heterogeneity may be caused by the introduction of many different interventions. Of the 10 interventions classified, 6 showed no significant publication bias based on Egger's test ($p > 0.05$) and funnel plots (**Supplementary Figures S4–S13**). For the schistosomiasis group, the intervention group of latrine improvement combined with population-level disease control, animal reservoir control, water supply improvement, and other comprehensive environmental improvement measures (I II III V), as well as the intervention group of latrine improvement combined with population-level disease control, animal reservoir control, and other comprehensive environmental improvement measures (I II V), some small sample studies overestimated the

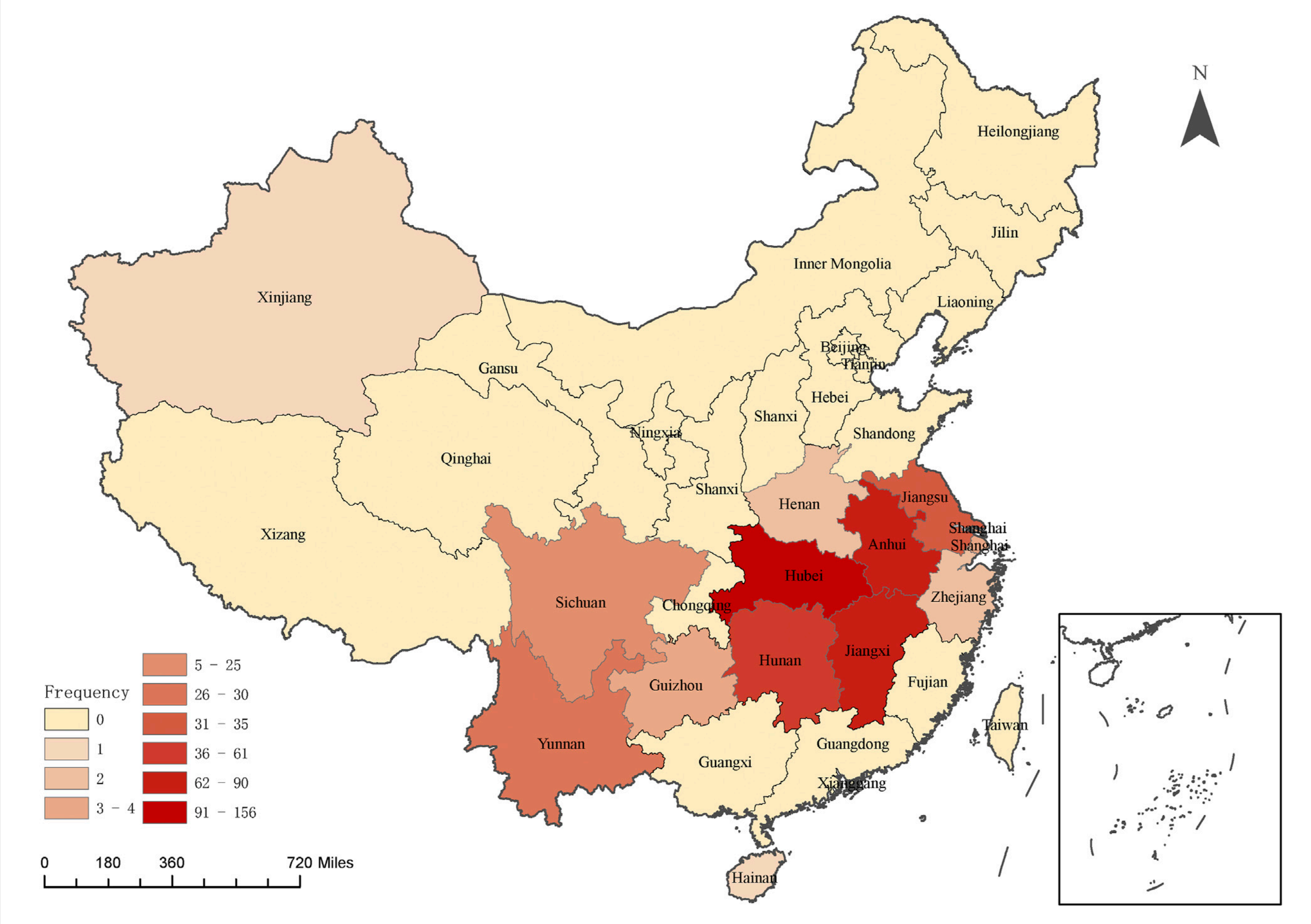

FIGURE 2 | Map of China with the number of eligible studies with extractable data by province.

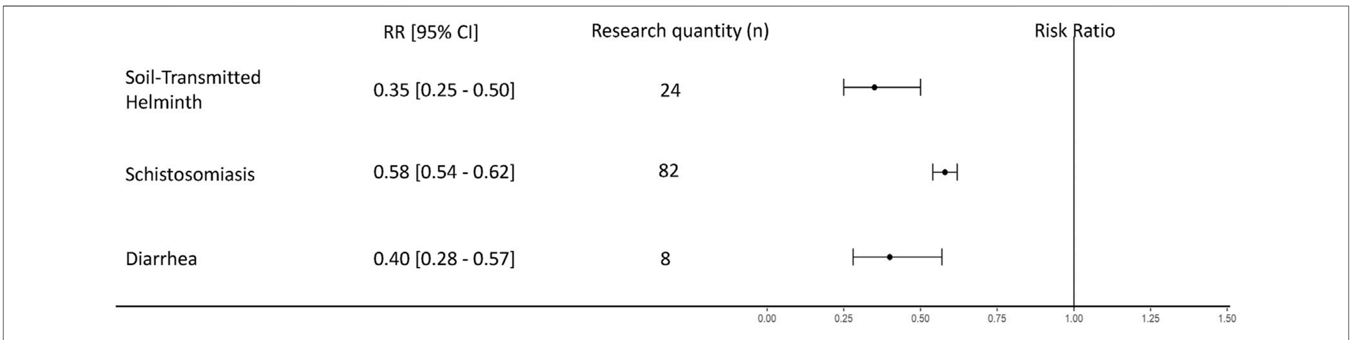

FIGURE 3 | Forest plot for schistosomiasis, diarrhea, and soil-transmitted helminths.

effects of intervention (Deng et al., 2009; He et al., 2011), resulting in publication bias. For STH, the intervention group of latrine improvement combined with population-level disease control and water supply improvement (I III) had a large regional span and wide distribution of intervention starting years in several studies, which led to failure to concentrate the intervention effects (Zhang et al., 2011; Zhu et al., 2011; Deng et al., 2012). In addition, the implementation of intervention measures failed to achieve good results for this group (Chen et al., 2015), which may have led to the observed bias.

3.5 Relationship Between Coverage Increment and Relative Risk

A logarithmic linear equation was adopted to fit the relationship between the annual increase of latrine coverage and RR of annual

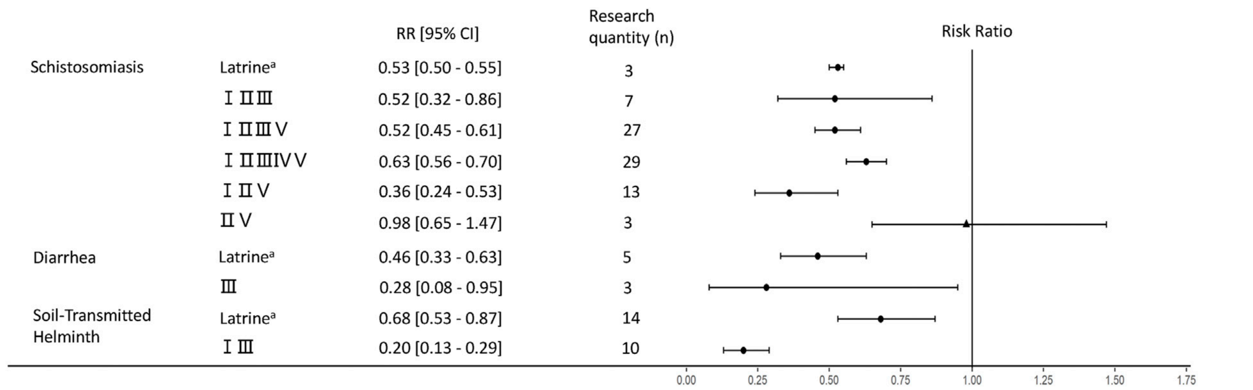

FIGURE 4 | Forest plot for latrine improvement and other interventions. Note: [a] indicate measures of latrine improvement; I–V correspond to the code of the intervention classification shown in **Table 1**; the figure shows the RR value when these measures are combined with latrine improvement measures; I refers to population-level disease control, II refers to animal reservoir control, III refers to water supply improvements, IV refers to agricultural and forestry measures, and V refers to other comprehensive environmental improvement measures; round dots in the figure indicate that the measure is a protective factor, and triangles indicate that the statistical test of the measure is not significant.

TABLE 3 | Overview of eligible records with latrine improvement and other intervention.

Disease types	Interventions	I-Squared (95%CI)	Egger's test (*p*-value)
Schistosomiasis	Latrine Improvement	0 (0–13.9)	0.865
	Latrine Improvement +I II III	66 (23.3–84.7)	0.412
	Latrine Improvement +I II III V	80 (71.7–86)	0.000
	Latrine Improvement +I II III IV V	99 (99.1–99.3)	0.077
	Latrine Improvement +I II V	92 (88.1–94.6)	0.008
	Latrine Improvement +II V	91 (76.7–96.6)	0.021
Diarrhea	Latrine Improvement	70 (24.4–88.3)	0.829
	Latrine Improvement +III	91 (77.3–96.6)	0.673
STH	Latrine Improvement	81 (68.5–88.1)	0.239
	Latrine Improvement +I III	97 (95.5–97.7)	0.009

Notes: I–V correspond to the code of the intervention classification shown in ***Table 1****. I refers to population-level disease control, II refers to animal reservoir control, III refers to water supply improvements, IV refers to agricultural and forestry measures, and V refers to other comprehensive environmental improvement measures.*

incidence rate of all included studies. As shown in **Figure 5**, RR was lower when there was a larger coverage increase, indicating that a greater intervention intensity was associated with better disease prevention effects.

3.6 Publication Bias

On the basis of the funnel plots and Egger's test, there was no significant publication bias in 8 of the 13 groups of evidence combinations.

4 DISCUSSION

Systematic review and meta-analysis were used to examine the relationship between latrine improvement in China and its health benefits. Our analysis revealed that latrine improvement measures, with or without other public health and nonpublic health interventions, were associated with lower risks of schistosomiasis, diarrhea, and STH infections. Both latrine improvement and the latrine revolution in rural China has had great social, economic, and health benefits, while also improving the environment of rural settlements. Moreover, the incidence of infectious diseases related to WASH has been decreasing annually. However, the incidences of diseases are related to many factors, such as society, the economy, the environment, and population health status. Therefore, more evidence-based data are needed to describe the health benefits of improved sanitation conditions. Nevertheless, this study revealed a correlation between China's latrine improvement and the incidence of diseases for the first time.

On the basis of our general research objectives, this study included more population-based community intervention trials. Although well designed randomized controlled trials (RCTs) can provide powerful evidence (Melnikow et al., 2013), population intervention trials are more popular in public health studies, especially for population-based sanitation intervention research. Sanitation intervention, especially improved latrine facilities, has been shown to be associated with the reduction of certain diseases in many studies. For example, a study in California showed that the children in households with no sanitary latrines were twice as likely to be infected with *Shigella* as those in homes with sanitary latrines (Schliessmann, 1959). Moreover, living in an area without

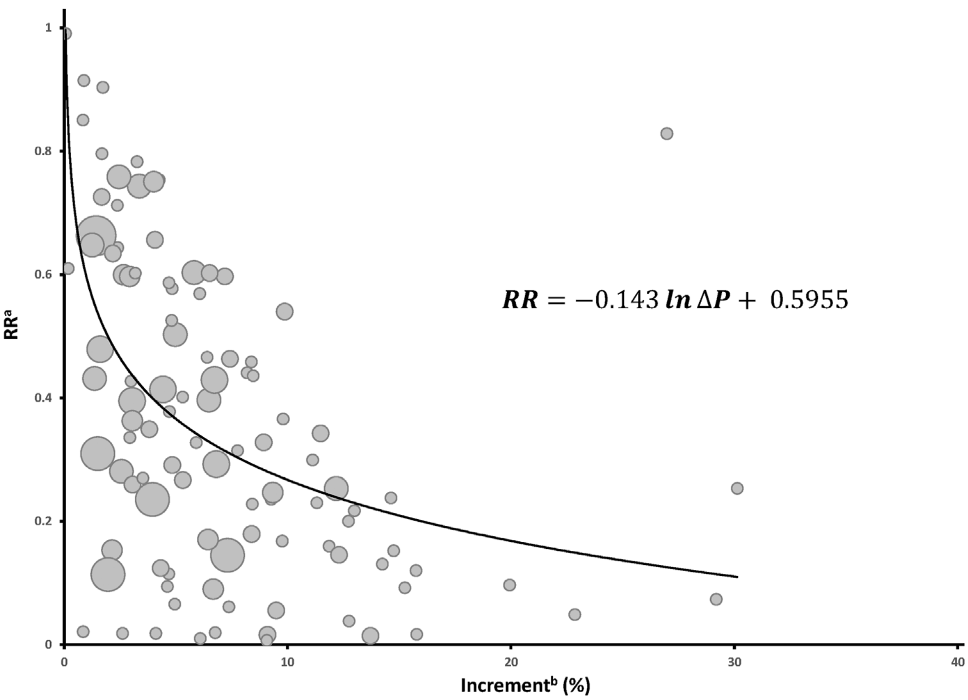

FIGURE 5 | Logarithmic fitting diagram of the increase in latrine coverage and relative risk (RR) value. Note: the size of the bubbles represents the number of studies pooled. [a] RR. This value contains the effect size of the original study and the pooled effect size of several studies (for similar studies with a number less than 3, effect values were not pooled). [b] Increase represents the annual coverage increase. In the function, ΔP was the annual coverage increase, which refers to the growth of latrine coverage in a year for an included study; *RR* was the relative risk of annual incidence.

sanitary latrines is a risk factor for *Hymenolepis nana* infection (Al-Mekhlafi, 2020). A meta-analysis of the effects of increased access to sanitation studies revealed that there was at least a 33% reduction in the chance of infection associated with individual WASH practices or access (Strunz et al., 2014). The present study adds to the growing body of evidence that improved sanitation, especially with respect to household latrines in China, is significantly associated with decreased incidence of diseases.

Improved latrines can affect the health of populations through direct or indirect ways. Direct effects include stopping the transmission of certain diseases. During fermentation of excreta in septic tanks, biogas digesters, or other sanitary facilities, pathogenic microorganisms are destroyed and the proliferation of pathogenic microorganisms is prevented, resulting in the excreta becoming harmless. In addition, closed septic tanks prevent microorganisms from entering the environment. When compared with direct application of feces to farmland, use of treated feces is safer and prevents soil pollution. In addition to direct health benefits, improved latrine facilities have indirect effects on human health. For example, household latrine improvements are often combined with improvements in water supply, sanitation, and other basic public health services. Moreover, many studies showed that the effects of combined water and sanitation interventions were often greater than the sum effects of individual measures (Fewtrell et al., 2005; Schmidt, 2014; Luby et al., 2018; Null et al., 2018). Improved sanitary conditions were also found to be beneficial to the formation of personal hygienic behaviors for family members. In addition, health education regarding comprehensive WASH interventions promoted changes in health behavior. At last, the improvement of latrines in rural areas has reduced the BOD of related diseases (Cheng et al., 2018; Chen and Kallawicha, 2021) and promoted increased household incomes, which has brought about further improvements in health and medical levels.

The results of this study revealed that there were similar health effects on water, sanitation, and hygiene (WASH)-related diseases in response to latrine improvement. Overall, there was a mean decrease of 60% in diarrhea risk, 42% for schistosomiasis risk, and 65% for STH risk compared to no intervention. Diarrhea caused a substantial disease burden in China, especially in rural areas and west China, where sanitation conditions are relatively poor. However, a significant decrease in the prevalence of diarrheal disease since the founding of the People's Republic of China was observed, which was a result of the implementation of many public and nonpublic health measures, including providing clean water supplies and improving latrines and sanitation in rural and poor areas (Cui et al., 2018; Lu, 2019; Cheng et al., 2022). STH was once a major parasitic disease that endangered the health of a large portion of the rural population in China. However, data collected during three national surveys revealed that the infection rate of STH decreased from 53.21% in the first survey (1988–1992) to 3.38% in the third survey (2014–2016). Intervention measures to control STH transmission in the population consisted of four improvement measures and one deworming event (drinking water improvement, latrine improvement, sanitation improvement, health behavior improvement, and mass deworming). In rural China, where there is a tradition of using compost to improve soil fertility, improved latrines have greatly reduced the risk of transmission of STH through the use of compost. Great achievements have also been made in the control of schistosomiasis in China, as indicated by the number of infected people decreasing from 9.49 million in 1957 to 30,000 in 2018 (Lv et al., 2019). Access to and the use of improved latrines will catch most Schistosoma eggs and will prevent miracidia from infecting intermediate host snails. This study confirmed that improvements in latrine facilities were associated with decreased likelihood of infection with schistosomiasis in China.

The most effective way of combatting diarrhea, STH, and schistosomiasis is improving access to water, sanitation, and hygiene. Moreover, WASH interventions are often not a single measure but multiple measures that are implemented at the same time. Therefore, this study evaluated the reduced risk of a disease associated with improved latrine facilities in combination with other improvements. In China, local governments coordinated health, agriculture, water, forestry, land, and other government resources to implement comprehensive measures for the prevention and control of WASH diseases, especially schistosomiasis (Yang et al., 2016). Our study revealed that the combination of various control and prevention measures had similar effects. The combination of these measures might be related to a specific local situation. Therefore, intervention study designers may develop personalized intervention strategies for specific public health problems in individual study areas.

Unlike previous systematic reviews, this study also focused on the relationship between increases in latrine coverage and RR value. Increasing sanitary latrine coverage was negatively correlated with RR, indicating that higher sanitary latrine coverage in a population results in a decreased likelihood of WASH-related diseases. This review provides more evidence linking latrine and sanitation interventions to human health. The results also indicate that latrine or sanitation improvement should not be based on individual household but should instead be promoted at the community level with the goal of improving the coverage of the entire population. Sanitary latrine coverage in rural China had reached more than 70.0% by 2022 (MARA, 2022). This rapid increase in coverage is due to a large amount of investment from local governments, as well as extensive social mobilization known as the latrine revolution.

It should be noted that this analysis may not have covered all WASH-related diseases. Moreover, the limited number of included diarrheal diseases and STH studies may affect the accuracy of the estimate of pooled effects.

5 CONCLUSION

This article provides evidence of the correlation between latrine improvement and reduced incidence of related diseases in rural China. The results of this study confirmed that latrine improvement in China played an important role in the prevention of many key infectious diseases. The overall estimates showed a mean reduction of 60% for diarrhea risk, 42% for schistosomiasis risk, and 65% for STH risk compared to no intervention.

Our research also confirmed that the intensity of health effects was positively correlated with the intensity of sanitation interventions (coverage of sanitary latrines) in China. The results presented herein suggest the important role of promoting access to sanitary latrines in disease prevention and control in China.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

SS managed data extraction and data cleaning, conducted the statistical analyses, created the tables and figures, and wrote the first draft of the manuscript. HL provided guidance on the study design and contributed to results interpretation and the final manuscript. SS, LW, WY, and LL conducted the search screening, full-text identification, review, and data extraction. RZ contributed to drafts and helped in writing the final manuscript.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.914751/full#supplementary-material.

REFERENCES

Al-Mekhlafi, H. M. (2020). The Neglected Cestode Infection: Epidemiology of Hymenolepis Nana Infection Among Children in Rural Yemen. *Helminthologia* 57 (4), 293–305. doi:10.2478/helm-2020-0038

Als, D., Meteke, S., Stefopulos, M., Gaffey, M. F., Kamali, M., Munyuzangabo, M., et al. (2020). Delivering Water, Sanitation and Hygiene Interventions to Women and Children in Conflict Settings: a Systematic Review. *BMJ Glob. Health* 5 (Suppl. 1), e002064. doi:10.1136/bmjgh-2019-002064

Asaolu, S. O., Ofoezie, I. E., Odumuyiwa, P. A., and Ogunniyi, T. A. B. (2002). Effect of Water Supply and Sanitation on the Prevalence and Intensity of *Ascaris lumbricoides* Among Pre-school-age Children in Ajebandele and Ifewara, Osun State, Nigeria. *Trans. R. Soc. Trop. Med. Hyg.* 96 (6), 600–604. doi:10.1016/S0035-9203(02)90323-8

Banke, R. O., Omudu, E. A., Ikenwa, D. A., and Feese, E. J. (2006). Prevalence of Gastro-Intestinal Parasites in Relation to Availability of Sanitary Facilities Among Schooling Children in Makurdi, Nigeria. *Anim. Res. Int.* 3 (2), 489–493. doi:10.4314/ari.v3i2.40777

Chen, M., Zhang, H., Hu, H., Liu, X., Liu, J., Zhang, X., et al. (2015). Analysis on the Measures and Effect Ofschistosomiasis Control at Pilot County Collaborated by

Provinces and Ministry in Jiangling County,Hubei Province (2009-2013). *J. Public Health. Prev. Med.* 26 (01), 39–42.

Chen, T., and Kallawicha, K. (2021). Association between Sanitary Toilet Coverage Rate and Intestinal Infectious Disease in Jiangsu Province, China. *Sci. Rep.* 11 (1), 12805. doi:10.1038/s41598-021-92291-z

Cheng, S., Li, Z., Uddin, S. M. N., Mang, H.-P., Zhou, X., Zhang, J., et al. (2018). Toilet Revolution in China. *J. Environ. Manag.* 216, 347–356. doi:10.1016/j.jenvman.2017.09.043

Cheng, S., Long, J., Evans, B., Zhan, Z., Li, T., Chen, C., et al. (2022). Non-negligible Greenhouse Gas Emissions from Non-sewered Sanitation Systems: A Meta-Analysis. *Environ. Res.* 212, 113468. doi:10.1016/j.envres.2022.113468

Clasen, T. F., Bostoen, K., Schmidt, W.-P., Boisson, S., Fung, I. C.-H., Jenkins, M. W., et al. (2010). Interventions to Improve Disposal of Human Excreta for Preventing Diarrhoea. *Cochrane. Database. Syst. Rev.* 6 (6), CD007180. doi:10.1002/14651858.CD007180.pub2

Coory, M. D. (2010). Comment on: Heterogeneity in Meta-Analysis Should Be Expected and Appropriately Quantified. *Int. J. Epidemiol.* 39 (3), 932. doi:10.1093/ije/dyp157

Cui, P., Li, J., Liu, N., and Duan, Z.-j. (2018). Incidence of Acute Diarrheal Illness in Chinese Communities: a Meta-Analysis. *BMC Gastroenterol.* 18 (1), 114. doi:10.1186/s12876-018-0839-2

Darmstadt, G. L., Pepper, K. T., Ward, V. C., Srikantiah, S., Mahapatra, T., Tarigopula, U. K., et al. (2020). Improving Primary Health Care Delivery in Bihar, India: Learning from Piloting and Statewide Scale-Up of Ananya. *J. Glob. Health.* 10 (2), 021001. doi:10.7189/jogh.10.02100110.7189/jogh.10.0201001

Deng, Y., Qiang, G., Cai, Z., Li, X., and Zhang, Y. (2012). Effect of the Comprehensive Control Measures with Emphasis on Infection Source for Schistosomiasis in Inland Water Network Areas. *J. Trop. Dis. Parasitol.* 10 (01), 5–7. doi:10.3969/j.issn.1672-2302.2012.01.002

Deng, Y., Qiang, G., You, P., Ren, J., Zhao, J., and Yang, X. (2009). Effect on Schistosomiasis Control by Comprehensive Measuers with Enphasis on Infection Source Control. *J. Trop. Dis. Parasitol.* 7 (02), 89–90. doi:10.3969/j.issn.1672-2302.2009.02.010

Deshpande, A., Miller-Petrie, M. K., Lindstedt, P. A., Baumann, M. M., Johnson, K. B., Blacker, B. F., et al. (2020). Mapping Geographical Inequalities in Access to Drinking Water and Sanitation Facilities in Low-Income and Middle-Income Countries, 2000-17. *Lancet Glob. Health.* 8 (9), e1162–e1185. doi:10.1016/S2214-109X(20)30278-3

Dong, B., Zou, Z., Song, Y., Hu, P., Luo, D., Wen, B., et al. (2020). Adolescent Health and Healthy China 2030: a Review. *J. Adolesc. Health* 67 (5), S24–S31. doi:10.1016/j.jadohealth.2020.07.023

Du, P., Sun, B., Pan, L. J., Cheng, Y. B., Li, T. T., Wang, X. L., et al. (2019). Achievements and Prospects on Environmental Health and Sanitary Engineering in China. *Zhonghua Yu Fang. Yi Xue Za Zhi* 53 (9), 865–870. doi:10.3760/cma.j.issn.0253-9624.2019.09.001

Esrey, S. A. (1996). Water, Waste, and Well-Being: a Multicountry Study. *Am. J. Epidemiol.* 143 (6), 608–623. doi:10.1093/oxfordjournals.aje.a008791

Feng, Y., Guo, Y., Yang, G., Qin, X., and Song, Z. (2012). Household Biogas Development in Rural China: On Policy Support and Other Macro Sustainable Conditions. *Renew. Sustain. Energy Rev.* 16 (8), 5617–5624. doi:10.1016/j.rser.2012.06.019

Fewtrell, L., and Bartram, J. (2001). *Water Quality: Guidelines, Standards and Health*. London: IWA Publishing.

Fewtrell, L., Kaufmann, R. B., Kay, D., Enanoria, W., Haller, L., and Colford, J. M., Jr. (2005). Water, Sanitation, and Hygiene Interventions to Reduce Diarrhoea in Less Developed Countries: a Systematic Review and Meta-Analysis. *Lancet Infect. Dis.* 5 (1), 42–52. doi:10.1016/s1473-3099(04)01253-8

GBD (2018). Estimates of the Global, Regional, and National Morbidity, Mortality, and Aetiologies of Diarrhoea in 195 Countries: a Systematic Analysis for the Global Burden of Disease Study 2016. *Lancet Infect. Dis.* 18 (11), 1211–1228. doi:10.1016/S1473-3099(18)30310-410.1016/S1473-3099(18)30362-1

Hannah, R., and Max, R. (2021). Clean Water and Sanitation. Available at: ourworldindata.org/clean-water-sanitation. (Accessed: 3 May 2022).

He, J., Zhang, S., Wang, T., Wu, H., Bao, J., Wang, Y., et al. (2011). Study on the Effectiveness of Schistosomiasis Control via Integrated Measure Emphasizing Infection Source Control. *J. Pathog. Biol.* 6 (10), 744–747+738. doi:10.13350/j.cjpb.2011.10.020

Higgins, J. P., Thomas, J., Chandler, J., Cumpston, M., Li, T., Page, M. J., et al. (2019). in *Cochrane Handbook for Systematic Reviews of Interventions*. Editor (Chichester (UK): John Wiley & Sons).

Li, Y., Cheng, S., Cui, J., Gao, M., Li, Z., Wang, L., et al. (2022). Mining of the Association Rules between Socio-Economic Development Indicators and Rural Harmless Sanitary Toilet Penetration Rate to Inform Sanitation Improvement in China. *Front. Environ. Sci.* 10, 817655. doi:10.3389/fenvs.2022.817655

Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Ioannidis, J. P. A., et al. (2009). The PRISMA Statement for Reporting Systematic Reviews and Meta-Analyses of Studies that Evaluate Health Care Interventions: Explanation and Elaboration. *J. Clin. Epidemiol.* 62 (10), e1–e34. doi:10.1016/j.jclinepi.2009.06.006

Lin, L., Wei, Y., Yao, W., Li, H., Liu, D., and Zhang, R. (2020). Improving Sanitary Latrines in Rural Areas Correlated to Decreasing the Related Disease Burden - China, 2006–2017. *Chin. CDC Wkly.* 2 (46), 873–876. doi:10.46234/ccdcw2020.238

Liu, J. L. (2011). The Role of the Funnel Plot in Detecting Publication and Related Biases in Meta-Analysis. *Evid. Based Dent.* 12 (4), 121–122. doi:10.1038/sj.ebd.6400831

Lu, X. (2019). Changes of Village Appearance and Village Planning in China in the Past 70 Years. *Chin. Dev. Obs.* 22 (3), 36–38. doi:10.12140/j.issn.1000-7423.2019.05.002

Luby, S. P., Rahman, M., Arnold, B. F., Unicomb, L., Ashraf, S., Winch, P. J., et al. (2018). Effects of Water Quality, Sanitation, Handwashing, and Nutritional Interventions on Diarrhoea and Child Growth in Rural Bangladesh: a Cluster Randomised Controlled Trial. *Lancet Glob. Health* 6 (3), e302–e315. doi:10.1016/S2214-109X(18)30005-610.1016/s2214-109x(17)30490-4

Lv, S., Xv, J., Cao, C., Zhang, L., Li, S., and Zhou, X. (2019). China Fighting against Schistosomiasis for 70 Years: Progress and Experience. *Chin. J. Parasitol. Parasit. Dis.* 37 (05), 514–519. doi:10.12140/j.issn.1000-7423.2019.05.002

MARA. (2022). The Rural Centralized Water Supply Rate and Tap Water Penetration Rate Reached 89% and 84% Respectively, and the Living Environment Sanitation of Farmers Was Significantly Improved. Available at: www.moa.gov.cn/ztzl/ymksn/rmrbbd/202204/t20220415_6396443.htm. (Accessed: 12 May 2022)

Massad, E., Ortega, N. R. S., de Barros, L. C., and Struchiner, C. J. (2009). *Fuzzy Logic in Action: Applications in Epidemiology and beyond*. Berlin: Springer Science & Business Media.

Melnikow, J., Lefevre, M., Wilt, T. J., and Moyer, V. A. (2013). Counterpoint. *Med. Care.* 51 (4), 301–303. doi:10.1097/MLR.0b013e31828a67d3

Morse, T., Tilley, E., Chidziwisano, K., Malolo, R., and Musaya, J. (2020). Health Outcomes of an Integrated Behaviour-Centred Water, Sanitation, Hygiene and Food Safety Intervention-A Randomised before and after Trial. *Ijerph* 17 (8), 2648. doi:10.3390/ijerph17082648

NHFPC (2017). *China Health and Family Planning Statistical Yearbook*. Beijing: Peking Union Medical College Press.

NHFPC (2012). *China Health Statistics Yearbook*. Beijing: Peking Union Medical College Press.

Null, C., Stewart, C. P., Pickering, A. J., Dentz, H. N., Arnold, B. F., Arnold, C. D., et al. (2018). Effects of Water Quality, Sanitation, Handwashing, and Nutritional Interventions on Diarrhoea and Child Growth in Rural Kenya: a Cluster-Randomised Controlled Trial. *Lancet Glob. Health* 6 (3), e316–e329. doi:10.1016/S2214-109X(18)30005-6

Odagiri, M., Schriewer, A., Daniels, M. E., Wuertz, S., Smith, W. A., Clasen, T., et al. (2016). Human Fecal and Pathogen Exposure Pathways in Rural Indian Villages and the Effect of Increased Latrine Coverage. *Water Res.* 100, 232–244. doi:10.1016/j.watres.2016.05.015

Patel, K., Kalpana, P., Trivedi, P., Yasobant, S., and Saxena, D. (2019). Assessment of Water, Sanitation and Hygiene in HCFs: Which Tool to Follow? *Rev. Environ. Health.* 34 (4), 435–440. doi:10.1515/reveh-2019-0001

Pickering, A. J., and Davis, J. (2012). Freshwater Availability and Water Fetching Distance Affect Child Health in Sub-saharan Africa. *Environ. Sci. Technol.* 46 (4), 2391–2397. doi:10.1021/es203177v

Reese, H., Routray, P., Torondel, B., Sinharoy, S. S., Mishra, S., Freeman, M. C., et al. (2019). Assessing Longer-Term Effectiveness of a Combined Household-Level Piped Water and Sanitation Intervention on Child Diarrhoea, Acute Respiratory Infection, Soil-Transmitted Helminth Infection and Nutritional Status: a Matched Cohort Study in Rural Odisha, India. *Int. J. Epidemiol.* 48 (6), 1757–1767. doi:10.1093/ije/dyz157

Rheinländer, T., Gyapong, M., Akpakli, D. E., and Konradsen, F. (2019). Secrets, Shame and Discipline: School Girls' Experiences of Sanitation and Menstrual Hygiene Management in a Peri-Urban Community in Ghana. *Health Care Women Int.* 40 (1), 13–32. doi:10.1080/07399332.2018.1444041

Schliessmann, D. J. (1959). Diarrhoeal Disease and the Environment. *B. World Health Organ.* 21 (3), 381. doi:10.1021/ed069p346

Schmidt, W.-P. (2014). The Elusive Effect of Water and Sanitation on the Global Burden of Disease. *Trop. Med. Int. Health.* 19 (5), 522–527. doi:10.1111/tmi.12286

Strunz, E. C., Addiss, D. G., Stocks, M. E., Ogden, S., Utzinger, J., and Freeman, M. C. (2014). Water, Sanitation, Hygiene, and Soil-Transmitted Helminth Infection: a Systematic Review and Meta-Analysis. *PLoS Med.* 11 (3), e1001620. doi:10.1371/journal.pmed.1001620

Tao, Y. (2019). Development Course from "rural Toilet Changing" to "toilet Revolution. *Chin. J. Public Health Eng.* 18 (04), 481–484.

Tumwine, J., Thompson, J., Katui-Katua, M., Mujwahuzi, M., Johnstone, N., and Porras, I. (2003). Sanitation and Hygiene in Urban and Rural Households in East Africa. *Int. J. Environ. Health Res.* 13 (2), 107–115. doi:10.1080/0960312031000098035

UN (2016). Transforming Our World: The 2030 Agenda for Sustainable Development. Available at: https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf (Accessed May 3, 2022).

UNICEF (2018). *Core Questions on Drinking Water, Sanitation and Hygiene for Household Surveys: 2018 Update*. New York: United Nations Children's Fund (UNICEF) and World Health Organization.

Wagner, E. G., and Lanoix, J. N. (1958). *Excreta Disposal for Rural Areas and Small Communities*. Geneva: World Health Organization.

WHO (2021). Drinking-water. Available at: www.who.int/news-room/fact-sheets/detail/drinking-water (Accessed May 3, 2022).

WHO (1981). *Global Strategy for Health for All by the Year 2000*. Geneva: World Health Organization.

WHO/UNIFC. (2021). Progress on Household Drinking Water, Sanitation and Hygiene 2000-2020: Five Years into the SDGs. Available at: washdata.org/report/jmp-2021-wash-households.pdf (Accessed: 3 May 2022).

Wu, S., Zhang, Y., and He, B.-J. (2022). Public Willingness to Pay for and Participate in Sanitation Infrastructure Improvement in Western China's Rural Areas. *Front. Public Health* 9, 788922. doi:10.3389/fpubh.2021.788922

Yang, N. (2004). Disease Prevention, Social Mobilization and Spatial Politics: The Anti Germ-Warfare Incident of 1952 and the "Patriotic Health Campaign". *Chin. Hist. Rev.* 11 (2), 155–182. doi:10.1080/1547402X.2004.11827202

Yang, Y., Zhou, Y.-B., Song, X.-X., Li, S.-Z., Zhong, B., Wang, T.-P., et al. (2016). Integrated Control Strategy of Schistosomiasis in the People's Republic of China. *Adv. Parasit.* 92, 237–268. doi:10.1016/bs.apar.2016.02.004

Young, S. L., Goodman, D., Farag, T. H., Ali, S. M., Khatib, M. R., Khalfan, S. S., et al. (2007). Geophagia Is Not Associated with Trichuris or Hookworm Transmission in Zanzibar, Tanzania. *Trans. R. Soc. Trop. Med. Hyg.* 101 (8), 766–772. doi:10.1016/j.trstmh.2007.04.016

Zhang, Q., Chen, Y., Xv, L., Zheng, C., and Li, H. (2011). Effect of Control on Infections of Soil-Transmitted Helminthes in Demonstration Plots of China for 3 Years. *Chin. J. Schistosomiasis Control* 23 (05), 476–482. doi:10.16250/j.32.1374.2011.05.018

Zhu, A., Li, A., Lin, G., Xv, J., and Sun, L. (2011). Effect of Comprehensive Control in Demonstration Plots of Parasitic Diseases in Guizhou Province. *Chin. J. Schistosomiasis Control.* 23 (05), 515–517. doi:10.3969/j.issn.1005-6661.2011.05.011

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Insights into the anaerobic digestion of fecal sludge and food waste in Tanzania

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With the increasing demand for renewable energy and environmental protection, biogas technology has attracted considerable attention around the world. Fecal sludge (FS) is rich in organic matter, and it contains high concentrations of excreted pathogens that cause gastro-intestinal infection. In Tanzania, fecal sludge management from on-site sanitation systems poses a threat on environmental safety. This study aimed to assess the feasibility of the use of anaerobic digestion (AD) for the treatment of FS and the production of biogas as renewable energy to achieve multiple benefits in Tanzania. For the experiments, FS and food waste (FW) were used as feedstock, and rice straw-derived biochar (RSB) was added as an additive to improve biogas production. The mesophilic anaerobic digestion resulted in a methane yield of 287.5 ml/g VS for FS + FW co-digestion and 396 ml/g VS for FS + FW + RSB co-digestion. At ambient temperature (20–26°C), the system produced a methane yield of 234 ml/g VS for FS + FW co-digestion and 275 ml/g VS for FS + FW + RSB co-digestion. Three different scenarios (digester with volumes of 4, 100, and 400 m^3, respectively) and strategies for FS treatment by AD in Tanzania were proposed and analyzed. These treatments can produce methane volumes of 1.95, 49.5, and 199.5 m^3 with pay-back periods of 3, 5, and 15 years and net present values of + 28, +1,337, and +52,351 USD, respectively. The calculations also showed that the heat value from the produced biogas and energy needed to heat the digester at 26–37°C resulted in energy balance values of + 0.012, + 0.53, and + 2.22 GJ/day for the 4, 100, and 400 m^3 digester volumes, respectively.

KEYWORDS

anaerobic digestion, fecal sludge, co-digestion, sanitation, energy balance

1 Introduction

Fecal sludge (FS), which is known as excreta, is the rejected waste from humans. Globally, innovative treatment systems are needed for safe fecal sludge management (FSM) (Bassan, 2014). In rural Tanzania, 83% of the population do not have access to basic sanitation. Communities rely on on-site sanitation such as septic tanks and pit latrines that are not safely managed and allow for fecal sludge to contaminate groundwater that is used for drinking (Mrimi et al., 2020). Approximately 90% of the Dar es Salaam inhabitants use on-site sanitation system facilities, where 60% of the inhabitants use pit latrines and 30% use septic tanks (Makoye, 2017). In comparison with the traditional disposal method such as landfilling, drying beds, and composting, anaerobic digestion (AD) of FS for biogas production is an effective treatment solution. Although AD is considered an alternative fuel production option for bioenergy production (Cheng et al., 2020), the use of FS as a substrate has shown some challenges, such as poor process stability and low methane productivity.

Anaerobic co-digestion (ACoD) is commonly used for enhancing biogas production during AD (Dhungana et al., 2022). ACoD is the process of feeding two or more kinds of organic substrates during AD. It offers a wide range of benefits compared with mono-digestion of FS, such as dilution of toxic substances, balancing of the C:N ratio, enhanced methane yield, the synergic effect of microorganisms, and nutrient balance (Hagos et al., 2017). Biogas production from co-mixed substrates has been widely studied (Yong et al., 2015). Nevertheless, the selection of appropriate co-substrates, their characterization, composition, and mixing ratio should be wisely considered.

In addition, additive materials (e.g., polyethylene, carbon, activated carbon, and polyvinyl alcohol) and conductive materials (e.g., conductive iron oxides, semi-conductive iron oxide minerals, and micrometer-sized magnetite) are used for immobilizing microorganisms and tackling inhibitions (Cai et al., 2016). However, the use of these additive media has shown some environmental and economic problems because they persist in anaerobic digestate and are mainly used as fertilizer or require some addition system for their separation from the digestate (Haider et al., 2015; Cai et al., 2016). Accordingly, environment-friendly and economic additives should be developed. Biochar, which has good adsorptive property, is an important additive for the AD process (Fagbohungbe et al., 2016; Pan et al., 2019). Recently, in Tanzania, it has been discussed on the applications of biochar in soil improvement, waste management, energy generation, and as an additive substance in AD (Hewage and Priyadarshani, 2016; Simeon, 2017). However, limited studies have used locally produced biochar as an additive in the AD process for improving the AD process of FS. Limited studies have also focused on the use of biochar in terms of biochar dose and its particle size that can be added in AD of organic matters to improve its efficiency. Therefore, this area needs to be further studied.

Millions of rural household biogas digesters that operate in developing countries in Asia and Africa are working under ambient conditions and are primarily unheated. Therefore, they experience maximum fluctuation of temperature, thus reducing biogas production (Khan and Martin, 2016; Lohani et al., 2022). A digester's operating temperature is recommended to be in the range of 33–37 or 45–55°C during the anaerobic start-up of the digester (Arikan et al., 2015). Failure to maintain the temperature within this range will inhibit methanogenic growth, increase the start-up time, and reduce biogas production (Dev et al., 2019). In most studies, acclimated seed (inoculum), the chemical and thermal pretreatments of feeding the substrate, and the mesophilic temperature are maintained to speed up the start-up process along with the overall AD process (Martí-Herrero et al., 2015). In retrospect, in most developing nations, the anaerobic digester is operated in ambient conditions without using the acclimated inoculum before actual feeding of substrates. Hence, many complexities arise, such as prolonged reactor start-up time and poor methane yield, which have been major challenges for domestic biogas plants in developing nations. Thus, an effective strategy for FS treatment in developing nations should be studied.

This study mainly aimed to determine whether the AD technology can be used as an FS treatment option in Tanzania, which is located in east Africa. The specific objectives were as follows: 1) to determine the specific biogas production of FS under the temperature-controlled mesophilic condition without or with additives; 2) to determine the specific biogas production of FS at ambient temperature without or with additives; 3) to calculate the energy balances of different digester scales; 4) to analyze the cost-benefit of three different application scenarios in Tanzania; and 5) to propose the strategy for FS treatment in three application scenarios.

2 Materials and method

2.1 Samples

2.1.1 Fecal sludge

The experiments were implemented in both China and Tanzania. FS was obtained from a vacuum toilet at the University of Science and Technology of Beijing (USTB) in China and from dormitory septic tanks at Ardhi University in Tanzania. After collecting FS from septic tanks by using a plastic bucket, the sample was filtered to remove large particles and thus avoiding blocking of the digester inlet and outlet pipes.

TABLE 1 Characteristics of FS, FW, and RSB at USTB, China, and Ardhi University, Tanzania.

Parameter	FW	FS	Biochar	Inoculum
USTB-China				
TS (%)	26.2	9.7	96	7.7
VS (%)	23.7	8.0	95.7	3.8
pH	4.5	8.2	8.8	7.5
COD (mg/l)	168000	84000		
TDS (mg/l)	93000	6,550		
Ardhi University—Tanzania				
TS (%)	20.3	17.6	96	
VS (%) pH	18.1	14.8	95.7	
COD (mg/l)	5.85	8.63	8.8	
TDS (mg/l)	152800	38400	—	
Temperature (C)	25.7	25	—	

2.1.2 Food waste

Food waste (FW) was collected from a restaurant USTB in China and a student canteen in Ardhi University in Tanzania. Considering that FW is mainly composed of vegetables, meat, fish, and bone materials, the samples were pre-treated manually before grinding to remove impurities such as tissue paper, plastic spoons, and straws. For the pre-treatment stage, FW was sorted and crushed into aqueous slurry. The FW sample was stored in a refrigerator at 4°C until use to avoid early decay.

2.1.3 Inoculum

In China, inoculated sludge was obtained from a pilot system fed with waste-activated sludge. The pilot-scale reactor is located in the wastewater treatment plant in Chaoyang District, Beijing China. In Tanzania, FS was used as the inoculum.

2.1.4 Rice straw-derived biochar

The rice straw-derived biochar (RSB) obtained from Henanlize Bioenergy Technology Development Company from Henan province in China was used during the experiment. The sample was oven-dried at 105°C for 24 h for physiochemical analysis. The volatile solid (VS) matter was determined as the weight loss after heating in a covered crucible at 550°C for 3 h by using the furnace. The RSB was characterized with a mean value of pH, total solid (TS), and VS. The biochar was sieved to obtain different particle sizes of 0.075, 0.15, and 0.45 mm by using a sieving machine. The characteristic of FS, FW, RSB, and the inoculum are shown in Table 1.

2.2 Experimental setup design

For the experimental run, two set-up ambient and mesophilic temperatures were used. Under the mesophilic condition at 37°C, six identical reactors made with the glass bottles having a total volume of 500 ml, including a headspace of 100 and 400 ml working volume (effective volume), were labeled as R_1, R_2, R_3, R_4, R_5, and R_6 and treated as the control for the co-digestion of FS and FW, while those labeled as M_1, M_2, M_3, M_4, M_5, and M_6 were used for co-digestion of FS, FW, and RSB at USTB China. At ambient temperature (20–26°C), nine reactors having a total volume of 1,000 ml with a working volume of 900 ml labeled as S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8, and S_9 were used for the co-digestion of FS, FW, and RSB with different biochar particle sizes of 0.075, 0.45, and 1 mm. The reactors named as A_1, A_2, A_3, and A_4 were used for the co-digestion of FS and FW experiments in various ratios on a TS basis at Ardhi University, Tanzania. The reactors (R_6, M_6, and A_5) were fed with inoculum only and were treated as a control, where the observed biogas production (volumetric test) of the experimental group subtracted the biogas production of the blank control group to obtain the net biogas production of the substrate. The reactors were operated at 37°C at USTB in China

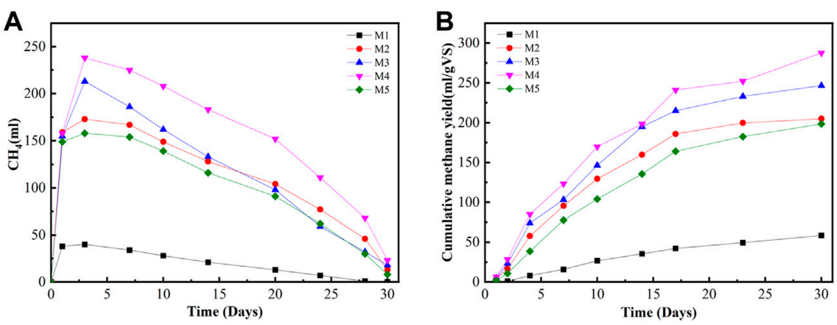

FIGURE 1
Daily methane production and cumulative methane production at different mixing ratios under mesophilic conditions. **(A)** Daily methane production. **(B)** Cumulative methane.

TABLE 2 Removal efficiency of TS, VS, and COD after anaerobic digestion for all mixing ratios.

	R1	R2	R3	R4	R5
TS initial (g/l)	78	97	108	139	144
TS final (g/l)	57	69	48	56	48
Efficiency of TS removal (%)	**26.9**	**39.8**	**55.6**	**59.7**	**66.7**
VS initial (g/l)	37.6	51.6	60	67.7	69.3
Final VS (g/l)	18.9	19.5	17.8	17.8	19.2
Efficiency of VS removal (%)	**49.7**	**62.2**	**70.3**	**73.7**	**72.3**
COD initial (g/l)	36.9	60.8	89.2	106.1	110.3
COD final (g/l)	21.5	30.3	35.3	35.1	39.3
Efficiency of COD removal (%)	**41.7**	**50.1**	**60.4**	**66.9**	**64.6**

and under ambient temperature (20–26°C) at Ardhi University in Tanzania (Supplementary Figure S1 in Supporting information). The retention time was approximately 30 days.

The biochemical methane potential (BMP) reactors were shaken manually twice a day. The production of biogas and methane was measured daily, and samples were obtained regularly to determine the physical and chemical indicators such as pH and total ammonia nitrogen (TAN). Cumulative methane volume production was calculated based on the sum of the daily methane volume, as indicated in the following equation (Ripoll et al., 2020):

$$Vt_{CH4} = Vi_{CH4} - V_{control}, \quad (1)$$

where $V_{t\ CH4}$ is the net volume of methane, $Vi_{\ CH4}$ is the experimental volume of methane measured when the co-substrate was used, and $V_{control}$ is the volume of methane produced in the control (inoculum) experiment. Methane productivity (Y_{CH4}) at the base of the initial VS of the substrate used was calculated as $Vt_{\ CH4}$ per g of initial VS (ml CH_4/g VS).

$$V_{CH4} = Vt_{CH4}/VS. \quad (2)$$

2.3 Analytical method

The collected samples were brought to USTB and Ardhi University laboratories for physical and chemical analyses. TS and VS were determined according to the standard (APHA, 2017), as described by Nandi et al. (2020). The pH of the samples was measured using a Hach pH meter (HQ 30 days). The daily biogas composition (CH_4, CO_2, and H_2S) was measured at an interval of time until 30 days by using a biogas analyzer (Geotechnical Producer Ltd., Gloucester, United Kingdom) at USTB. The water displacement method was used for biogas production measurement at Ardhi University, Tanzania, and the biogas volume was measured using a 200-ml plastic syringe. The concentrations of the TAN and chemical oxygen demand (COD) were determined using

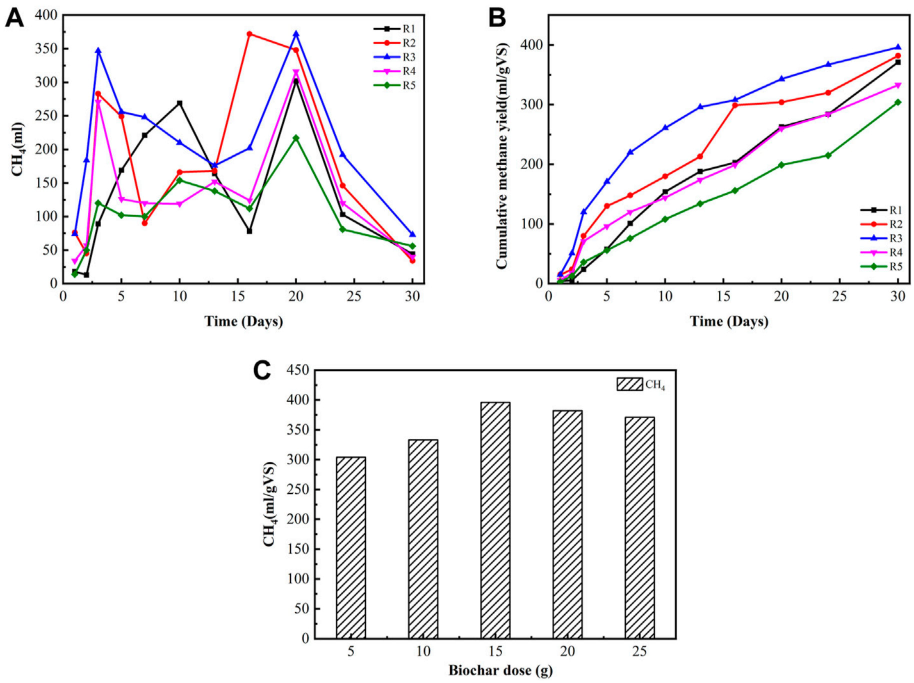

FIGURE 2
Daily methane production, cumulative methane yield, and specific methane yield production with different biochar doses under mesophilic temperature. **(A)** Daily methane production. **(B)** Cumulative methane yield. **(C)** Specific methane yield at different biochar doses.

the kits and the Hach DR 2800 portable spectrophotometer, respectively (APHA, 2017).

3 Results and discussion

3.1 Biomethane potential test at the mesophilic condition in China

The different substrate mixing ratios and biochar doses for the BMP test by using mesophilic temperature at USTB are shown in Supplementary Tables S1, S2.

3.1.1 Co-digestion of FS and food waste

The cumulative value of methane production is shown in Figure 1. The mixing ratio of 75:25 (FW: FS) in R_4 produced the maximum cumulative methane. The methane yields were 59, 205, 247.6, 287.5, and 199 ml/g VS in R_1, R_2, R_3, R_4, and R_5, respectively. The value of the methane yield of ACoD in this study was 1.5–4.9 times larger than FS and FW mono-digestion. The findings are lower than the methane production from the previous study (410–680 ml/g VS) (Zhang et al., 2019) because of the difference in raw materials and reaction conditions. The result is also comparable with the findings of Minale and Worku (2014), in which high cumulative biogas was obtained when the easily biodegradable organic component in the sample was higher. Similar results were also obtained by Minale and Worku (2014), in which the maximum overall biogas yield was obtained by the co-digestion of potato processing wastewater and pig slurry compared with individual potato wastewater or pig slurry digestion. Afifah and Priadi (2017) found high values of methane yield at FS and FW ratios of 3:1 and 1:1 with concentrations of 300 and 560 ml/g VS. Therefore, although the study was conducted at the mesophilic condition by using a hand stirrer, the reactors can produce methane yields that were as high as previous studies with the optimum temperature.

3.1.2 Removal of TS, VS, and COD at different mixing ratios

The characteristics of the effluent were analyzed after 30 days of digestion, and the removal efficiency was calculated. The TS of the effluent in different mixing ratios was reduced to 26.9%–66.7%. VS reduction ranged from 49.7% to 72.3%. A high TS reduction value was recorded at 100:0 (FW: FS). The high VS reduction and removal efficiency were achieved at 75:25. The higher removal efficiency of VS than the TS was a very good indication of a high uptake rate of the organic fraction of TS by methanogenic bacteria (Minale and Worku, 2014). COD reduction ranged from 41.7% to 66.9%, as shown in Table 2. Similar results were obtained by Afifah and Priadi (2017), in which the VS removal efficiency reached 92.43% at the ratio of 1:1 (FS: FW), while 79.43% at the ratio of 1:3 (FS: FW). This value was almost the same as the COD removal efficiency, which reached 87.55% at a ratio of 1:1 (FS: FW) and 72.42% at a ratio of 1:3(FS: FW).

3.1.3 Co-digestion of FS, food waste, and rice straw-derived biochar

The study also determined the AD process based on different biochar doses in digesters. The daily biogas production rate and methane contents are shown in Figure 2. It shows that the production rates vary according to different amounts of biochar addition. All biochar-supplemented groups had high cumulative methane yields and short lag phases. The cumulative methane yields at biochar doses of 25, 20, 15, 10, and 5 g were 291, 328, 396, 293, and 226 ml/g VS, which were 232, 123, 149, 5, and 27 ml/g VS more than the methane yield of reactors without biochar, respectively. In addition, cumulative methane yield had improved with the corresponding increment in biochar addition. This finding was obtained because biochar supports the rapid development of biofilms with balanced acidogenic and methanogenic bacteria through the enrichment of bacteria and methanogens, thereby enhancing their synergy and activity (Cooney et al., 2016; Soler-Cabezas et al., 2018), thus contributing to the increase of cumulative methane yields in the digesters with biochar. The difference among the five groups in terms of methane yield became increasingly large from day 5 with a prolonged digestion period. From the 10th day to the 28th day, the cumulative methane yields (CMYs) from digesters M_2 (20 g biochar) and M_3 (15 g biochar) were significantly higher than those of digesters M_1 (25 g), M_4 (10 g biochar), and M_5 (5 g biochar). The maximum methane yield produced was 396 ml/g VS in reactor M_3 (15 g biochar addition), as shown in Figure 2. The biochar effect in terms of higher methane yield in the present study was comparable with the results in the previous research (Vanegas and Bartlett, 2013). Additionally, Shanmugam and Horan, 2009 reported that 16.6 g/L biochar input could be optimal among different biochar loadings in the range of 8.3–33.3 g/L in a two-phase batch AD digester, and biochar dosages greater than 16.6 g/L resulted in lower cumulative methane production. CMY decreased at a higher biochar dosage, possibly because excessive biochar could not further provide enhancing effects for microbial communities in a fixed reactor space but can adsorb more methane-rich biogas because of the biochar's high adsorption capacity (Browne et al., 2015). Biochar addition enhanced biogas production, possibly because of the ability of the biochar to adsorb ammonium ions and promote electron transfer between itself and other substrates. Sinervo (2017) reported that different types of biochar have variable ammonium ion adsorption values depending on biochar types and concentrations while using zeolite to obtain reference results.

3.1.4 TS, VS., chemical oxygen demand removal, and pH change at different biochar doses

The COD removal efficiency is a critical parameter, which reflects the efficiency of AD. The effluent sample was obtained from different reactors and analyzed after 30 days of the BMP

TABLE 3 TS, VS, and COD removal efficiency with different biochar doses at mesophilic temperature.

Reactor	M_1	M_2	M_3	M_4	M_5
TS initial (g/l)	75	90	96	104	112
TS final (g/l)	18	21.9	25.3	28.8	34.3
Efficiency of TS removal (%)	**76.2**	**75.7**	**73.6**	**72.3**	**69.4**
VS initial (g/l)	42	56	64	69	73
Final VS (g/l)	8.2	10.1	13.1	15.2	17.3
Efficiency of VS removal (%)	**80.5**	**81.9**	**79.6**	**77.9**	**76.4**
COD initial (g/l)	64	72	96	102	118
COD final (g/l)	13.9	15.2	21.8	23.6	29.4
Efficiency of COD removal (%)	**78.4**	**78.9**	**77.3**	**76.9**	**75.2**

test, and the removal efficiency was calculated. For mesophilic temperature, the TS removal efficiency was in the range of 69.4%–76.2%, the VS removal efficiency was 76.4%–80.5%, and the COD removal efficiency was 75.2%–78.9%, as shown in Table 3. The COD removal efficiencies were only 78.4%, 78.9%, 77.3%, 76.2%, and 75.2% at biochar doses of 25, 20, 15, 10, and 5 g, respectively. A low COD removal efficiency was observed in the reactors because excessive molasses loading may reduce the digester's ability to decompose COD because of insufficient biochar, thereby inhibiting the activity of microorganisms that can degrade the organic matter (Cooney et al., 2016; Soler-Cabezas et al., 2018). The pH in the mesophilic temperature was higher and stable than that in the ambient temperature. Nasir et al. (2012) reported a stable and neutral pH at higher temperatures (30 and 35°C) than at lower temperatures (20 and 25°C), thus increasing the CH_4 concentration. During the experiment, the methane concentration reached 72.3%, in which the pH value was stable near the neutral value (~7.0) under the mesophilic condition.

3.2 Biomethane potential test at ambient conditions in Tanzania

The different substrate mixing ratios for the BMP test under the ambient temperature at Ardhi University, Tanzania, are presented in Supplementary Tables S3, S4.

3.2.1 Co-digestion of FS and food waste

The daily biogas production from four reactors labeled A_1, A_2, A_3, and A_4 over a period of 30 days is shown in Figure 3. The experimental results show that biogas production was slow at the beginning and after the observation of the experiment. Biogas production was generally slow within the first few days of the experiment because of the lag phase of the microbial growth, where methanogens (microbial community) become established to the medium within the digester (Simeon, 2017). The maximum values of daily biogas production were recorded on the 10th–14th before a gradual fall in the production rate was recorded for the rest of the study period. The daily biogas production decreased at the end of the experiment, possibly because of the pH drop, resulting in an increase in the concentration of ammonia nitrogen that could inhibit the process.

The cumulative methane yields in reactors A_1, A_2, A_3, and A_4 were 187, 234, 192, and 173 ml/g VS. The substrate mixing of 1:2 (FW:FS) had high cumulative methane production. The highest total methane yield was 234 ml/g VS. The BMP results suggest that a higher proportion of FS is beneficial for methane production from a substrate mixture, possibly because of its highly biodegradable and nutritionally balanced organic matter.

3.2.2 Co-digestion of FS, food waste, and rice straw-derived biochar

Figure 4 presents the daily methane production and cumulative methane yield in different biochar doses under ambient temperature. Three different types of rice RSB doses of 20, 15, and 10 g were used in this study with different particle sizes of 0.075, 0.15, and 0.45 mm. Biogas yield increased to 275 ml/g VS when the particle size of biochar was reduced to 0.075 mm. This amount is equivalent to a 19.3% increment compared with 222 ml/gVS when the biochar particle size was 0.45 mm. Notably, the digester with 0.45 mm biochar particle size showed the lowest average methane yield among all the biochar-amended digesters, possibly because of the floating of the large particle size. He et al. (2018) found that different biochar particle sizes could exhibit significant differences in some physicochemical properties, such as elemental composition, surface functional groups, microcrystalline structure, and pore size distribution. The addition of biochar with different particle sizes could effectively tolerate high substrate loading rates and avoid the excessive accumulation of organic acids and potential digester failure. The average maximum methane contents during the 30 days of AD operation were 50.1%, 48.4%, and 45.9% for 0.075, 0.15, and 0.45 mm, respectively. The digester pH was a key indicator of the process stability for the AD operations (Mehariya et al., 2018). The variation performance of these digesters could be ascribed to the similar physicochemical properties, such as density, surface area, and pore size of the supplemented biochar with different particle sizes.

3.2.3 Removal efficiency of TS, VS, chemical oxygen demand, and pH fluctuation

pH and COD are two key indicators of the process stability for the AD operations (Mehariya et al., 2018). Hence, pH and COD values were examined during the AD process to understand the changing tendency of methane yields in different digesters.

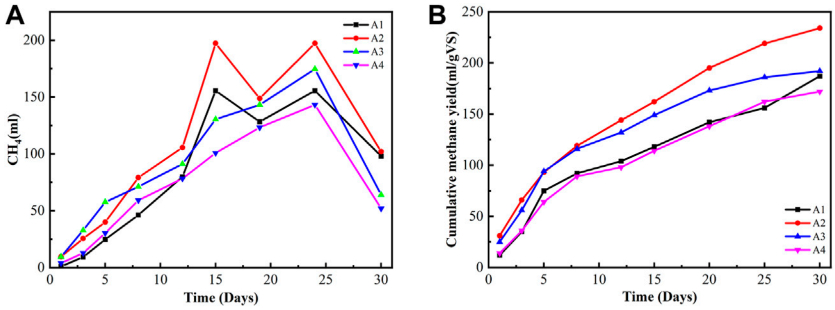

FIGURE 3
Daily methane production and cumulative methane yield in different mixing ratios under ambient temperature. **(A)** Daily methane production. **(B)** Cumulative methane yield.

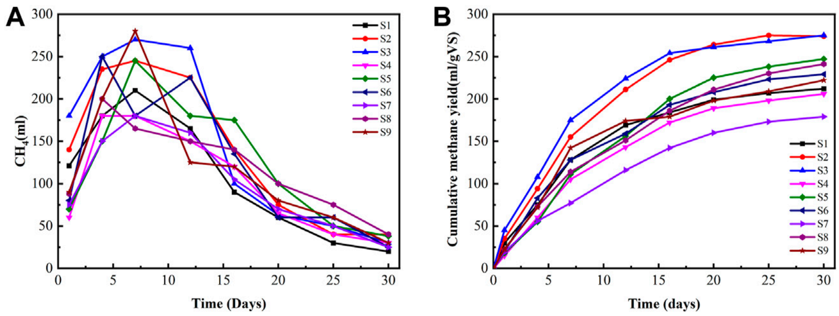

FIGURE 4
Daily methane production and cumulative methane yield in different biochar doses under ambient temperature. **(A)** Daily methane production. **(B)** Cumulative methane yield.

The TS of the effluent in different mixing ratios was reduced to 50.9%–59.2%. VS reduction was also in the range of 50.1%–65.5%. COD reduction ranged from 59.3% to 69.6%. The maximum COD reduction was achieved in the S_1, S_2, and S_3 digesters at a biochar size of 0.075 mm with a biochar addition dose of 10 g, in which the maximum amount of gas was produced. Recent experimental works has proven that substrates with a high COD value resulted in good performance in terms of biogas production and COD reduction (Filer et al., 2019; Bakraoui et al., 2020). The methane concentration also depends on pH. The biogas composition shifts more toward CH_4 when the pH is high because of the increased alkalinity caused by the NH_3 release. Nasir et al. (2012) reported a stable and neutral pH at higher temperatures (30 and 35°C) than at lower temperatures (20 and 25°C), resulting in a high CH_4 concentration. Sabbir et al. (2022) reported that the average methane concentrations were 61.43%, 59.75%, and 56.3% in the autumn, late autumn, and winter, respectively, where the pH in the autumn was higher and stable than that in late autumn and winter. The removal efficiencies for TS, VS, and COD and the pH fluctuation are shown in Table 4.

3.3 Lesson learnt for biogas technology in China

The Chinese biogas industry deviates from the usual development path compared with developing countries. Tanzania can learn numerous lessons, which should be reconsidered.

3.3.1 National subsidy

The development of China's biogas industry is successful with the aid of the government subsidy. At present, the central government policy aims to establish and subsidize thousands of bio-natural gas plant installations in rural areas to promote biogas production. The Ministry of Agriculture aims for a daily bio-methane generation of >10,000 m^3 and a total digester volume of >16,000 m^3. Accordingly, it provides 2,500 CNY (375 USD) subsidy per cubic meter of the methane generation capability. This subsidy is 40% of the total financial aid and is equivalent to 40 million CNY (6,000,000 USD) in subsidy by the central government of China (Zheng et al., 2020). Small-scale digesters are subsidized

TABLE 4 TS, VS, and COD removal efficiency at ambient temperature (20–26°C).

Reactor	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9
Initial TS	75 g/L	79 g/L	82 g/L	76 g/L	80 g/L	82 g/L	76 g/L	81 g/L	84 g/L
Final TS	31.9 g/L	32.2 g/L	32.4 g/L	36.4 g/L	35 g/L	35.8 g/L	37.3	38.5	41 g/L
% TS removal	**57.5**	**59.2**	**58.3**	**52.1**	**56.3**	**55.6**	**50.9**	**52.5**	**51.3**
Initial VS	40.6 g/L	41.3 g/L	43.2 g/L	40.9 g/L	41.6 g/L	44.2 g/L	40.4 g/L	41.9 g/L	43.9 g/L
Final VS	14.5 g/L	14.2 g/L	14.0 g/L	16.6 g/L	16.6 g/L	16.7 g/L	20.2 g/L	20.1 g/L	20.1 g/L
% VS removal	**64.3**	**65.5**	**67.6**	**59.4**	**60.1**	**62.3**	**50.1**	**52.0**	**54.3**
Initial COD	60.8 g/L	62.3 g/L	66.1 g/L	60.5 g/L	62.1 g/L	66.2 g/L	60.6 g/L	62.5 g/L	65.8 g/L
Final COD	22.9 g/L	21.1 g/L	20.1 g/L	24.3 g/L	24.1 g/L	24.1 g/L	24.7	24.5 g/L	24.9 g/L
% COD removal	**62.4**	**66.1**	**69.6**	**60.0**	**61.3**	**63.6**	**59.3**	**60.9**	**62.0**

with 1,500 CNY (225 USD) per cubic meter of the fermentation volume for biogas power generation, including heating and cooking (domestic consumption). This value represents 35% of the total investment and is equivalent to a subsidy of 30 million (4,500,000 USD) CNY from the federal government. Approximately 386 small-scale biogas projects and 25 engineering biogas projects were subsidized in 2015, and these numbers increased by 552 in 2016. A large amount of subsidy was also provided for digestate fertilizers for the replacement of mineral fertilizers with organic fertilizers for improved vegetable and fruit production. A total of 100 demo counties were constructed in 2017 (Zheng et al., 2020).

3.3.2 Equipment and technology innovation

The industrialization level of China's biogas industry remains high compared with that of Africa. The use of advanced equipment can lead to high biogas production and utilization efficiency. For instance, the poor pre-treatment technology of feedstock leads directly to low gas production rates (Yu et al., 2019). The key components should be feedstock crushing or chopping equipment for straw. The use of mixing devices is important to guarantee the homogenization of feedstock. Moreover, the biogas desulfurization efficiency is used in China, and solid chemical adsorption technology is employed. Regular process monitoring and control are required to provide information about general process performance and safety and recognize and respond to process instabilities/disturbance (Jimenez et al., 2015).

3.3.3 Co-digestion plant

By comparison, very few biogas plants in China adopt the co-digestion technology, although numerous laboratory studies have investigated the co-digestion technology. Co-digestion provides great benefits for China. In China's urbanization, the amount of household garbage and other organic wastes such as food waste is expected to increase remarkably (Hagos et al., 2017). The sewage sludge production in cities reached 10.53 million tons (dry matter) in 2017 (Skovsgaard and Jacobsen, 2017). The construction of a centralized co-digestion plant can be encouraged by introducing a special subsidy for feedstock in Tanzania. A detailed category for different substrates could be built.

4 Strategy for FS management at different AD scales in Tanzania

FS is a critical issue in Tanzania to archive the targets of Sustainable Development Goal (SDG) 6, such as SDG target 6.1: By 2030, achieve universal and equitable access to safe and affordable drinking water for all. FS is mainly stored in septic tanks and pit latrines, where sludge is removed either manually or mechanically. Collecting, emptying, and transport services are provided by the government water supply and sanitation authorities and informal and unregulated private operators by using vacuum trucks. In informal settlements, FS is collected but not treated, and much of it is dumped into landfill or water bodies, such as the ocean. This practice does not promote hygiene for all and does not end open defecation. In 1975, the development of biogas in Tanzania is credited to the Small Industries Development Organization (SIDO), which installed approximately 120 anaerobic digesters of the floating drum types, mostly in schools (Mshandete and Parawira, 2009). Biogas plants with digester volumes of 8, 12, to 16 m^3 were deployed. After 5 years of the program, new standardized plant sizes were added with volumes of 12, 16, 30, and 50 m^3 for institutions, households, and special "toilet biogas plants" (Mshandete and Parawira, 2009), while toilet biogas plants have been widely disseminated in China (Cheng et al., 2018). An augmentation was observed in the unit cost for installing an anaerobic digester ranging from Tshs 300,000 (USD 130) at 1989 to between Tshs 4,000,000 (1,700 USD) and Tshs 7,000,000 (3,000 USD) in the 1990s. Cheng et al. (2014) found that the initial cost of biogas plants can be reduced by introducing a low-cost polythene biodigester for African countries in 1993, and these digesters use animal manure as their feedstock. Tanzania has a successful biogas program, and approximately 8,796 biogas plants have been deployed (Mshandete and Parawira, 2009; Rupf et al., 2015). This finding serves as a good basis to introduce AD technology for FS treatment. Considering the context of Tanzania in the sub-Saharan African region, the FS treatment units at three different scales that are targeted for household-level, community-scale, and large-scale digesters are proposed, and the energy balances are analyzed.

4.1 Scenarios for FS treatment by AD

4.1.1 Household biogas digester (4 m^3)

Most of household biogas digesters in Tanzania are operated under ambient temperature at 15–28°C depending on seasonal variation. The calculation of energy balances shows that the energy of 0.019 GJ/d can heat the digester and increase its temperature from 26 °C to 37°C (Fuchs et al., 2018; Campello et al., 2021). Without heating the digester, it can produce a methane volume of 1.95 m^3/day under ambient temperature, and this volume can generate an energy of 0.031 GJ/d. The results show that heating energy could be balanced by the produced methane gas. Therefore, the introduction of the heating unit for household digesters is not feasible. The cost of installing the 4-m^3 digester in Tanzania requires approximately 764 USD, as shown in Supplementary Table S5, and this amount includes the construction and operation cost. The household FS treatment and biogas production together with FW and animal manure can upgrade biogas production. Heating cost can be avoided by burying the digester underground without special isolation and heating measures.

4.1.2 Community-scale biogas digester (100 m^3)

For the community-scale digester, a volume of 100 m^3 can treat the FS from 50 families. The calculation shows that an energy of 0.27 GJ/day is required to heat the digester from 26 to 37°C (Fuchs et al., 2018; Campello et al., 2021). Under ambient temperature, the biogas digester with a working volume of 100 m^3 in Tanzania costs 40,825 USD, as shown in Supplementary Table S6, and this piece of equipment could provide a heating value of 0.8 GJ/day, which is enough to reach a positive energy balance if the biogas is partially used for heating the digester. For the community-scale FS digester, the isolation measure could be implemented, and the heating unit could be installed if surplus biogas production is present and professional staff for operation and maintenance is available locally.

4.1.3 Large-scale biogas digester (400 m^3)

For a large-scale digester (working volume, 400 m^3) with the co-substrate, the initial installation cost is 1,820,454 USD, as shown in Supplementary Table S7; this cost includes the heating, feedstock, operation, and construction cost, where the plant can produce an energy production rate of 3.2 GJ/day (Fuchs et al., 2018; Campello et al., 2021) under ambient temperature, resulting in positive energy balance. Digester heating cost is avoided using different methods which are used on energy recovery; a system with energy recovery from produced biogas means that the heat and electricity produced from the digester can be utilized and re-used for supplying heat.

4.2 Biogas production and energy balance estimation

The AD process is complicated, and it depends on various parameters, such as the composition, size of feedstock, and operational conditions.

To make an AD model simple, basic assumptions have been made as follows:

1 The amount of biogas produced can be predicted based on the experimental results;
2 The digesters work at a hydraulic retention time of 30 days;
3 During the experimental period, no heat dispassion was observed from the digesters, and the ambient temperature was in the range of 20–26°C instead of temperature control;
4 A cubic meter of methane is equivalent to 34 MJ of energy;
5 The specific heat capacity (C) for FS is 4.2 MJ ton^{-1}°C^{-1}; and
6 Generally, 1 kg of FS generates approximately 15 L of biogas (0.015 m3/kg).

4.2.1 Methane production calculation

4.2.1.1 Methane yield at the 400-m^3 digester

Daily feedstock volume (Q) = 400/30 = 13.3 m^3 day^{-1} = 13,300 kg/day.

Methane gas production rate = Q × Biogas yield in fresh biogas feedstock.

Methane gas production rate is 13,300 kg/day × 0.015 m^3/kg = 199.5 m^3/day.

4.2.1.2 Methane yield at the 100-m^3 digester.

Q = 100/30 = 3.3 m^3 day^{-1} = 3,300 kg/day.

Methane gas production rate = Q × Biogas yield in fresh biogas feedstock.

Methane gas production rate = 3,300 kg/day × 0.015 m^3/kg = 49.5 m^3/day.

4.2.1.3 Methane yield at the 4-m^3 digester.

Q = 4/30 = 0.13 m^3 day^{-1} = 130 kg/day.

Methane gas production rate = Q × Biogas yield in fresh biogas feedstock.

Methane gas production rate = 130 kg/day × 0.015 m^3/kg = 1.95 m^3/day.

4.2.2 Energy balance calculations

The energy balance in AD system describes how much energy is used in an AD plant and how much is generated. Two sources of heat are required in AD as follows:

➢ Heat loss of the digester;
➢ Heat to bring the feedstock material up to the digester temperature.

4.2.2.1 Heat loss calculations

According to Fuchs et al. (2018), the expected heat loss (HL) from the digester surface can be calculated using the following equation:

$$\text{Heat loss (HL)} = UA\Delta T\,(\text{kw}), \tag{3}$$

where U = overall coefficient of heat transfer, W $m^{-2°}C^{-1}$, A = surface area of the digester m^2, and ΔT = temperature drop across the surface in question, °C.

According to Sapkota and Poudel (2019), the reported digester heat transfer coefficient is $U = 1.7$ W $m^{-2°}C^{-1}$.

(a) Heat loss for the 400-m^3 digester

Working volume: 80% of total volume.
$D = 1.3078\ V^{1/3} = 8.5$ m;
$H = 4 \times 0.3142\ D^3/3.14\ D^2 = 2.83$ m;
$A = V/H = 320/2.83 = 113.074\ m^2$.
The heat loss at the digester temperature of 37°C is as follows:
$HL = UA\ (T_2–T_1)$
HL = 1.7 × 113.074 × (37–26) = 2,114 kW = 0.36 GJ day^{-1}.

(b) Heat loss for the 100-m^3 digester

Working volume: 80% of total volume.
$D = 1.3078\ V^{1/3} = 4.7$ m;
$H = 4 \times 0.3142\ D^3/3.14\ D^2 = 1.87$ m;
$A = V/H = 80/1.87 = 42.78\ m^2$.
The heat loss at the digester temperature of 37°C is as follows:
$HL = UA\ (T_2\text{-}T_1)$
HL = 1.7 × 42.78 × (37–26) = 799.986 kW = 0.12 GJday^{-1}.

(c) Heat loss for the 4-m^3 digester

Working volume: 80% of total volume.
$D = 1.3078\ V^{1/3} = 1.8$ m;
$H = 4 \times 0.3142\ D^3/3.14\ D^2 = 0.72$ m;
$A = V/H = 3.2/0.72 = 4.4\ m^2$.
The heat loss at a digester temperature of 37°C is as follows:
$HL = UA\ (T_2–T_1)$
HL = 1.7 × 4.4 × (37–26) = 82.28 kW = 0.013 GJday^{-1}.

4.2.2.2 Heating of the feedstock

According to Fuchs et al. (2018), the feedstock added to the digester must be brought up to the operating temperature of the digester, as expressed in Eq. 4 as follows:

$$Q = Cp\,Q\Delta T, \tag{4}$$

where C = specific heat capacity of the feedstock (MJ $tonne^{-1°}C^{-1)}$, Q = volume to be added (m^3/day), and ΔT = temperature difference (°C)

(a) Heat required for the 400-m^3 digester

A 400-m^3 digester running at 37°C with a retention time of 30 days.
Volume added (Q) = 400/30 = 13.3 m^3 day^{-1};
Specific heat capacity (C) = 4.2 MJ $ton^{-1°}C^{-1}$;
Feedstock temperature = 26°C;
Heat required = 4.2 × 13.3 × (37–26) = 0.62 GJ day^{-1};
Total heat requirement = heat loss + heat for feedstock;
Total heat requirement including heat loss = 0.62 + 0.36 = 0.98 GJ day^{-1}.

(b) Heat required for the 100-m^3 digester

Volume added (Q) = 100/30 = 3.3 m^3 day^{-1};
Specific heat capacity (C) = 4.2 MJ $ton^{-1°}C^{-1}$;
Heat required = 4.2 × 3.3 × (37–26) = 0.153 GJ day^{-1};
Total heat requirement including heat loss = 0.15 + 0.12 = 0.27 GJ day^{-1}.

(c) Heat required for the 4-m^3 digester

Volume added (Q) = 4/30 = 0.13 m^3 day^{-1};
Specific heat capacity (C) = 4.2 MJ ton^{-1} °C^{-1};
Heat required = 4.2 × 0.13 × (37–26) = 0.006 GJ day^{-1};
Total heat requirement including heat loss = 4.2 × 0.13 × (37–26) = 0.006 + 0.013 = 0.019 GJ day^{-1}.

4.2.3 Energy generated from the produced biogas

The energy balance of digesters in scenarios 1, 2, and 3 was determined by assuming that the biogas produced was utilized using a combined heat and power (CHP) system. The energy output from the three digestion systems was calculated as described by Campello et al. (2021).

Electricity generated from the biogas produced = Biogas produced (m^3) × LHVCH4 × methane content (%) × engine efficiency.

Heat generated from biogas produced = Biogas produced (m^3) × LHVCH4 × methane content (%) × engine efficiency.

TABLE 5 Summary of three scenarios for FS anaerobic digestion.

Description	Scenario 1 (under ambient temperature)	Scenario 2	Scenario 3
Volume of the digester	4 m^3	100 m^3	400 m^3
Hydraulic retention time (days)	30	30	30
Feedstock volume (m^3/d)	0.13	3.3	13.3
Methane produced (m^3)	1.95	49.5	199.5
Heat value from biogas (GJ/d)	0.031	0.8	3.2
Energy demand for heating (GJ/d)	0.019	0.27	0.98
Energy balance (Eout-Ein) GJ/d	**+0.012**	**+ 0.53**	**+2.22**
Characteristics	Digester and fitting device	Digester, fitting device, and other equipment	Digester, equipment, fittings, and co-generator
Cost benefit analysis	The cooking fuel expenditure should be kept at a similar level, and based on the monthly expected biogas price, around 0.4 USD/m^3 can be charged equivalent to 264 USD/yr. Comparing to investment capital cost (764 USD), the project can pay back after 3 years of investment with a net present value of (NPV) + 28 USD	The minimum price of biogas that would make the project profitable is 0.40 USD/m^3, making a revenue of 7027 USD/year. So it is possible to pay back the investments cost of a well-planned 100-m^3 biogas plant within less than 6 years of investment with a net present value of (NPV) +1337 USD	The economic feasibility of the solution can be studied by comparing the costs and revenues. The revenue of the project is estimated to be 126,187.19 USD/yr (biogas sale, electricity, and diesel savings). From the analysis, it is clear that the project would be profitable at the end of its lifetime (15 years) compared to the total investment cost 1,840,454 USD; the project will have a net present value of (NPV) +52351 USD

The assumptions made were as follows: lower heating value (LHV) of methane of 35.59 MJ/m^3 and engine efficiencies of 40% for electrical energy and 50% for heat energy.

(a) Energy generated from biogas produced at the 400-m^3 digester

Heat generated from biogas produced = Biogas produced (m^3) × $LHVCH_4$ × methane content (%) × engine efficiency.

(199.5% × 35.59% × 50.4% × 40%) + (199.5% × 35.59% × 50.4% × 50%) = 3,195 MJ = 3.2 GJ.

(b)Energy generated from biogas produced at the 100-m^3 digester

Heat generated from biogas produced = Biogas produced (m^3) × $LHVCH_4$ × methane content (%) × engine efficiency.

(49.5% × 35.59% × 50.4% × 40%) + (49.5% × 35.59% × 50.4% × 50%) = 800 MJ = 0.8 GJ.

(c) Energy generated from biogas produced at the 4-m^3 digester

Heat generated from biogas produced = Biogas produced (m^3) × $LHVCH_4$ × methane content (%) × engine efficiency.

(1.95% × 35.59% × 50.4% × 40%) + (1.95% × 35.59% × 50.4% × 50%) = 31.23 MJ = 0.031 GJ.

The energy balance analysis of biogas produced during the whole study period from the 4, 100, and 400 m^3 digesters is shown in Table 5, where the biogas produced energy outputs of 0.031, 0.8, and 3.2 GJ. After subtracting the energy input (energy required in the system) from the energy output (energy leaving the system), the energy balance values were + 0.012, + 0.53, and + 2.22 GJ for the 4, 100, and 400 m^3 digesters, respectively.

4.3 Cost and benefit analysis for biogas technology dissemination in the context of Tanzania in terms of FS treatment.

4.3.1 Benefit analysis

Tanzania, which belongs to sub-Saharan African (SSA) countries, has several favorable conditions for biogas technology utilization. The country is dominated by a tropical climate with an average monthly temperature above 18°C throughout the year, which is well suited for AD (Mshandete and Parawira, 2009). Livestock keeping and on-site sanitation infrastructures are abundant to provide a significant potential for biogas production from animal excreta. The increasing prices of fossil fuels and fertilizer have helped in making biogas an attractive alternative for energy and fertilizer production in Tanzania. The increasing prices of fuel wood and other energy sources for cooking and expensive lighting costs when using kerosene have prompted interest in biogas as a cheaper, cleaner, and more convenient alternative energy source. The benefits of biogas to Tanzania are categorized in the three main pillars of sustainability, namely, environmental, social, and economic factors.

4.3.1.1 Environmental benefits

Inadequate sanitation deteriorates the environment and public health in urban areas of developing countries than in rural areas, where simple and sustainable on-site sanitation solutions can be implemented. Emptying pit latrines is a major problem in urban sanitation in low-income countries. Biogas can offer a sanitation solution in urban areas and has gained prominence in recent years. A biogas latrine is an integrated waste management system that provides a sanitation solution and energy in the form of biogas, and it reduces the collection and transportation cost of FS from an on-site system to a treatment facility (Mutai et al., 2016). Biogas generation may improve the water quality. Moreover, AD deactivates pathogens and parasites; thus, it is also quite effective in reducing the incidence of waterborne diseases. Similarly, waste collection and management are remarkably improved in areas with biogas plants. This condition leads to improvements in the environment, sanitation, and hygiene (Berhe et al., 2017). Firewood is the main energy source for cooking in Tanzania. The cutting down of trees for firewood has resulted in the rapid deterioration of forest reserves. In recent years, the abundant natural vegetation in the country has been cleared/transformed for agriculture, habitation, and firewood, thus contributing to climate change (Velempini et al., 2018). Brown (2006) added that a well-designed and installed biogas digester has several benefits; "it improves sanitation by converting generated FS into biogas; it reduces greenhouse gas (GHG) emissions; it serves time to search firewood and charcoal for cooking, preserve deforestation and natural vegetation, and it provides a high-quality organic fertilizer." Berhe et al. (2017) viewed biogas systems as a sustainable source of energy that can provide low-cost energy without gathering wood as fuel; it can lessen the degradation of indigenous forests, reduce GHG emissions into the air, and improve the carbon sequestration of indigenous forests. Kelebe and Olorunnisola, 2016 confirmed this finding and stated that 12 rural households that substituted firewood with biogas resulted in a decrease of 50%–60% of firewood consumption. They also stated that the 9,577 domestic biogas systems installed in Ethiopia in 2014 saved approximately 2,873 ha of the forest land. Minde et al. (2013) pointed out that if 1 kg of wood is burned in traditional cookstoves, it generates approximately 318 g of C. However, if biogas is used, each household saves the consumption of 3 metric ton of firewood annually. Biogas technology for FS treatment can combat environmental challenges such as spread of diseases, eutrophication, acidification, air pollution, and climate change issues (Cheng et al., 2022).

4.3.1.2 Social benefits

FSM is not gender-neutral and could deepen gender inequalities if not handled appropriately. Interventions must be based on a good understanding of gender-specific needs and, in particular, the constraints faced by women and girls in accessing safe sanitation. The lack of access to sanitation facilities has a differential impact on gender because of expectations regarding modesty and personal security. The unavailability of good sanitation facilities can lead to psychosocial stress for girls, whereas access to good sanitation reduces child mortality and death while supporting health (Hirve et al., 2014). The major responsibility of energy needs in terms of access to wood fuel requirements lies largely with women and children who have to trek long distances to harvest them for domestic use. This process is time-consuming and tiring because the loads are usually very heavy. This cultural practice is carried out mainly by women and children, especially young girls, who spend much time to search firewood in many parts of SSA countries. Lambe et al. (2015), Minde et al. (2013), and Fullerton et al. (2008) pointed out that biomass burning releases pollutants such as carbon monoxide, methane, nitrogen oxides, benzene, formaldehyde, benzopyrene, aromatics, and particulate matter, which cause considerable damage to women and children because they are more at risk for prolonged exposure. An additional indirect benefit of the use of AD systems is a product of the biogas generated and captured from these systems. Several communities that utilize AD and capture biogas do not have access to the main electric grid because of the remoteness or the high cost. The electricity produced from biogas becomes a tremendous social benefit to communities as it can change the way communities interact. AD systems can give farmers energy independence and make them self-sufficient. Another social benefit is the creation of jobs. When farms or mills utilize workers for daily operations, the addition of an AD system can create new jobs. Learning how to operate an AD system and perform routine operations and maintenance checks also improves laborer skills and can help establish the local expertise needed for additional biomass electricity systems. Smokeless biogas is an excellent substitute for use in developing countries, especially in Tanzania, to improve the well-being of women and children. The time saved from gathering fuelwood can be used for productive ventures and provide females with an opportunity to be in school.

4.3.1.3 Economic benefits

The inappropriate FSM facilities cause economic losses because of the cost of treating illnesses that result from poor sanitation and the loss of income through reduced productivity. Emptying FS remains a challenge in many cities because low-income households cannot afford the service (Cheng et al., 2017). Enormous revenue is generated by the various service providers who are active in this segment of FSM. In Tanzania, the Ministry of Water reported the emptying charges that occasionally elevates to as high as TZS 300,000 (130 USD) per trip when servicing far distances by using a private operator. AD systems eliminate the need to transport waste to an established waste disposal facility. The use of waste onsite cuts the upfront costs of transportation and generates financial gains with the byproducts produced. The process creates a viable energy source that can be used for heating and electricity for homes or the facility itself. This biomass energy may come with a net zero cost and offset electrical costs, thus providing new forms of energy to areas that may not have access to traditional electrical energy sources or generating profit if the energy produced can be sold. The bio-slurry from biogas plants is estimated to have high a nitrogen content compared with fresh manure, thus allowing AD systems to generate commodities such as fertilizer, which can be used at the site or sold for additional income. When bio-slurry is considered as manure, the return on investment in the process can be realized within 3–4 years (Minde et al., 2013). A nationwide deployment of biogas technology for institutions will generate many jobs in the form of carpentry, masonry, and plumbing. Cost savings on fossil fuel importation will also be realized.

4.3.2 Cost analysis

The cost of a domestic biogas digester falls into two categories, namely, construction and operation. The construction cost has three major components, namely, materials (e.g., cement, sand, gravel, bricks, steel rods and wire, and coatings), excavation and construction (e.g., technician service, labor, and steel mold used to cast concrete), and gas appliance parts (e.g., pipeline and valves, gas pressure gauge, desulfurizer, gas cooker, and gas lamp).

Operational costs also have three major components, namely, (e.g., collection, preparation, and purchase), maintenance (e.g., feeding and discharge), and repair or replacement of parts (e.g., gas pressure gauges, pipeline and valves, cooker spare parts, and lamp mantles). However, major difficulties are encountered in calculating operational costs. However, the manure or other feedstock generated by individual households has no commercial value in that case, and the operation cost is 2%–10% of the construction cost (Carmatec, 2020). The calculation shows that the total construction cost of 4, 100, and 400 m^3 digesters are 764, 40,825, and 1,820,454 USD, respectively.

5 Conclusion

In developing countries such as Tanzania, FSM is indeed a big challenge toward goal 6 of SDGS. Based on the laboratory tests by using mesophilic digestion at 37°C, a methane yield of 396 ml/g VS was achieved with the increment of 109 ml/g VS compared with the non-biochar addition experiment. The results showed that FS is a good raw material to be used for biogas production. The study provided a good insight into biochar-amended mesophilic AD of FS for enhanced methane production in terms of biochar dosage and particle sizes with the optimal dosage of 10–20 g/L. In comparison with the control digester without biochar amendment, average methane yields increased to 234–396 ml/gVS.

Considering the tropic climate, the laboratory test under ambient conditions in Tanzania showed that although the specific biogas production was relatively low, such digesters may have a great potential for practical applications in Tanzania because of the low capital and ease of operation. The theoretical analyses show that energy consumes large amounts of biogas when relied upon heating the digesters. However, the energy needed to optimize the reactor temperature can be balanced out by a partial amount of biogas produced. A strategy for FS treatment systems in the context of Tanzania has been proposed and developed. The practical application options for different local conditions include a household FS treatment and biogas production system (where a digester could be buried underground without special isolation and heating measures), community-scale FS treatment and a biogas production system (where isolation measures could be taken, and heating could be installed if there is surplus biogas, and professional staff for operation and maintenance is available locally), and large-scale FS treatment and biogas production equipped with modern technology and equipment for maximum biogas production. Although this study has been a successful comparative study, local biochar (man-made) and industrially produced biochar could be used for more clarification.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding authors.

Author contributions

MK contributed to the writing of the original draft and methodology. SC contributed to the conceptualization, writing, reviewing, and editing of the manuscript. SM, SN, and KV contributed to the methodology, writing, reviewing, and editing of the manuscript. XL and KD contributed to the data curation of the study. XW contributed to visualization of the study. ZL contributed to the funding acquisition and supervision of the study. All authors approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.911348/full#supplementary-material

References

Afifah, U., and Priadi, C. R. (2017). Biogas potential from anaerobic co-digestion of faecal sludge with food waste and garden waste. *AIP Conf. Proc.* 1826, 020032. doi:10.1063/1.4979248

APHA (2017). *Standard methods for the examination of water and wastewater*. 23rd Edition. Washington, DC: American Public Health Association APHA.

Arikan, O. A., Mulbry, W., and Lansing, S. (2015). Effect of temperature on methane production from field-scale anaerobic digesters treating dairy manure. *Waste Manag.* 43, 108–113. doi:10.1016/j.wasman.2015.06.005

Bassan, M. (2014). in *Faecal sludge management: Systems approach for implementation and operation*. Editors L. Strande, L. Ronteltap, and D. Brdjanovic (London: IWA publishing).

Bakraoui, M., Karouach, F., Ouhammou, B., Aggour, M., Essamri, A., and El Bari, H. (2020). Biogas production from recycled paper mill wastewater by UASB digester: Optimal and mesophilic conditions. *Biotechnol. Rep.* 25, e00402. doi:10.1016/j.btre.2019.e00402

Berhe, M., Hoag, D., Tesfay, G., and Keske, C. (2017). Factors influencing the adoption of biogas digesters in rural Ethiopia. *Energy sustain. Soc.* 7, 10. doi:10.1186/s13705-017-0112-5

Brown, V. J. (2006). Biogas: A bright idea for Africa. *Environ. Health Perspect.* 114, A300–A303. doi:10.1289/ehp.114-a300

Browne, J. D., Gilkinson, S. R., and Frost, J. P. (2015). The effects of storage time and temperature on biogas production from dairy cow slurry. *Biosyst. Eng.* 129, 48–56. doi:10.1016/j.biosystemseng.2014.09.008

Cai, J., He, P., Wang, Y., Shao, L., and Lu, F. (2016). Effects and optimization of the use of biochar in anaerobic digestion of food wastes. *Waste Manag. Res.* 34, 409–416. doi:10.1177/0734242x16634196

Campello, L. D., Barros, R. M., Tiago Filho, G. L., and dos Santos, I. F. S. (2021). Analysis of the economic viability of the use of biogas produced in wastewater treatment plants to generate electrical energy. *Environ. Dev. Sustain.* 23, 2614–2629. doi:10.1007/s10668-020-00689-y

Carmatec (2020). *Tanzania domestic biogas program report 2020*. Dar es Salaam: Centre for Agricultural Mechanization and Rural Technology CARMATEC.

Cheng, Q., Xu, C., Huang, W., Jiang, M., Yan, J., Fan, G., et al. (2020). Improving anaerobic digestion of piggery wastewater by alleviating stress of ammonia using biochar derived from rice straw. *Environ. Technol. Innovation* 19, 100948. doi:10.1016/j.eti.2020.100948

Cheng, S. K., Zheng, S., Bai, X., and Zhao, S. M. Y. (2017). Assessment of two faecal sludge treatment plants in urban areas: Case study in Beijing. *Int. J. Agric. Biol. Eng.* 10, 237–245. doi:10.3965/j.ijabe.20171003.3067

Cheng, S., Li, Z., Mang, H. P., Huba, E. M., Gao, R., and Wang, X. (2014). Development and application of prefabricated biogas digesters in developing countries. *Renew. Sustain. Energy Rev.* 34, 387–400. doi:10.1016/j.rser.2014.03.035

Cheng, S., Li, Z., Uddin, S. M. N., Mang, H. P., Zhou, X., Zhang, J., et al. (2018). Toilet revolution in China. *J. Environ. Manag.* 216, 347–356. doi:10.1016/j.jenvman.2017.09.043

Cheng, S., Long, J., Evans, B., Zhan, Z., Li, T., Chen, C., et al. (2022). Non-negligible greenhouse gas emissions from non-sewered sanitation systems: A meta-analysis. *Environ. Res.* 212, 113468. doi:10.1016/j.envres.2022.113468

Cooney, M. J., Lewis, K., Harris, K., Zhang, Q., and Yan, T. (2016). Start up performance of biochar packed bed anaerobic digesters. *J. Water Process Eng.* 9, e7–e13. doi:10.1016/j.jwpe.2014.12.004

Dev, S., Saha, S., Kurade, M. B., Salama, E. S., El-Dalatony, M. M., Ha, G. S., et al. (2019). Perspective on anaerobic digestion for biomethanation in cold environments. *Renew. Sustain. Energy Rev.* 103, 85–95. doi:10.1016/j.rser.2018.12.034

Dhungana, B., Lohani, S. P., and Marsolek, M. (2022). Anaerobic Co-digestion of food waste with livestock manure at ambient temperature: A biogas based circular economy and sustainable development goals. *Sustainability* 14, 3307. doi:10.3390/su14063307

Fagbohungbe, M. O., Herbert, B. M., Hurst, L., Li, H., Usmani, S. Q., and Semple, K. T. (2016). Impact of biochar on the anaerobic digestion of citrus peel waste. *Bioresour. Technol.* 216, 142–149. doi:10.1016/j.biortech.2016.04.106

Filer, J., Chang, S., and Ding, H. (2019). Biochemical methane potential (BMP) assay method for anaerobic digestion research. *Water* 11. doi:10.3390/w11050921

Fuchs, W., Wang, X., Gabauer, W., Ortner, M., and Li, Z. (2018). Tackling ammonia inhibition for efficient biogas production from chicken manure: Status and technical trends in Europe and China. *Renew. Sustain. Energy Rev.* 97, 186–199. doi:10.1016/j.rser.2018.08.038

Fullerton, D. G., Bruce, N., and Gordon, S. B. (2008). Indoor air pollution from biomass fuel smoke is a major health concern in the developing world. *Trans. R. Soc. Trop. Med. Hyg.* 102, 843–851. doi:10.1016/j.trstmh.2008.05.028

Hagos, K., Zong, J., Li, D., Liu, C., and Lu, X. (2017). Anaerobic co-digestion process for biogas production: Progress, challenges and perspectives. *Renew. Sustain. Energy Rev.* 76, 1485–1496. doi:10.1016/j.rser.2016.11.184

Haider, M. R., ZeshanYousaf, S., Malik, R. N., and Visvanathan, C. (2015). Effect of mixing ratio of food waste and rice husk co-digestion and substrate to inoculum ratio on biogas production. *Bioresour Technoogy* 190, 451–457. doi:10.1016/j.biortech.2015.02.105

He, P., Liu, Y., Shao, L., Zhang, H., and Lu, F. (2018). Particle size dependence of the physicochemical properties of biochar. *Chemosphere* 212, 385–392. doi:10.1016/j.chemosphere.2018.08.106

Hewage, S., and Priyadarshani, R. (2016). *Effect of charred digestate (biochar) and digestate on soil organic carbon and nutrients in temperate bioenergy crop production systems*. Hamburg, Germany: Universität Hamburg Hamburg.

Hirve, S., Lee, P., and Weiss, M. (2014). Psychosocial stress associated with sanitation practices: Experiences of women in a rural community in India. *J. Water, Sanitation Hyg. Dev.* 5, 115–126. doi:10.2166/washdev.2014.110

Jimenez, J., Latrille, E., Harmand, J., Robles, A., Ferrer, J., Gaida, D., et al. (2015). Instrumentation and control of anaerobic digestion processes: A review and some research challenges. *Rev. Environ. Sci. Biotechnol.* 14, 615–648. doi:10.1007/s11157-015-9382-6

Kelebe, H. E., and Olorunnisola, A. (2016). Biogas as an alternative energy source and a waste management strategy in Northern Ethiopia. *Biofuels* 7, 479–487. doi:10.1080/17597269.2016.1163211

Khan, E. U., and Martin, A. R. (2016). Review of biogas digester technology in rural Bangladesh. *Renew. Sustain. Energy Rev.* 62, 247–259. doi:10.1016/j.rser.2016.04.044

Lambe, F., Jürisoo, M., and Wanjiru, H. (2015). *Bringing clean, safe, affordable cooking energy to households across Africa: An agenda for action*. Stockholm and Nairobi, for the new climate economy: Prepared by the Stockholm Environment Institute.

Lohani, S. P., Pokhrel, D., Bhattarai, S., and Pokhrel, A. K. (2022). Technical assessment of installed domestic biogas plants in Kavre, Nepal. *Renew. Energy* 181, 1250–1257. doi:10.1016/j.renene.2021.09.092

Makoye, K. (2017). *Tanzanian city gets new sewage scheme to curb disease, ocean pollution*. Zanzibar, Tanzania: WIOMSA and UN-Habitat.

Martí-Herrero, J., Alvarez, R., Cespedes, R., Rojas, M., Conde, V., Aliaga, L., et al. (2015). Cow, sheep and llama manure at psychrophilic anaerobic co-digestion with low cost tubular digesters in cold climate and high altitude. *Bioresour. Technol.* 181, 238–246. doi:10.1016/j.biortech.2015.01.063

Mehariya, S., Patel, A. K., Obulisamy, P. K., Punniyakotti, E., and Wong, J. W. (2018). Co-digestion of food waste and sewage sludge for methane production: Current status and perspective. *Bioresour. Technol.* 265, 519–531. doi:10.1016/j.biortech.2018.04.030

Minale, M., and Worku, T. (2014). Anaerobic co-digestion of sanitary wastewater and kitchen solid waste for biogas and fertilizer production under ambient temperature: Waste generated from condominium house. *Int. J. Environ. Sci. Technol. (Tehran).* 11, 509–516. doi:10.1007/s13762-013-0255-7

Minde, G., Sandip, S., and Kalyanraman, V. (2013). Biogas as a sustainable alternative for current energy need of India. *J. Sustain. Energy & Environ.* 4, 121–132.

Mrimi, E. C., Matwewe, F. J., Kellner, C. C., and Thomas, J. M. (2020). Safe resource recovery from faecal sludge: Evidence from an innovative treatment system in rural Tanzania. *Environ. Sci. Water Res. Technol.* 6, 1737–1748. doi:10.1039/c9ew01097a

Mshandete, A., and Parawira, W. (2009). Biogas technology research in selected sub-Saharan African countries - a review. *Afr. J. Biotechnol.* 8, 116–125.

Mutai, P., Charles, N., John, B. T., and Robinah, N. (2016). Key factors affecting performance of biogas latrines in urban informal areas: Case of Kampala and Nairobi, East Africa. *Afr. J. Environ. Sci. Tech.* 10, 207–220. doi:10.5897/ajest2016.2108

Nandi, R., Saha, C. K., Sarker, S., Huda, M. S., and Alam, M. M. (2020). Optimization of reactor temperature for continuous anaerobic digestion of cow manure: Bangladesh perspective. *Sustainability* 12, 8772. doi:10.3390/su12218772

Nasir, I. M., Mohd Ghazi, T. I., and Omar, R. (2012). Anaerobic digestion technology in livestock manure treatment for biogas production: A review. *Eng. Life Sci.* 12, 258–269. doi:10.1002/elsc.201100150

Pan, J., Ma, J., Liu, X., Zhai, L., Ouyang, X., and Liu, H. (2019). Effects of different types of biochar on the anaerobic digestion of chicken manure. *Bioresour. Technol.* 275, 258–265. doi:10.1016/j.biortech.2018.12.068

Ripoll, V., Agabo-Garcia, C., Perez, M., and Solera, R. (2020). Improvement of biomethane potential of sewage sludge anaerobic co-digestion by addition of "sherry-wine" distillery wastewater. *J. Clean. Prod.* 251, 119667. doi:10.1016/j.jclepro.2019.119667

Rupf, G. V., Bahri, P. A., de Boer, K., and McHenry, M. P. (2015). Barriers and opportunities of biogas dissemination in Sub-Saharan Africa and lessons learned from Rwanda, Tanzania, China, India, and Nepal. *Renew. Sustain. Energy Rev.* 52, 468–476. doi:10.1016/j.rser.2015.07.107

Sabbir, A. S. M. Y. B., Saha, C. K., Nandi, R., Zaman, M. F. U., Alam, M. M., and Sarker, S. (2021). Effects of seasonal temperature variation on slurry temperature and biogas composition of a commercial fixed-dome anaerobic digester used in Bangladesh. *Sustainability* 13, 11096. doi:10.3390/su131911096

Sapkota, P., and Poudel, L. (2019). Heat exchanger for bio-digester under thermophilic range. *J. Adv. Coll. Engin. Mgt.* 5, 79–88. doi:10.3126/jacem.v5i0.26691

Shanmugam, P., and Horan, N. J. (2009). Optimising the biogas production from leather fleshing waste by co-digestion with MSW. *Bioresour. Technol.* 100, 4117–4120. doi:10.1016/j.biortech.2009.03.052

Simeon, M. I. (2017). *Biogas production from the Co-digestion of cow dung and poultry droppings using a plastic cylindrical digester*.

Sinervo, R. (2017). *Effects of biochar addition on anaerobic digestion and comparison of different biochar qualities*.

Skovsgaard, L., and Jacobsen, H. K. (2017). Economies of scale in biogas production and the significance of flexible regulation. *Energy Policy* 101, 77–89. doi:10.1016/j.enpol.2016.11.021

Soler-Cabezas, J. L., Mendoza-Roca, J., Vincent-Vela, M., Lujan-Facundo, M., and Pastor-Alcaniz, L. (2018). Simultaneous concentration of nutrients from anaerobically digested sludge centrate and pre-treatment of industrial effluents by forward osmosis. *Sep. Purif. Technol.* 193, 289–296. doi:10.1016/j.seppur.2017.10.058

Vanegas, C., and Bartlett, J. (2013). Anaerobic digestion of laminaria digitata: The effect of temperature on biogas production and composition. *Waste Biomass Valorization* 4, 509–515. doi:10.1007/s12649-012-9181-z

Velempini, K., Smucker, T. A., and Clem, K. R. (2018). Community-based adaptation to climate variability and change: Mapping and assessment of water resource management challenges in the north pare highlands, Tanzania. *Afr. Geogr. Rev.* 37, 30–48. doi:10.1080/19376812.2016.1229203

Yong, Z., Dong, Y., Zhang, X., and Tan, T. (2015). Anaerobic co-digestion of food waste and straw for biogas production. *Renew. Energy* 78, 527–530. doi:10.1016/j.renene.2015.01.033

Yu, Q., Liu, R., Li, K., and Ma, R. (2019). A review of crop straw pretreatment methods for biogas production by anaerobic digestion in China. *Renew. Sustain. Energy Rev.* 107, 51–58. doi:10.1016/j.rser.2019.02.020

Zhang, L., Guo, B., Zhang, Q., Florentino, A., Xu, R., Zhang, Y., et al. (2019). Co-digestion of blackwater with kitchen organic waste: Effects of mixing ratios and insights into microbial community. *J. Clean. Prod.* 236, 117703. doi:10.1016/j.jclepro.2019.117703

Zheng, L., Cheng, S., Han, Y., Wang, M., Xiang, Y., Guo, J., et al. (2020). Bio-natural gas industry in China: Current status and development. *Renew. Sustain. Energy Rev.* 128, 109925. doi:10.1016/j.rser.2020.109925

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WASH facilities prevalence and determinants: Evidence from 42 developing countries

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Improved WASH facilities are crucial for reducing infectious diseases such as diarrhoea, malaria, dengue, and worms, etc. However, a large proportion of households in developing countries lack basic WASH facilities. Therefore, the current paper uses the household data from 733,223 households in fourty two developing countries to explore the prevalence rate of basic WASH facilities. The result shows that access to basic drinking water is much better than access to other WASH facilities, such as basic sanitation and hygiene facilities. However, the prevalence of basic drinking water, basic sanitation, and basic hygiene vary across different regions and countries-low in Africa and South Asia. The multi-level regression model shows that households with better economic status and education and urban households are more likely to use basic WASH facilities. Further, women empowerment and already having one WASH practice are also positively associated with the adoption of other WASH facilities. The policy should aim at improving awareness about the benefit of WASH facilities through education, and it should also subsidize WASH facilities for poor households and those living in rural areas.

KEYWORDS
WASH services, developing countries, basic sanitation facilities, basic hygiene facilities, wealth, and education

1 Introduction

"*WASH*" stands for three critical aspects for health, survival, and development: Water, Sanitation, and Hygiene. Access to improved water, sanitation, and hygiene practices contributes to a healthy life and is documented to benefit the economy. Realizing the importance of access to WASH facilities, in 2010, the United Nations General Assembly endorsed access to safe drinking water and sanitation as a fundamental human right (UN Assembly, 2010). Diarrhoeal diseases due to poor sanitation, poor hygiene, or unsafe drinking water were responsible for 9 percent of the deaths of children under five (484,000) (UNICEF, 2022). Children who live in inadequate WASH systems not only suffer from an increased risk of mortality but also experience severe nutritional deficiency (World Health Organization, 2015). The latest Global Nutrition report quoted that globally 45.4 million children aged 5 years and less are wasted (Global Nutrition Report, 2021). Adoption of good sanitation and hygiene practices is well established as a cost-effective, easy to practice, and most effective public health intervention in preventing infectious diseases like diarrhoea, cholera, hepatitis, etc. (Fewtrell et al., 2005). Therefore, Government in developing countries has been making a serious effort to meet Sustainable Development Goal 6 (SDG-6) and its sub-targets (Targets 6.1 and 6.2) under the 2030 Agenda for Sustainable Development.

Recent research shows that appropriate disposal of excreta, hand wash habits, and treated water reduce diarrhoeal cases from 48 percent to 17 percent (Cairncross et al., 2010). According to Wolfe et al. (2018), at 75 percent coverage, sanitation reduces diarrhoea risks by 25–30 percent, with a further 45 percent reduction when sanitation coverage exceeds 75 percent. Additionally, safely managed water, which is defined as the treatment of basic water alone, can considerably reduce diarrhoeal deaths (Fewtrell et al., 2005; Clasen et al., 2007). Studies also established that the practice of basic hygiene in households, i.e., using water and soap for hand-washing, prevents diarrhoea (44%) and pneumonia (25%) in children under age five (WHO, 2005). A study conducted in Nigeria found that about 17 percent of under-five deaths caused due to diarrhoea can be prevented through proper sanitation (Oloruntoba et al., 2014). Some deadly diseases like cholera and typhoid are also avoidable by exercising good sanitation and water treatment (Aiello et al., 2008; World Health Organization, 2015). There are enough shreds of evidence to support the fact that maternal health is also interlinked with WASH services-water, sanitation, and hygiene act as a catalyst in improving maternal health outcomes and postpartum. A systematic review conducted in 2014 found a significant association between poor WASH practice and maternal mortality (Benova, et al., 2014). Furthermore, the historical link between hygiene and childbirth and the effect of clean water accessibility on safe delivery is well recognized (Semmelweis and Semmelweis, 1983; Gould, 2010; Nalule, Y. et al., 2021). Therefore, improved WASH is crucial to promote health and sustainable development, as evidenced by the studies described above.

Through the combined efforts of public and private sector stakeholders, about 2.1 billion people have had access to improved sanitation facilities, and 2.6 billion people have been exposed to improved water sources globally since 1990 (UNICEF, 2016). During the same period, encouraging better sanitation practices deepened through sector programming and planning; the proportion of people who washed their hands with soap and water benefited, and the taboos to discuss defecation and menstrual hygiene weakened (UNICEF, 2016).

Despite several gains, the Millennium Development Goal (MDG) and its important targets were missed by a wide margin. Over 2 billion people lack drinking water that is readily available at home and free from contamination. Nearly 2 billion people lack access to basic water needs, which can be fetched within 30 min round trip, and almost 122 million people drink untreated water from surface sources like lakes, rivers, etc. (World Health Organization/United Nations Childrens' Fund, 2021). Different regions observed different challenges regarding water services. The supply of a safely managed water source remains a challenge in the least developed countries, where an estimated 1.2 billion people depend on sources or systems with significant sanitation risks (Onda et al., 2012). In sub-Saharan Africa, approximately 25–40 percent of water sources were not functioning at any given time (Tincani et al., 2015). At the same time, globally, every third person does not have access to basic sanitation, defined as facilities for the safe disposal of human waste. According to the Joint Monitoring report (JMP), nearly half of the world's population lacked safely managed sanitation services, and approximately 71 percent of population used water and soap after defecation (World Health Organization, 2021). Another study supports the previous arguments that, 502,000 diarrhoeal deaths were due to unsafe drinking water, 280,000 deaths were attributable to poor sanitation, and 297,000 were due to inadequate hand-washing practices (Prüss-Ustün et al., 2014).

The attention shifted from millennium development goals to sustainable development goals (SDG) with an ambitious vision to achieve global access to "safely managed water" and "basic sanitation facility," and ¨hygiene¨ by 2030. The target defined under SDG 6 (6.1 and 6.2) ensures continuous and universal access to basic WASH resources, i.e., Water, Sanitation, and Hygiene, to address deficiencies prevalent among low- and middle-income countries (LMICs) and populations living in vulnerable situations (Nagabhatla et al., 2019). The approach from MDGs to SDGs has shifted from" "to achieve the set goals" to "growth for all".

Against the backdrop of a lack of comparative analysis covering different countries and continents, this paper fills in the important research gap by examining the level of WASH services in 42 low and middle-income countries and the drivers of the adoption of WASH facilities. This paper also contributes to the literature as it uses multi-level logit modeling, which accounts for the country and regional level differences. Further, it sheds light on the nature of inequalities that exist in different settings and addresses challenges that still exist in ensuring that progress reaches all.

2 Data and methodology

2.1 Data sources

The study is based on recent Demographic Health Surveys (DHS) conducted between 2010 and 2020 in 42 developing countries from Asia, Sub-Saharan Africa, Latin America, and the Caribbean, Europe, and the Oceania region[1]. The total sample

1 The Country with survey year are given as follows: Afghanistan: 2015, Bangladesh: 2017–18, Cambodia: 2014, India: 2015–16, Indonesia: 2017, Maldives: 2016–17, Nepal: 2016, Pakistan: 2017–18, Philippines: 2017, Timor-Leste: 2016, Papua New Guinea: 2016–17, Columbia: 2015–16, Guatemala: 2014–15, Haiti: 2016–17, Tajikistan: 2017, Albania: 2017–18, Armenia: 2015–16, Jordan: 2017–18, Turkey: 2013, Angola: 2015–16, Benin: 2017–18, Burkina Faso: 2010, Burundi: 2016–17, Cameroon: 2018–19, Chad: 2014–15:, Ethiopia: 2016, Gambia: 2019–20, Ghana: 2014, Guinea: 2018, Kenya:2 020, Liberia: 2019–20, Malawi: 2015–16, Mali: 2018, Nigeria: 2018, Rwanda: 2019–20, Senegal: 2019, Sierra Leone: 2019, South Africa: 2016, Tanzania: 2015–16, Uganda: 2016, Zambia: 2018, Zimbabwe: 2015.

used in the study is 733,223 from 42 countries, and the sample size by country is provided in Supplementary Appendix 1, Supplementary Table A1. DHS, funded by U.S. Agency for International Development (USAID), is a nationwide survey collected every 5 years across low- and middle-income countries and employs stratified multi-stage sampling techniques to ensure national and sub-national representativeness. With the broad objective, the survey estimates core demographic indicators like fertility, mortality, and family planning and provides information on maternal and child health indicators such as immunization, skilled birth attendance, domestic violence, etc. A detailed description of the study design, sampling frame, survey implementation, weighting mechanism and quality of data collection, and corresponding non-sampling errors are published for each round of national reports (ICF International, 2012). The study used the household file to elicit inequality in access to water, sanitation, and hand-washing facilities across 42 developing countries. These files provide characteristics of the dwelling unit, e.g., source and access to water, sanitation, and hygiene, ownership of various durable goods, type of cooking fuel, materials used for house construction, etc. Permission to use the data set was sought from Measure DHS. The data set is publically available at the Measure DHS website and can be accessed on request from https://dhsprogram.com/data/available-datasets.cfm.

2.2 Empirical methodology

Multi-level logistic regression models was employed to elicit variations in coverage of basic WASH. Because of the hierarchal nature of the influence of households and communities on access to basic WASH services, three-level binary logistics regression was used for the analysis. DHS surveys in selected countries used a uniform multi-stage cluster sampling approach. This procedure introduces multi-level dependency among the observations, and the dependency issue often arises due to the hierarchical nature of data. In DHS survey research, clustered samples have several levels, e.g., cluster, community, and geographical regions. Besides using household socioeconomic factors as explanatory variables, including these geographical settings will control for other potential factors such as environment, development, and infrastructures that facilitate the utilization of basic WASH services.

Therefore, traditional logistic regression (single-level) in the nested setting invites errors on various fronts. Firstly, logistic regression requires the assumptions: 1) independence of the observations conditional on the explanatory variables and 2) uncorrelated residual errors, and these assumptions are not always met when analyzing nested data (Snijders, and Bosker, 2011; Goldstein, 2011). Secondly, due to heterogeneity at the regional level, a single-level model is no longer valid and reasonable and gives errors in estimating the model parameters. Hence to evaluate the differences offered by different layers of explanatory variables on the access to basic water, sanitation, and hygiene services and to measure the regional and country-level variations, multi-level binary regression model was adopted. This allows for the simultaneous examination of the effects of group-level (cluster and region) and household-level variations on outcomes, while accounting for the non-independence of observations within groups (Raudenbush and Bryk, 2002). The multi-level analysis facilitates the investigation of between-group and within-group variability and how variables at both the group and individual levels are related to the variability.

In multi-level analyses using pooled data (combining 42 countries), the household is considered at the first level, the country at the second level, and the region at the third level. Moreover, a two-level binary logistic regression model has been used to assess variations at the country level, where the household is at level one, and the region within the country is at level two. Thus, we can consider the effect of both sample clustering and unobserved factors at the community level. The formal econometric model used in the analysis is as follows;

$$log\frac{\left(p_{kji}\right)}{\left(1-p_{kji}\right)} = \alpha + X_{kji}\beta + \mu_{kj} + \delta_k \quad (1)$$

Where, subscript k, j, i denote region, country, and household, respectively;

p_{kji} is the probability of i-th household of country j and region k reported basic WASH service (water, sanitation, and hygiene); α the constant corresponding to the study variable; X_{kji} the covariates for household i for country j and region k, including selected explanatory variables; β the vector of parameters to be estimated corresponding to the selected explanatory variables at the household level; μ_{kj} the random effect at the country level within region k; and; δ_k the random effect at the region k level.

Both μ_{kj} and δ_k are random variables at the country and region level and assume to follow multivariate normal distributions.

2.3 Dependent and independent variable

To assess the progress in WASH services, WHO and JMP have developed a new ladder: Basic, Limited, and Unimproved/No facility. These have been updated and expanded to facilitate enhanced global monitoring of drinking water, sanitation, and hygiene. These modified ladders build on the previously defined improved/unimproved classification, thereby providing continuity with past monitoring and introducing new rungs with additional criteria relating to service levels. For this study, we concentrated on three dependent variables defined

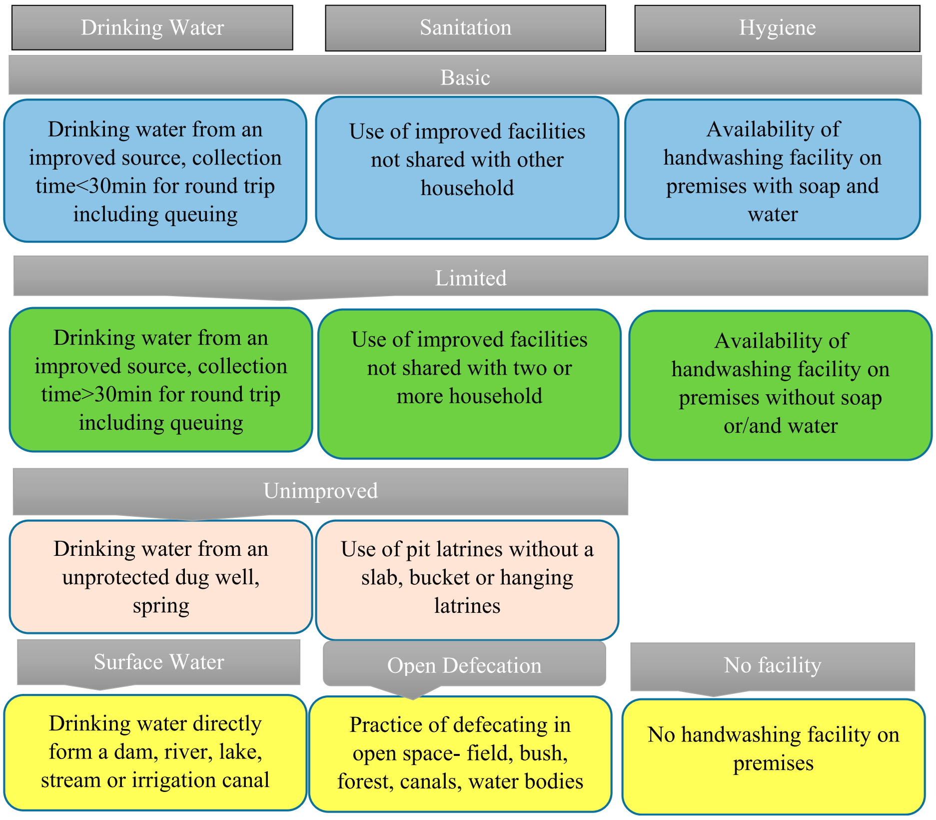

FIGURE 1
Definition of Water, Sanitation, and Hygiene facilities according to JMP (WHO) ladder.

for the study population, which assign a value of 1 to households that use basic services (water, sanitation, and hygiene) and 0 to those households that use limited or unimproved services, and had no facility of hand-washing, practiced open defecation and used surface water for drinking. The definition of WASH indicators is given in Figure 1.

Seven explanatory variables were used in the study, a dummy of the place of residence (rural *versus* urban), a dummy of the sex of the household head (male *versus* female), the age of the household head, the dummy for the education of household head (no education, primary, secondary, and higher), wealth index dummy (poorest, poorer, middle, richer, and richest), dummy of the sex composition of the household (three groups: number of males equals number of females; number of males > number of females; number of males < number of females), and women's decision-making power. The decision-making power of women is a composite variable derived from three questions. We have recorded the composite variable into three categories: *no decision*-if all three answers to the questions on the decision are no; *one or two decisions*—if at least one or two responses are yes; *three decisions*-if answers of all three questions are yes. These variables were selected based on their significant association with the outcome variable and the literature review. Three dependent variables, i.e., basic drinking water facility (yes/no), basic sanitation facility (yes/no), and basic hygiene facility (yes/no), were also added to the regression analysis to examine if having one of the WASH facilities also influence the adoption of the other.

3 Results

3.1 Status of WASH facilities

Before delving into the detailed statistical explanation of models on how socioeconomic and demographic factors affect access to basic WASH services, this section presents the coverage of basic water, sanitation, and hygiene practices among the countries used in the study (see Supplementary Table A1; Supplementary Figures 1A–3A in Appendix 1). The selected countries from West Asia and European regions have the highest prevalence of basic drinking water services (see Figure 2). Almost all households in these regions have universal access to basic drinking water facilities (98%). The

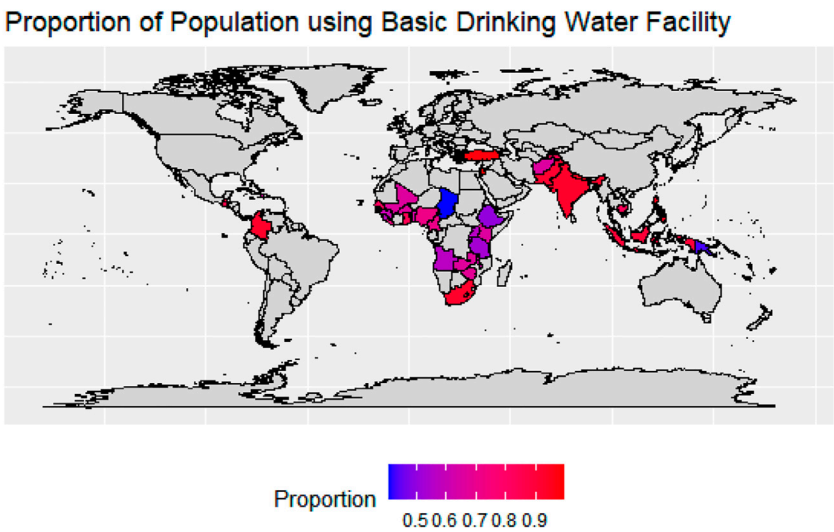

FIGURE 2
Proportion of population using basic drinking water facility in the study countries. Note: Proportion estimated as the share of sampled households using basic drinking water facility to the total sampled households by countries. Source: Authors estimation based on the DHS data.

proportion of households with access to basic water services in the countries in this region ranges from 97% to 99.6%.

In five of the nine countries (Bangladesh was dropped due to limited data) listed in the South and Southeast Asian region, more than 90 percent of households have access to basic drinking facilities; these six countries are India (92.7%), Indonesia (90%), Maldives (99.4%), Nepal (94.8%), Pakistan (91.6%), Philippines (95.2%). The region is ranked second in terms of access to basic drinking water facilities, with a prevalence rate of 91 percent. It is noteworthy to mention that there is wide variation between countries in the region—35 percent of households in Afghanistan still lack basic drinking water services, followed by Timor-Leste (25%) and Cambodia (17%). In Latin America and the Caribbean region, Colombia has the highest prevalence of basic drinking water (around 93 percent), followed by Guatemala (86%). In Haiti, 3 out of 10 households still did not have access to basic drinking water. Regional level prevalence shows that Latin America and the Caribbean region rank third with an 86 percent prevalence of basic water access.

In 23 Sub-Saharan African (SSA) countries, the prevalence of basic drinking water facilities is around 64 percent and ranges from 41 percent in Chad to 92 percent in Gambia and South Africa. Out of 23 countries, 16 had less than 70 percent basic drinking water coverage, and the rest seven countries with more than 70% coverage are Cameroon (71%), Gambia (92.3%), Ghana (83.7%), Liberia (74.7%), Nigeria (71.8%), Senegal (81.6%), South Africa (92.3%). Coverage of basic drinking water services was lowest in Papua New Guinea, nearly 57 percent of households still use limited or unimproved or surface water facilities.

Albania (97%), Turkey (96.6%), Jordan (98.2%), and Tajikistan (96.5%) seem to be doing well in terms of basic sanitation, with all most every household having access to basic sanitation (see Figure 3 and Supplementary Table A1; Supplementary Figures 1A–3A in Appendix 1); in contrast, in Armenia, only 77.6 percent had access to sanitation. Nearly half of the households in 10 South and Southeast Asian countries covered in this research still use limited/unimproved facilities or practice open defecation; these countries are Afghanistan (26.1%), Bangladesh (441%), Cambodia (46.11%), India (48.51%), Timor-Leste (51.81%). Among South and Southeast Asian countries listed in this research, the coverage of basic sanitation facilities was highest in Maldives (99.4%), whereas 11 out of 42 countries registered >70 percent coverage of basic sanitation services. The lowest coverage was recorded in two SSA countries, Chad and Ethiopia, where only 6 out of 100 households had access to basic sanitation facilities. Of the remaining 21 SSA countries, 13 had less than 40 percent coverage of basic sanitation facilities. In SSA countries, only 31 percent of households had access to basic sanitation services. West Asia, Latin America, and the Caribbean regions are the second-best regions, with 66 percent of households with access to basic sanitation facilities. After desegregating this prevalence at the country level, we found a skewed distribution ranging from 31.1 percent in Haiti to 84.4 percent in Columbia.

Figure 4 and Supplementary Table A1; Supplementary Figures 1A–3A in Appendix 1 shows that 38 out of 42 countries had data to estimate the coverage of basic hygiene facilities. Due to a lack of data on hand-washing, four countries—Albania, Jordan, Turkey, and Columbia-were

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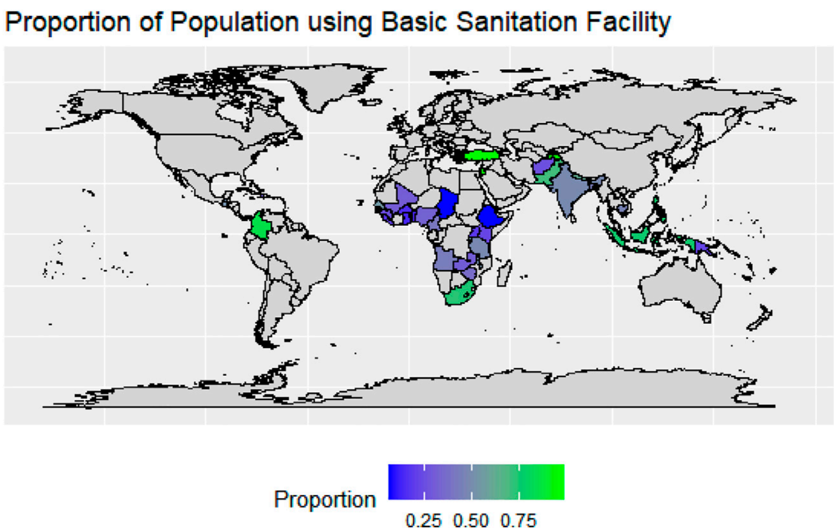

FIGURE 3
Proportion of population using basic sanitation facility in the study countries. Note: Proportion estimated as the share of sampled households using basic sanitation facility to the total sampled households by countries. Source: Authors estimation based on the DHS data.

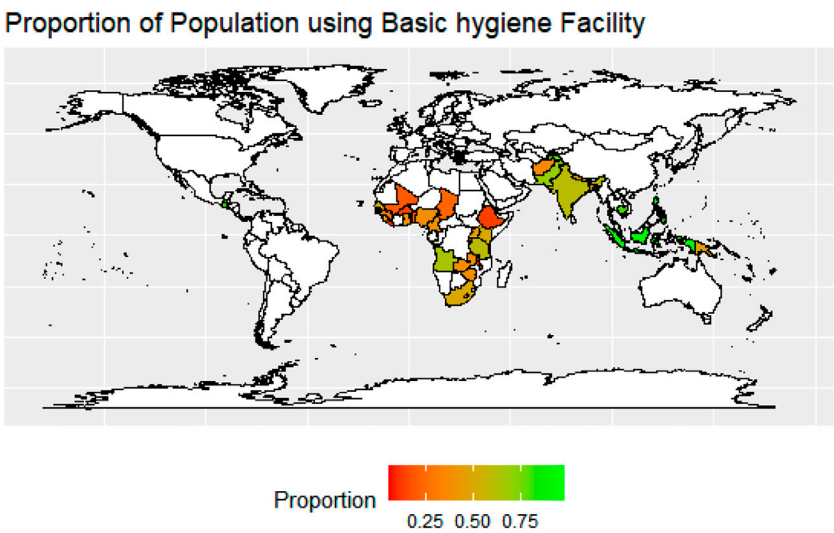

FIGURE 4
Proportion of population using basic hygiene facility in the study countries. Note: Proportion estimated as the share of sampled households using basic hygiene facility to the total sampled households by countries. Source: Authors estimation based on the DHS data.

dropped from the analysis. Only 4 out of 38 countries had more than 90 percent coverage of basic sanitation facilities, of which three were from the South and Southeast Asia region (Indonesia, Maldives, and the Philippines) and one from West Asia (Armenia). Only 31 out of 100 households had hand-washing facilities with water and soap in the SSA region. The lowest coverage of basic hygiene practice was recorded in Burundi (5.3%), followed by Malawi (10.5%) and Gambia (12.5%). A large gap has been recorded between the two countries listed in Latin America and the Caribbean region; the prevalence of basic hygiene facilities was reported at 80.4 percent in Guatemala, while about 75 percent of households still lack basic hand-washing facilities in Haiti. With 62 percent coverage, the South and Southeast Asia region ranks third with regard to the availability of basic hygiene facilities. We found a skewed distribution in South and Southeast Asia-ranging from

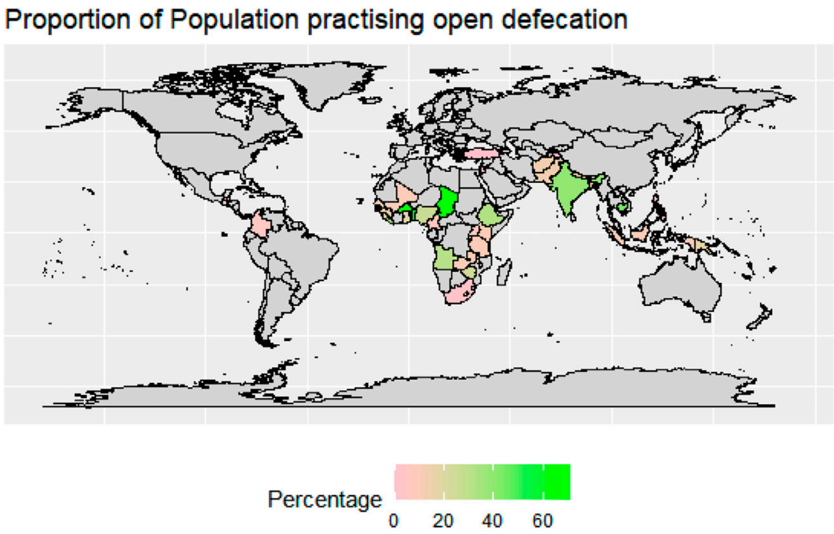

FIGURE 5
Proportion of population practicing open defecation in the study countries. Note: Proportion estimated as the share of sampled households practicing open defecation to the total sampled households by countries. Source: Authors estimation based on the DHS data.

28 percent in Timor-Leste to 97.8 percent in the Maldives. However, Indonesia, which shares its border with Timor-Leste, registered a 93 percent prevalence of basic hygiene practices. Less than half of the surveyed households had access to hand-washing facilities with soap and water in South Asian countries like Afghanistan (35.9%), Bangladesh (38.7%), and Nepal (47.1%) (see Supplementary Table A1; Supplementary Figures 1A–3A in Appendix 1).

Eliminating open defecation has been identified as a primary goal to achieve global equality in WASH services. It is explicitly referenced in SDG target 6.2 and is closely linked with wider efforts to end extreme poverty by 2030. Figure 5 depicts the proportion of households practicing open defecation. It is evident from the figure that all five countries listed under Central Asia, West Asia, and Europe have already eliminated open defecation (<1%), while the highest burdened countries with rates of more than 30 percent are from the SSA region. Regional analysis shows that South Asia has reported the highest prevalence (33%), followed by the SSA region (21%). However, it is important to mention that the highest prevalence of open defecation was reported in Chad, where 71 out of 100 households still practice open defecation. At the time of the survey, more than 50 percent of households in Burkina Faso and Benin (62% and 54%, respectively) used open defecation rather than any improved sanitation facilities. In 6 out of 10 South and Southeast Asian countries, at least >10 percent of households still defecate in open spaces, whereas except for Haiti, which recorded 25 percent prevalence, the rest of the two Latin American countries had reduced open defecation to below 6 percent.

3.2 Socioeconomic and demographic differentials of basic WASH services

Table 1 shows the descriptive statistics of the variable used in the empirical analysis of households' access to basic drinking water, sanitation, and hygiene facilities for pooled data from 42 developing countries. Table 1 shows the existence of significant inequalities between urban and rural areas. Globally, coverage of all three basic WASH services (water, sanitation, and hygiene) was higher among urban households than rural households, but the degree of inequality varies. The highest rural-urban coverage gap was recorded for sanitation services at around 27 percentage points.

Results show that access to basic WASH services was nearly identical in male and female-headed households. The sex of the household head and the sex composition of household members failed to explain the inequality in access to basic WASH services. As expected, the age and education of the household head show a significant association with access to basic WASH services. A monotonically increasing association was noted between education and the proportion of households using basic WASH services; access to basic WASH facilities was lowest for households with illiterate heads, which gradually increased with levels of education.

Further, with the increase in the age of household heads, the percentage of households using basic WASH services increases. For drinking water, coverage increased from 79 percent for households with heads in the age group 10–30 years to 86 percent for the age group >70 years. The difference between the household with head age group 10–30 years

TABLE 1 Socioeconomic Indicators and Coverage of Basic WASH Services in 42 selected countries, 2010–2020.

		Basic drinking water		Basic sanitation facility		Basic hygiene facility	
Covariates	**Label**	**Prop**	**SE**	**Prop**	**SE**	**Prop**	**SE**
Place of residence	Urban	0.93	0.001	0.67	0.001	0.73	0.001
	Rural	0.80	0.001	0.40	0.001	0.49	0.001
Sex of household head	Male	0.84	0.000	0.49	0.001	0.57	0.001
	Female	0.85	0.001	0.49	0.002	0.56	0.002
Age of household head	10–30 yrs	0.79	0.001	0.32	0.001	0.46	0.002
	31–50 yrs	0.84	0.001	0.48	0.001	0.57	0.001
	51–70 yrs	0.86	0.001	0.57	0.001	0.62	0.001
	70 above	0.86	0.002	0.62	0.003	0.65	0.003
Education of household head	No education	0.79	0.001	0.31	0.001	0.39	0.001
	Primary	0.79	0.001	0.44	0.001	0.52	0.001
	Secondary	0.89	0.001	0.56	0.001	0.66	0.001
	Higher	0.94	0.001	0.78	0.002	0.81	0.002
Wealth Index	Poorest	0.72	0.001	0.13	0.001	0.28	0.001
	Poorer	0.78	0.001	0.30	0.001	0.45	0.001
	Middle	0.84	0.001	0.49	0.001	0.59	0.001
	Richer	0.90	0.001	0.68	0.001	0.70	0.001
	Richest	0.96	0.001	0.84	0.001	0.83	0.001
Sex composition of HH members	No of Male = No of Female	0.85	0.001	0.50	0.001	0.59	0.001
	No of Male > No of Female	0.84	0.001	0.48	0.001	0.57	0.001
	No of Male < No of Female	0.84	0.001	0.48	0.001	0.56	0.001
Women Decision making power	No decision	0.87	0.001	0.47	0.001	0.58	0.001
	One or two decision	0.75	0.002	0.45	0.002	0.47	0.002
	Three and more decision	0.81	0.001	0.53	0.001	0.58	0.001
Basic Drinking water facility	No			0.29	0.001	0.34	0.001
	Yes			0.52	0.001	0.61	0.001
Basic Sanitation facility	No	0.78	0.001			0.41	0.001
	Yes	0.90	0.001			0.74	0.001
Basic Hygiene Facility	No	0.76	0.001	0.29	0.001		
	Yes	0.90	0.000	0.63	0.001		

Note: SE- standard error.

and >70 years was highest for sanitation facilities (30%), followed by hygiene facilities (19%). A similar direct and significant association also manifested between the household's wealth status and coverage of basic WASH facilities. The percentage of households with access to WASH facilities increases with the family's wealth. Analysis shows that 72 percent of the poorest household have access to basic drinking water services compared to 96 percent in the richest group. Significant gaps were observed across the income groups in the selected countries for the other two WASH components, such as sanitation and hygiene. About 84 percent of the richest households used basic sanitation services compared to the poorest households (13%). Similarly, about 83 percent of the richest households used basic hygiene services, compared to just 28 percent of the poorest households. However, it is important to note that there is wide variation between the countries, which is shown in the analysis in Supplementary Appendix 2; Supplementary Tables 1B–42B.

It is worthwhile to mention that coverage of any basic WASH component is directly driven by access to the other WASH facilities (i.e., having one WASH facility will induce the households to have other WASH facilities). Households with basic sanitation and hygiene facilities had higher drinking water source coverage than their counterparts. Similarly, accessibility of basic sanitation facilities promoted the usage of basic drinking water and hygiene services. A similar result was found for hygiene facilities; households with basic water or basic sanitation facilities had 33 and 27 percentage points higher coverage of hand-washing facilities with soap and water compared to the households with no basic WASH facility. A

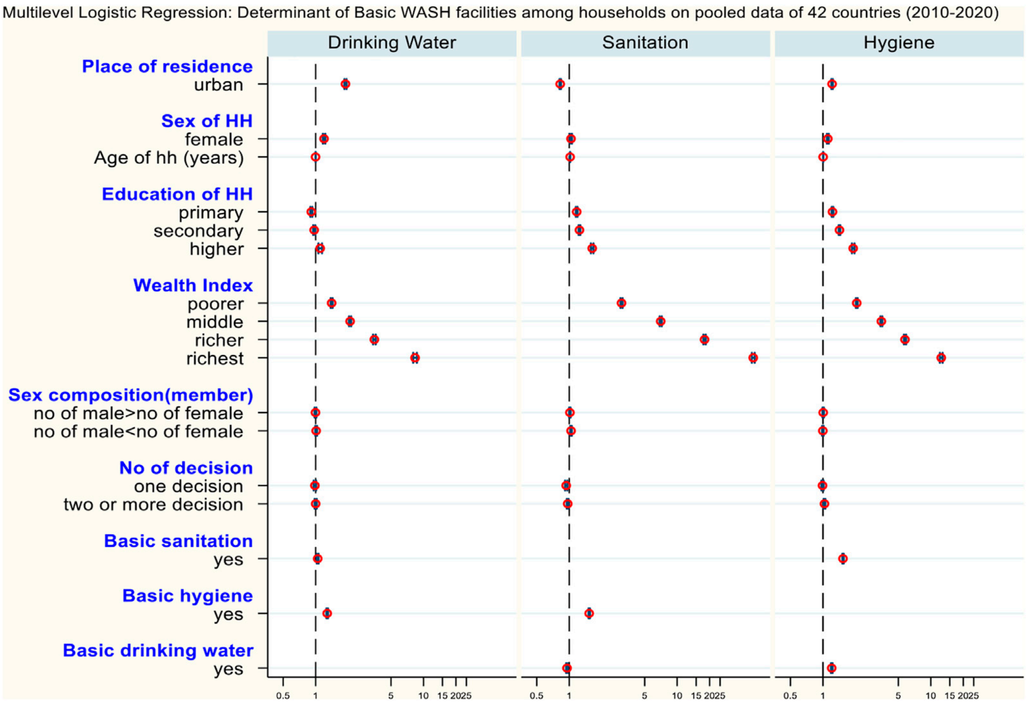

FIGURE 6
Multi-level Logistics determinants of Basic WASH facilities among households in pooled data of 42 countries (2010–2020).

chi-square test was performed, and these associations were significant at 5 percent significance level. The country-wise descriptive statistics of the variable used in the empirical analysis of households' access to basic drinking water, sanitation, and hygiene facilities are also provided in Supplementary Appendix 2; Supplementary Tables 1B–42B, and the result shows a similar kind of association between WASH facilities use (basic drinking water, basic sanitation, basic hygiene) and location (rural and urban), education of head, and wealth status of the households.

3.3 Multi-level regression analysis

Having identified the factors influencing the choice of WASH facilities in the previous bivariate analysis and literature review, a multi-level logistic model is used to evaluate their simultaneous effect on the coverage of individual basic WASH services (Water, Sanitation, and Hygiene). For multi-level analysis, the age of the household head is used as a continuous predictor, unlike categorical, as is done in bivariate analysis, to avoid incorporating more variables in the model. In the multi-level logit model, units at the lower level (level-1) are households that are nested within units at higher levels-country and region (42 countries at level 2 and 6 regions at level 3). The regression result in terms of log odds with 95 percent confidence interval (CI) is reported in Figure 6. Urban households were 1.9 and 1.2 times more likely to access basic drinking water and hygiene facilities than rural households. In contrast, the coverage of basic sanitation facilities was 18 percent lesser among urban dwellers compared to rural dwellers.

Female-headed households were more likely to access basic WASH services compared to their male counterparts. Notably, the chance of using basic drinking water, sanitation, and hygiene services was 19 percent, 3 percent, and 11 percent higher among female-headed households than male-headed households. The multi-level models show that the odds of accessing basic drinking water and sanitation services increased significantly with the age of the household head. The household head's education level seems to be an influential factor in regulating the coverage of basic WASH services; the direction of causality indicates a monotonic increase in the coverage of basic WASH services as the education of the household head increases. Households with highly educated household heads were 10, 63, and 91 percent more likely to have access to drinking water, sanitation, and hygiene than households with illiterate household heads.

It is evident from Figure 6 that the wealth index comes out as a significant correlate of basic WASH service use. Higher wealth quantile leads to higher odds of using basic WASH services. The

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richest households had 8, 50, and 12 times higher likelihood of having improved drinking water, sanitation, and hygiene facility compared to the poorest households. The sex composition of households did not appear to be a significant factor in the use of improved WASH services except for sanitation facilities. Households with more women than men show a slightly higher likelihood of accessing basic sanitation facilities (about 3%) than those households with equal members of both sexes. Women's decision-making power is insignificant for the odds of using basic drinking water services. In contrast, households with empowered women (who took all three decisions) had 1.03 times higher likelihood of using basic hygiene facilities than households with women with no decision-making power. Unlike this, the inverse association is manifested between the decision-making power and the use of basic sanitation facilities.

Household likelihood of usage of any basic WASH component has been significantly affected by practice of the remaining two facilities. Households with basic drinking water sources were 20 percent more likely to practice basic hygiene services, whereas the likelihood of using basic sanitation facilities was 5 percent lesser. Likewise, the odds of having basic drinking water and hygiene facilities were 1.04 and 1.53 times higher among households with basic sanitation facilities than their counterparts. Households with basic hygiene services were 53 percent and 28 percent more likely to use basic drinking water and sanitation services compared to households with unimproved or no hand-washing facilities.

The random effect model is used to measure the unobserved heterogeneity present in the data, and the computed variations at both country and region levels in terms of Variance (var) are given in Figure 6. The random effects are significant at the country level, suggesting considerable heterogeneity between countries in access to basic sanitation and hygiene services, which strongly indicates the presence of some unobserved factors working at the country level affecting the coverage of basic WASH practice. There may be unobserved components related to the coverage of basic WASH facilities, such as availability of improved toilet/hygiene facilities, quality of the facilities, accessibility to facilities, as well as social and behavioural development at the country level, which jointly affect the use of basic WASH services. Lastly, the significant value of the likelihood ratio test confirms that the model is adequately fitted.

3.4 Multi-level regression analysis by country

This study also performed a multi-level logistic model separately for 42 countries for different WASH practices (Water, Sanitation, and Hygiene), and the summarized result is presented in Table 2, while the detail result by country is presented in Supplementary Appendix 3; Supplementary Tables S1C–S45C.

For basic drinking facilities, wealth status emerges as the most significant driver in most countries, followed by the place of residence (urban), other wash facilities, and the household head's education level. Of 42 countries, 40[2] countries show that households with higher economic status are more likely to adopt basic drinking water, and in 32[3] countries, households in urban areas were more likely to use basic drinking water. The female head dummy was significant and positive only in 9[4] countries for the adoption of basic drinking facilities. Compared to the illiterate, the household with primary, secondary, and higher education was positive and significant in 9, 14, and 11 countries.

For basic sanitation facilities also, the wealth status emerges as the most significant driver in the majority of the countries, followed by the age of the household, other wash facilities, the level of education of the household head, and the place of residence (urban). In over 37 countries, more affluent households are more likely to use basic sanitation facilities. Compared to the illiterate, the household with primary, secondary, and higher education was positive and significant for basic sanitation practices in 12, 16, and 29 countries. The age of the household head is positive and significantly related to basic sanitation facilities in 34 countries, highlighting the fact that elderly households are more likely to use basic sanitation facilities. We also noted a positive and significant relationship between a basic sanitation facility and a basic hygiene facility.

For basic hygiene, wealth status emerges as the most significant driver in the majority of the countries, followed by gender composition, other wash facilities, the level of education of the household head, the place of residence (urban), and the women's decision-making power.

4 Discussion

The current work is an effort to analyze the reach of basic WASH facilities in developing countries and the factor influencing its adoption. Using aggregated data from forty-two developing countries from different regions allowed us to

2 Armenia and Bangladesh was not included in the analysis for access to drinking water due to lack of data.

3 Afghanistan, Cambodia, India, Indonesia, Pakistan, Philippines, Timor leste, Papua New Guinea, Columbia, Guatemala, Haiti, Tajikistan, Albania, Jordan, Turkey, Angola, Benin, Burkin Faso, Burundi, Cameroon, Chad, Ethiopia, Guinea, Kenya, Liberia, Malawi, Nigeria, Rwanda, Sierra Leone, South Africa, Tanzania, Uganda, Zambia. It was negative and significant for Nepal and Zimbabwe.

4 It was positive and significant for Cambodia, India, Burkin Faso, Cameroon, Gambia, Rwanda, Sierra Leone, Uganda, Zimbabwe. It was negative and significant at 1% in case of Pakistan.

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TABLE 2 Multi-level Logistic Regression: Determinant of coverage of Basic Drinking Water facility among households of 42 selected countries, 2010–2020.

	Place of residence (ref: Rural)	Sex of HH (ref: Male)	Education of HH (ref: No education)				Wealth index (ref: poorest)				Sex composition of HH member (ref: no of male = no of female)		Women decision making (ref: No decision)		Basic sanitation facility	Basic hygiene facility
	Urban	Female	Age of HH	Primary	Secondary	Higher	Poorer	Middle	Richer	Richest	No of Male > No of Female	No of Male < No of Female	One or two decisions	Three and more decision	Yes	Yes
Basic Drinking Water																
(+) ***	29	4	3	6	10	10	31	38	38	39	1	1	2	4	8	18
(+) **	3	5	3	3	4	1	5		1	1		1	1	2		6
(+) *																
(–) ***	2	1	3	1	2							1	1			1
(–) **				1		2							2	1	1	1
(–) *																
Insig	6	30	31	29	24	27	4	2	1	0	39	37	34	33	31	14
NA	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	42	42	42	42	42	42	42	42	42	42	42	42	42	42	42	42
Basic Sanitation facility																
(+) ***	11	4	31	9	12	26	29	37	37	39	6	4	3	4	9	29
(+) **		2	3	3	4	3	4				1	3	2	2	5	2
(+) *																
(–) ***	16	1		1			1	1	2	1				1		
(–) **	4	3	1	1									1		1	
(–) *																
Insig	11	32	7	28	26	13	8	4	3	2	35	35	36	35	27	11
NA																
	42	42	42	42	42	42	42	42	42	42	42	42	42	42	42	42

(Continued on following page)

TABLE 2 (*Continued*) Multi-level Logistic Regression: Determinant of coverage of Basic Drinking Water facility among households of 42 selected countries, 2010–2020.

	Place of residence (ref: Rural)	Sex of HH (ref: Male)	Education of HH (ref: No education)				Wealth index (ref: poorest)				Sex composition of HH member (ref: no of male = no of female)		Women decision making (ref: No decision)		Basic sanitation facility	Basic hygiene facility
	Urban	**Female**	**Age of HH**	**Primary**	**Secondary**	**Higher**	**Poorer**	**Middle**	**Richer**	**Richest**	**No of Male > No of Female**	**No of Male < No of Female**	**One or two decisions**	**Three and more decision**	**Yes**	**Yes**
Basic Hygiene																
(+) ***	10	1	5	14	21	30	19	24	29	38	34		6	11	17	30
(+) **	1	3	3	5	3	3	5	2	4		1		5	2	3	2
(+) *																
(–) ***	2										1		2	3	1	
(–) **	1										2		3	3	1	
(–) *								1								
Insig	24	34	30	19	14	5	14	11	5			38	22	19	16	6
NA	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	42	42	42	42	42	42	42	42	42	42	42	42	42	42	42	42

+ stands for odds ratio>1, – stands for odds ratio<1, *** – *p* value < 0.001, ** – *p* value < 0.005, * – *p* value < 0.010, NA-data not available, HH-Household hea.

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conduct a comparative study that further delineates the mechanisms that explain variation in the practice of basic WASH services. The comparable quantitative indicators computed through advance statistical techniques have the potential to exploit spatial variation that gives credence to the value of multi-country studies. In addition, hierarchical models were used to identify a broad array of elements located on different levels of the WASH model (i.e., household, socioeconomic, behavioural, regional) that affect basic WASH practices. Both national and sub-national comparisons and further multi-level models have moved knowledge forward at various levels of inquiry for the coverage of water, sanitation, and hygiene services.

This study is the first such application of the multi-level regression technique on pooled cross-sectional surveys to gain insight into prevalence as well as covariates of practicing basic WASH services in different regional settings. The advantage of this methodology over a single model is its hierarchical design which enables the proper investigation of the effects of all covariates measured at country and regional levels on the response variable, i.e., coverage of basic WASH services. Notably, the significant random effects suggest the existence of dependencies between household observations because instead of using simple random sampling, the DHS data is based on multi-stage cluster sampling from geographical areas. The significant variation at the global and national levels suggests that geographical disparities surpass the socioeconomic and demographic inequalities in access to basic WASH services (World Health Organization, 2021).

A multitude of studies advocates the importance of basic WASH services in safeguarding human health (Armah et al., 2018; Okurut et al., 2015). We used the JMP ladder to analyze the coverage of basic WASH services in forty-two countries. The result of this paper favour variation present in the access to individual WASH components-drinking water, sanitation, and hygiene. For instance, the prevalence of basic drinking water facilities at the household level was 83 percent, whereas the prevalence of sanitation and hygiene facilities was 48 percent and 56 percent. Conspicuously, this variation was clearly visible at the regional and national levels. This finding suggests that only 64 percent of households in sampled SSA countries had access to basic drinking water facilities, which is lower than the MDG figure of 68 percent reported in 2015 (UN, 2015). The difference may be attributed to the number of countries included in the analysis. The situation is most critical in Chad and Ethiopia, where about half of the households use unimproved or surface water sources (Zerbo et al., 2021). Unlike SSA, in South and Southeast Asian countries, more than 90 percent of households had access to basic drinking water facilities, which increased from 73 percent since 1990, however still 134 million people do not have access to improved water facilities, and it is estimated that almost 68 to 84 percent of water sources are contaminated (Unicef, 2016). Switching to the definition of basic services from improved ones has changed the scenario completely. For instance, previous studies set on SSA countries indicate that more than half of the households had access to improved sanitation facilities, though the offered prevalence had a wide variation across countries (Armah et al., 2018; Pullan et al., 2014; Yu et al., 2014) whereas our findings revealed that only 30 percent of households ranging from 6 percent to 57 percent, used improved sanitation facility which was not shared with any other households.

Most African and South Asian countries are still practicing open defecation, which is considered as a major cause of infectious diseases and mortality among children. The much argued reason for poor sanitation is the high urbanization rate without a similar increase in income. The level of per capita income does not accompany the urbanization rate, and it leads to an increase in the urban poor population (World Bank Group, 2015). According to UNDESA (2014), with more than 50 percent urbanization rate, Africa's urban population is projected to reach 1.2 billion by 2050, which is a cause of concern. According to Marx et al. (2013), in SSA countries, the slum population is growing by 4.5 percent annually and is expected to double in the next 15 years. Adding to this, a study by Ndikumana and Pickbourn (2017) in SSA and Arias Granada et al. (2020) in Bangladesh has shown that urban poor are less likely to access improved WASH services. Some studies have also mentioned that the lack of improved sanitation facilities forces the urban poor to use polythene bags and/or defecate in nearby open stream drains or natural water sources, which leads to severe environmental contamination and disease-related hazards (Isunju et al., 2011; Konteh, 2009; Cheng et al., 2018).

In sum, SSA countries may lose their momentum on the coverage of basic WASH indicators and may not achieve SDGs goals if the comprehensive WASH approach is not adopted, i.e., ensure universal access to basic WASH facilities, particularly to the rural poor households. On the contrary, basic sanitation and hygiene coverage estimates were very high in Western and Central Asian countries, with almost zero open defecation; these countries set a roadmap for others to achieve universal access to basic sanitation facilities. Although, the literature on access to basic WASH services in development studies is very scanty and mostly focused on African and south Asian countries. Further, a detail examination of policies, behavioural shifts, and interventions are needed to understand the achievement of western and central Asian countries.

Socioeconomic dimensions have an overarching influence on access to WASH services, and the effects are not linear as expected. The selected covariates–dwelling setting, age, sex and education of household head, and household wealth, show significant association with the coverage of basic WASH services, separately computed for each component. The patterns are fairly consistent, with varying intensities in different countries. Our results suggest that affluent households have higher coverage of basic WASH facilities; a positive association was established between the wealth index and access to WASH facilities. This finding shows that access to basic drinking water, sanitation, and hygiene is more concentrated among rich households than poorer ones. This relationship offers concordance with an earlier study carried out in Cambodia, Ghana, Nepal, and some of the SSA countries (Mulenga et al., 2017; Tuyet-Hanh et al., 2016; Yang et al., 2013; Lawrence et al., 2002). Place of residence (urban *versus* rural) emerged as another influential covariate for WASH coverage. Finding reveals that rural households were less likely to access basic drinking water and hygiene facilities compared to urban households, and this finding is in agreement with several other studies (Tuyet-Hanh et al., 2016; Yang et al., 2013; World Health Organization, 2021). Further, some studies have found within rural, socioeconomic development influences sanitary toilet penetration (Li et al., 2022). In terms of the household head's education, an insignificant relationship between the education level and odds of having basic drinking water facilities is unexpected and inconsistent with a previous study conducted by Irianti et al., 2016.

Combining the above two major findings raises two fundamental issues-economic and spatial access. Spatially, rural areas have lesser knowledge, advancement, and access to basic needs. There is a need for a Knowledge, Access, and Practice (KAP) approach to increase the coverage of basic drinking water and sanitation services in rural areas. Along with access to services, there is a need for behavioral change interventions to inculcate the habit of hand-washing and better sanitation. Economically, poorer households are not able to bear the cost of improved sanitation and drinking water services. This finding could be an important precursor for the policymakers to introduce future WASH interventions with some solutions to the issues associated with socially deprived strata.

Furthermore, the study also unraveled that female-headed households had higher odds of using basic WASH services than male-headed households. In most households, women are solely responsible for all household chores, such as fetching water, cleaning toilets, and managing hygiene services (Gomez M et al., 2019). As the welfare of women is directly connected with WASH services, the female head focuses more on access to WASH than its counterparts, i.e., the male head. This finding is consistent with Mulenga et al. (2017) and Osei et al. (2015). A similar explanation can justify the positive correlation between women's decision-making power and the use of basic sanitation facilities. Education of household heads depicts a significant and positive relationship with the use of basic WASH services, which is in concurrence with several studies conducted in developing countries (Abubakar, 2017; Okurut et al., 2015; Adams et al., 2016). This result advocates that education increases the use of WASH facilities through better awareness of the benefit of using improved WASH facilities. The study also suggests robust interlinkages of all three components of WASH. The finding shows that households with coverage of one basic WASH service had higher access to the other two WASH components. It may be attributed to the fact that exposure to any improved facility encourages people to use other WASH facilities too. Having a better facility may increase the knowledge about the respective benefit of these services. Previous studies Kema et al. (2012), Abubakar (2017), and Gomez et al. (2019) conclude that awareness about the benefit of improved WASH facilities over health and development increases the likelihood of having access to improved WASH services.

5 Conclusion

By inspecting a connection between access to basic WASH services with selected household-level indicators, this study confirms the importance of these covariates–socioeconomic status, sex, age, and education of household heads, and women empowerment in the practice of improved WASH facilities. As wealth (economic status) has emerged as an important driver of the adoption of WASH facilities, it highlights the affordability aspect. Therefore, the government-supported sanitation program should focus on poor households. Analysis shows that rural households are more deprived of improved WASH facilities, the sanitation program should make an effort to scale WASH facilities in rural areas. However, the urban poor also deserves the attention of the sanitation program. As women are more concerned about the well-being of the family and children, women could play an important role in scaling improved WASH facilities.

It is worth noting that the use of WASH services could increase by improving awareness about the impact of safe sanitation, hygiene, and water supply on human development as well as providing opportunities to take advantage of these services through education and improvement of residential areas. The region with high urbanization without the same pace of economic growth may increase the slum population in urban areas. This suggests that robust policy interventions are required to tackle the urbanization issues by investing in housing, economy, and infrastructure. The collective efforts of different sectors, e.g., government, non-government and private sectors, are needed to increase access to basic water, sanitation, and hygiene facilities, giving extra attention to the underprivileged populations. The national and sub-national analysis shed light on the inequalities that exist in the coverage of basic WASH facilities at the cluster level. A common intervention will not be favorable for all countries in a region. Formulating more decentralized schemes is necessary to tackle community and country-specific issues. Policymakers and demographers need to develop a plan for sustainable WASH solutions for LMICs and spend more effort there to achieve the SDG goals. The empirical method employed here offers a base that can be expanded in different research areas to test the hypothesis using a repeated cross-sectional survey. This multi-level approach can confer significant resource efficiency to future multi-country studies.

Besides interesting findings, this study also has certain limitations. Most of these are related to the questionnaire and data reporting. DHS record all the WASH-related questions at the household level instead of the individual level, which may introduce underestimation in the inequality of access to basic WASH services. Our analysis ignores the intra-household inequality, i.e., the disparities in access to WASH services among the members in the same households are not covered in the study. Another limitation is the retrospective recall bias present in measuring some of the information (like age, education, etc.) We believe that this bias is random and somewhat mitigated with the use of average proportions. Finally, the survey year is different for different countries; the majority of participating countries are not measured at the same time, which imposes limitations on the cross-national comparisons.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://dhsprogram.com/.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

AS: Contributed to conceptualization of the research idea, data cleaning, analysis, write-up, editing, and structuring DR: Contributed to conceptualization of the research idea, data cleaning, analysis, write-up, editing, and structuring. TS: Contributed to conceptualization of the research idea, write-up, editing, and structuring.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material showing the descriptive and econometric analysis for each countries for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.1013657/full#supplementary-material

References

Abubakar, I. R. (2017). Access to sanitation facilities among Nigerian households: Determinants and sustainability implications. *Sustainability* 9 (4), 547. doi:10.3390/su9040547

Adams, E. A., Boateng, G. O., and Amoyaw, J. A. (2016). Socioeconomic and demographic predictors of potable water and sanitation access in Ghana. *Soc. Indic. Res.* 126 (2), 673–687. doi:10.1007/s11205-015-0912-y

Aiello, A. E., Coulborn, R. M., Perez, V., and Larson, E. L. (2008). Effect of hand hygiene on infectious disease risk in the community setting: A meta-analysis. *Am. J. Public Health* 98 (8), 1372–1381. doi:10.2105/ajph.2007.124610

Arias Granada, Y., Haque, S. S., Joseph, G., and Yanez Pagans, M. (2020). Water and sanitation in dhaka slums: Access, quality, and informality in service provision. *Water Int.* 45 (7-8), 791–811. doi:10.1080/02508060.2020.1786878

Armah, F. A., Ekumah, B., Yawson, D. O., Odoi, J. O., Afitiri, A. R., and Nyieku, F. E. (2018). Access to improved water and sanitation in sub-Saharan Africa in a quarter century. *Heliyon* 4 (11), e00931. doi:10.1016/j.heliyon.2018.e00931

Benova, L., Cumming, O., and Campbell, O. M. (2014). Systematic review and meta-analysis: Association between water and sanitation environment and maternal mortality. *Trop. Med. Int. Health* 19 (4), 368–387. doi:10.1111/tmi.12275

Cairncross, S., Hunt, C., Boisson, S., Bostoen, K., Curtis, V., Fung, I. C., et al. (2010). Water, sanitation and hygiene for the prevention of diarrhoea. *Int. J. Epidemiol.* 39, i193–i205. doi:10.1093/ije/dyq035

Cheng, S., Li, Z., Uddin, S. M. N., Mang, H. P., Zhou, X., Zhang, J., et al. (2018). Toilet revolution in China. *J. Environ. Manag.* 216, 347–356. doi:10.1016/j.jenvman.2017.09.043

Clasen, T., Schmidt, W. P., Rabie, T., Roberts, I., and Cairncross, S. (2007). Interventions to improve water quality for preventing diarrhoea: Systematic review and meta-analysis. *Bmj* 334 (7597), 782. doi:10.1136/bmj.39118.489931.be

Fewtrell, L., Kaufmann, R. B., Kay, D., Enanoria, W., Haller, L., and Colford, J. M., Jr (2005). Water, sanitation, and hygiene interventions to reduce diarrhoea in less developed countries: A systematic review and meta-analysis. *Lancet Infect. Dis.* 5 (1), 42–52. doi:10.1016/s1473-3099(04)01253-8

Global Nutrition Report (2021). *The state of global nutrition*. Bristol, UK: Development Initiatives.

Goldstein, H. (2011). *Multi-level statistical models*. New Jersey, United States: John Wiley & Sons. doi:10.1002/9780470973394

Gomez, M., Perdiguero, J., and Sanz, A. (2019). Socioeconomic factors affecting water access in rural areas of low and middle income countries. *Water* 11 (2), 202. doi:10.3390/w11020202

Gould, I. M. (2010). Alexander Gordon, puerperal sepsis, and modern theories of infection control—Semmelweis in perspective. *Lancet Infect. Dis.* 10 (4), 275–278. doi:10.1016/s1473-3099(09)70304-4

ICF International (2012). *Demographic and health survey sampling and household listing manual. MEASURE DHS*. Calverton, Maryland, U.S.A. ICF International.

Irianti, S., Prasetyoputra, P., and Sasimartoyo, T. P. (2016). Determinants of household drinking-water source in Indonesia: An analysis of the 2007 Indonesian family life survey. *Cogent Med.* 3 (1), 1151143. doi:10.1080/2331205x.2016.1151143

Isunju, J. B., Schwartz, K., Schouten, M. A., Johnson, W. P., and van Dijk, M. P. (2011). Socioeconomic aspects of improved sanitation in slums: A review. *Public health* 125 (6), 368–376. doi:10.1016/j.puhe.2011.03.008

Kema, K., Semali, I., Mkuwa, S., Kagonji, I., Temu, F., Ilako, F., et al. (2012). Factors affecting the utilisation of improved ventilated latrines among communities in Mtwara Rural District, Tanzania. *Pan Afr. Med. J.* 13 (Suppl 1), 4. Epub December 25, 2012.

Konteh, F. H. (2009). Urban sanitation and health in the developing world: Reminiscing the nineteenth century industrial nations. *Health Place* 15 (1), 69–78. doi:10.1016/j.healthplace.2008.02.003

Lawrence, P. R., Meigh, J., and Sullivan, C. (2002). *The water poverty index: An international comparison*. Keele, Straffordshire, UK: Department of Economics, Keele University.

Li, Y., Cheng, S., Cui, J., Gao, M., Li, Z., Wang, L., et al. (2022). Mining of the association rules between socio-economic development indicators and rural harmless sanitary toilet penetration rate to inform sanitation improvement in China. *Front. Environ. Sci.* 10, 74. doi:10.3389/fenvs.2022.817655

Marx, B., Thomas, S., and Tavneet, S. (2013). The economics of slums in the developing world. *J. Econ. Perspect.* 27 (4), 187–210.

Mulenga, J. N., Bwalya, B. B., and Chishimba, K. K. (2017). Determinants and inequalities in access to improved water sources and sanitation among the Zambian households. *Int. J. Dev. Sustain.* 6 (8), 746–762.

Nagabhatla, N., Avellan, T., Pouramin, P., Qadir, M., Mehta, P., Payne, J., et al. (2019). *UNESCO world water assessment programme (WWAP). The united nations world water development report 2019: Leaving No one behind*. Paris: UNESCO, 44–57.

Nalule, Y., Buxton, H., Ir, P., Leang, S., Macintyre, A., Pors, P., et al. (2021). Hand hygiene during facility-based childbirth in Cambodia: A theory-driven, mixed-methods observational study. *BMC Pregnancy Childbirth* 21 (1), 429. doi:10.1186/s12884-021-03901-7

Ndikumana, L., and Pickbourn, L. (2017). The impact of foreign aid allocation on access to social services in sub-Saharan Africa: The case of water and sanitation. *World Dev.* 90, 104–114. doi:10.1016/j.worlddev.2016.09.001

Okurut, K., Kulabako, R. N., Abbott, P., Adogo, J. M., Chenoweth, J., Pedley, S., et al. (2015). Access to improved sanitation facilities in low-income informal settlements of East African cities. *J. water, sanitation Hyg. Dev.* 5 (1), 89–99. doi:10.2166/washdev.2014.029

Oloruntoba, E. O., Folarin, T. B., and Ayede, A. I. (2014). Hygiene and sanitation risk factors of diarrhoeal disease among under-five children in Ibadan, Nigeria. *Afr. Health Sci.* 14 (4), 1001–1011. doi:10.4314/ahs.v14i4.32

Onda, K., LoBuglio, J., and Bartram, J. (2012). Global access to safe water: Accounting for water quality and the resulting impact on MDG progress. *Int. J. Environ. Res. Public Health* 9 (3), 880–894. doi:10.3390/ijerph9030880

Ordinioha, B., and Owhondah, G. (2008). Sanitation facilities and hygiene practices in a semi-urban community in Rivers State, south-south Nigeria. *Niger. Health J.* 8 (1–2), 10–15.

Osei, L., Amoyaw, J., Boateng, G. O., Boamah, S., and Luginaah, I. (2015). The paradox of water accessibility: Understanding the temporal and spatial dimensions of access to improved water sources in Rwanda. *J. Water, Sanitation Hyg. Dev.* 5 (4), 553–564. doi:10.2166/washdev.2015.029

Prüss-Ustün, A., Bartram, J., Clasen, T., Colford, J. M., Jr, Cumming, O., Curtis, V., et al. (2014). Burden of disease from inadequate water, sanitation and hygiene in low-and middle-income settings: A retrospective analysis of data from 145 countries. *Trop. Med. Int. Health* 19 (8), 894–905. doi:10.1111/tmi.12329

Pullan, R. L., Freeman, M. C., Gething, P. W., and Brooker, S. J. (2014). Geographical inequalities in use of improved drinking water supply and sanitation across sub-saharan Africa: Mapping and spatial analysis of cross-sectional survey data. *PLoS Med.* 11 (4), e1001626. doi:10.1371/journal.pmed.1001626

Raudenbush, S. W., and Bryk, A. S. (2002). *Hierarchical linear models: Applications and data analysis methods*, Vol. 1. California, United States: SAGE Publications.

Semmelweis, I., and Semmelweis, I. F. (1983). *The etiology, concept, and prophylaxis of childbed fever*. Madison, Wisconsin: Univ of Wisconsin Press.

Snijders, T. A., and Bosker, R. J. (2011). *Multilevel analysis: An introduction to basic and advanced multilevel modeling*. California, United States: SAGE Publications Ltd. Available at: https://us.sagepub.com/en-us/nam/multilevel-analysis/book234191.

Tincani, L., Ross, I., Zaman, R., Burr, P., Mujica, A., and Evans, B. E. (2015). *Regional assessment of the operational sustainability of water and sanitation services in Sub-Saharan Africa*. Report. Oxford, UK: Oxford Policy Management.

Tuyet-Hanh, T. T., Lee, J. K., Oh, J., Van Minh, H., Ou Lee, C., Hoan, L. T., et al. (2016). Household trends in access to improved water sources and sanitation facilities in vietnam and associated factors: Findings from the multiple indicator cluster surveys, 2000–2011. *Glob. Health Action* 9 (1), 29434. doi:10.3402/gha.v9.29434

UN Assembly (2010). Resolution adopted by the general assembly on 28 July 2010: 64/292. The human right to water and sanitation. Available at: https://www.un.org/en/ga/search/view_doc.asp (Accessed July 20, 2022).

UNDESA (2014). *World urbanization prospects, the 2011 revision*. United Nations Secretariat: Population Division, Department of Economic and Social Affairs.

UNICEF (2022). Estimates of child cause of death, diarrhea. [Data file]. Available from: https://data.unicef.org/topic/child-health/diarrhoeal-disease/ (Accessed July, 2022).

UNICEF (2016). *Strategy for water, sanitation and hygiene 2016–2030*. New York, United States: Programme Division, United Nations International Children's Emergency Fund.

WHO (2005). *Health through safe drinking water and basic sanitation*. Geneva Switzerland: World Health Organization.

Wolfe, M., Kaur, M., Yates, T., Woodin, M., and Lantagne, D. (2018). A systematic review and meta-analysis of the association between water, sanitation, and hygiene exposures and cholera in case–control studies. *Am. J. Trop. Med. Hyg.* 99 (2), 534–545. doi:10.4269/ajtmh.17-0897

World Bank Group (2015). *Stocktaking of the housing sector in sub-saharan Africa: Challenges and Opportunities*. Washington, DC: The World Bank. Available at: https://openknowledge.worldbank.org/handle/10986/23358

World Health Organization (2015). *Improving nutrition outcomes with better water, sanitation and hygiene: Practical solutions for policies and programmes*. Geneva, Switzerland: WHO Press, World Health Organization.

World Health Organization (WHO)/United Nations Childrens' Fund (UNICEF) (2021). *Progress on household drinking water, sanitation and hygiene 2000–2020: Five years into the SDGs*. Situation report. Geneva: World Health Organization (WHO) and the United Nations Childrens' Fund (UNICEF).

WHO/UNICEF Joint Water Supply, and Sanitation Monitoring Programme (2015). *Progress on sanitation and drinking water: 2015 update and MDG assessment*. World Health Organization.

Yang, H., Bain, R., Bartram, J., Gundry, S., Pedley, S., and Wright, J. (2013). Water safety and inequality in access to drinking-water between rich and poor households. *Environ. Sci. Technol.* 47, 1222–1230. doi:10.1021/es303345p

Yu, W., Bain, R. E., Mansour, S., and Wright, J. A. (2014). A cross-sectional ecological study of spatial scale and geographic inequality in access to drinking-water and sanitation. *Int. J. Equity Health* 13 (1), 113–115. doi:10.1186/s12939-014-0113-3

Zerbo, A., Delgado, R. C., and González, P. A. (2021). Water sanitation and hygiene in Sub-Saharan Africa: Coverage, risks of diarrheal diseases, and urbanization. *J. Biosaf. Biosecurity* 3 (1), 41–45. doi:10.1016/j.jobb.2021.03.004

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Using illustrated system analysis for qualitative risk assessment of emptying of pit latrines

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Pit latrines as the primary means of sanitation for billions of people. Fecal sludge must be removed regularly when pit latrines fill up, and the workers who empty these latrines are essential service providers. Pit latrine emptying services and approaches are highly variable, ranging from highly trained teams using vacuum trucks with a suite of personal protective equipment to individuals with no protection using simple manual tools like buckets and shovels. While national governments and nonprofits endeavor to make pit latrine emptying safer, the people making day-to-day decisions such as local pit emptying associations, sanitation businesses, utilities, and local governments have limited resources to evaluate how different emptying practices vary in terms of risk. In this paper we describe the development of an open-source Illustrated System Analysis tool for the fecal sludge management community. This tool can be used in conjunction with a simple risk assessment matrix to help decision makers describe, compare, and prioritize risks for mitigation. We demonstrate this process by outlining how a pit emptying team can compare mechanical and manual emptying with respect to ingestion of fecal material and inhalation of fecal bioaerosols. Illustrated System Analysis can be a tool to analyze fecal sludge management systems, and the associated challenges and opportunities so that they could be understood and referenced by the wider public and used to spark innovation. We provide a library of graphics freely under creative commons.

KEYWORDS

fecal, fecal sludge management, pit latrine emptying, risk assessment, graphics

1 Introduction

Nearly 1.8 billion people around the world depend on pit latrines as the primary means of sanitation (Graham and Polizzotto, 2013). It is estimated that there are nearly 772 million onsite sanitation facilities (pit latrines and septic tanks) around the world (Greene et al., 2021), and these need regular desludging for regular maintenance and to increase the lifetime of the pit (Mubatsi et al., 2021). The workers that empty latrines and septic tanks provide an essential service while facing several occupational dangers. Pit latrine emptiers in India expressed that they face hazards such as direct contact with fecal sludge, exposure to noxious gases and chemicals, and risk of injury (Gautam et al., 2021).

The materials that sanitation workers handle harbor a range of waterborne bacterial, viral, and parasitic pathogens (World Health Organization, 2018), and antimicrobial resistance and multidrug resistant strains have been found in these pits (Beukes et al., 2022).

For individuals and small entities that provide sanitation services, it can be difficult to decide how to adjust current practices, especially if resources are tight. Often the service providers have limited funds to purchase necessary equipment or tools (Gautam et al., 2021). In addition, there is a wide variety of pit latrine emptying practices. An estimated 32% of pits are emptied mechanically *via* pumps and trucks and 50% are emptied through non-mechanized means (Greene et al., 2021). Practices are affected by pit contents (including improperly disposed trash), accessibility of the pit, sludge thickness, transport options, costs, regulations, and resources available to a given emptying team (Gurksi et al., 2022). The marginalized status of pit emptiers leads to the informal nature of labor; this in turn contributes to non-uniformity and lack of standardization in the profession (Gautam et al., 2021).

The World Health Organization's (WHO) guidelines on sanitation safety (World Health Organization, 2015) emphasize the importance of identifying hazards and hazard events and assessing and prioritizing exposure risks. The WHO described three different approaches to evaluating risk, with the most complex being quantitative methods such as Quantitative Microbial Risk Assessment (QMRA). QMRA involves hazard identification, dose-response assessment, and risk characterization to estimate an adverse health outcome from pathogen exposure (Haas, 2020). While there are QMRA based studies that have looked at risks of subprocesses in pit latrine emptying, these studies use a more data- and resource-intensive process; getting appropriate and reliable data (e.g., video data or counts of facial touches) can be expensive and time consuming (Bischel et al., 2019; Sklar et al., 2021). Organizations such as pit emptying associations, local governments, or businesses might not have the in-house expertise to carry out these studies (World Health Organization, 2015).

The WHO identifies two additional, more feasible approaches. The first is a team-based descriptive risk assessment, where a sanitation team collectively judges a hazardous event and qualitatively classifies activities as high, medium, low or uncertain risk (World Health Organization, 2015). There are already resources that guide teams to consider relative hazards and degree of these hazards associated with different sanitation and emptying technologies (Stenström et al., 2011). The second approach is using a semi-quantitative risk assessment method, where a team assigns a likelihood and severity of a hazardous event (World Health Organization, 2015). This use of qualitative methods to characterize hazards is not new; they have been used in the field of occupational hazards when there is little or no information on established exposure limits (Schulte, 2009; Revitt et al., 2021). While both approaches are insightful, they do not clearly give guidance on how to analyze individual steps in the emptying process.

Recently, Gautam et al. (2021) identified a framework for examining the safety of vacuum truck pit emptiers after extensive stakeholder interviews and observations from two separate Indian cities. The framework includes a 55-step desludging process flowchart that starts from when operators leave home and ends with a tank emptier exiting a septic tank after finishing a job. The fine detail of the flowchart helps stakeholders see the individual steps involved with emptying. We propose that these granular process maps can be improved with illustrations and a qualitative risk assessment index. The addition of these two elements can enhance a stakeholder's ability to model pit latrine emptying and subsequently identify and evaluate risks in individual steps.

Illustrations are a popular, proven, and useful gateway to succinct information and comprehension. Illustrations allow us to define a set of standardized symbols to allow people to quickly communicate ideas (Ashwin, 1984). Microbiologists, for example have been using animations to illustrate complex processes and illustrate hypotheses. This has been particularly useful in surfacing differences among researchers in their understanding of how different molecular processes occur (Iwasa, 2022). Illustrations can also play a key part in conveying information and discoveries to non-experts, helping audiences with diverse backgrounds and goals quickly understand and discuss information (McGill, 2022). Illustrations are powerful tools that overcome language barriers and deliver a large amount of information (Leach, 2022), and spur new observations, ideas and thinking even for those already familiar with the process (McGill, 2022).

An Illustrated System Analysis involves identifying the stakeholders, tools, and processes and illustrating how system elements interact with one another. An Illustrated System can then be paired with a risk assessment matrix, which allows decisions for how activities can be prioritized for further research or mitigation (Revitt et al., 2021). We demonstrate how Illustrated System Analysis can be applied to identifying health risks during pit latrine emptying from indirect ingestion of fecal material *via* facial contact and inhalation of fecal bioaerosols.

2 Materials and methods

2.1 Creation of illustrated systems for pit emptying

The first step of Illustrated System Analysis is visually depicting individual elements of the emptying process. The illustrations are assembled in a storyboard to describe how stakeholders, tools, and processes interact with one another. Based on direct observations of pit emptiers in Zambia, Kenya, Tanzania, and India, we developed illustrations for three different fecal sludge removal processes and scenarios:

2.1.1 Scenario 1: Manual emptying with proper disposal

Fecal sludge and trash from a pit latrine are removed with manual tools into a barrel and transported to a treatment facility for proper disposal. Five operators and one driver are part of the process. Data were collected in Lusaka, Zambia in 2017 by taking and analyzing photographs and videos and conducting stakeholder interviews of the pit latrine emptying process. Two manual pit latrine emptying teams with the Lusaka Water and Sewerage Company were observed, including the tools used, protective measures taken by personnel, and their interactions with the homeowners.

2.1.2 Scenario 2: Vacuum truck emptying with proper disposal

Fecal sludge is removed using a vacuum truck and transported to a waste treatment facility for proper disposal. At the end of the day, the outside of the vacuum truck is also cleaned. Three operators and one driver are part of the process. The research team collected data in Kisumu, Kenya in 2018 by observing pit emptying with vacuum trucks with the Kisumu Water and Sanitation Company Limited (KIWASCO).

2.1.3 Scenario 3: Vacuum truck emptying interrupted by a clog with improper disposal

This scenario shows operators emptying a pit where trash clogs are removed in the middle of latrine emptying, based on field observations in Kisumu, Kenya and outside Dar es Salaam, Tanzania. This scenario also shows steps that happen if the fecal sludge is improperly disposed in an open field, a process seen when there is a lack of supporting sanitation infrastructure, as was noted in field observations outside Bangalore, India.

The storyboards were developed based on field observations. Each scenario had time assigned to each individual step informed by time motion data recorded in Zambia and Kenya and are in line with previously reported pit latrine emptying time motion data (Rutayisire et al., 2022).

2.2 Qualitative risk scores

The illustrations and storyboards were used to guide the qualitative assessment of risk to workers based on exposure to aerosol inhalation and fecal ingestion at each step of the emptying process. Risk scores were estimated for each step in the emptying process using the equation:

$$R = M \times L$$

Where R = risk index.

M = magnitude, rated on a scale of 1–4, based on how potentially dangerous an undesired event is, with 1 as “negligible”, 2 as “marginal”, 3 as “critical”, and 4 as “high”.

L = likelihood, rated on a scale of 1–5 based on how many opportunities are there for the undesired event to occur, with 1 as “minimal”, 2 as ‘marginal”, 3 as “some opportunities”, 4 as “several opportunities”, and 5 as “maximum opportunities”.

M and L ratings were qualitatively assessed based on the field observations in Zambia, Kenya, Tanzania, and India. Considerations for assigning values included our evaluation of answers to questions (in the context of fecal ingestion and aerosol inhalation) such as: How much cognitive load is involved with the activity (e.g., higher cognitive load, lower rating)? How active are the workers’ hands? How far along are the workers in the emptying process? How close are the workers to open fecal sludge? How much direct contact with fecal sludge is involved? How much mechanical disturbance is occurring in the process?

Multiplying the M and L ratings resulted in a Risk Score for the undesired event, with 1–4 as “very low”, 5–8 as “low”, 9–12 as “medium”, and 15–20 as “high”.

3 Results

3.1 Illustrated systems

The data informed the creation of a list of all individual elements of the system (Figure 1); these elements were used to construct a storyboard to describe manual pit latrine emptying. All illustrations are available under creative commons CC-BY license.

3.1.1 Scenario 1: Manual emptying with proper disposal

The manual emptying storyboard describes teams loading emptying equipment at the headquarters, interfacing with customers, and preparing fecal sludge removal at the site. Fecal sludge removal includes opening the pit latrine, collecting fecal sludge and trash into barrels, transporting barrels to a centralized wastewater treatment plant, and disposing fecal sludge and trash at the treatment center (Figure 2).

3.1.2 Scenario 2: Vacuum truck emptying with proper disposal. Operator does not enter the truck for cleaning

This storyboard included new elements such as a vacuum truck to describe vacuum truck emptying, starting from

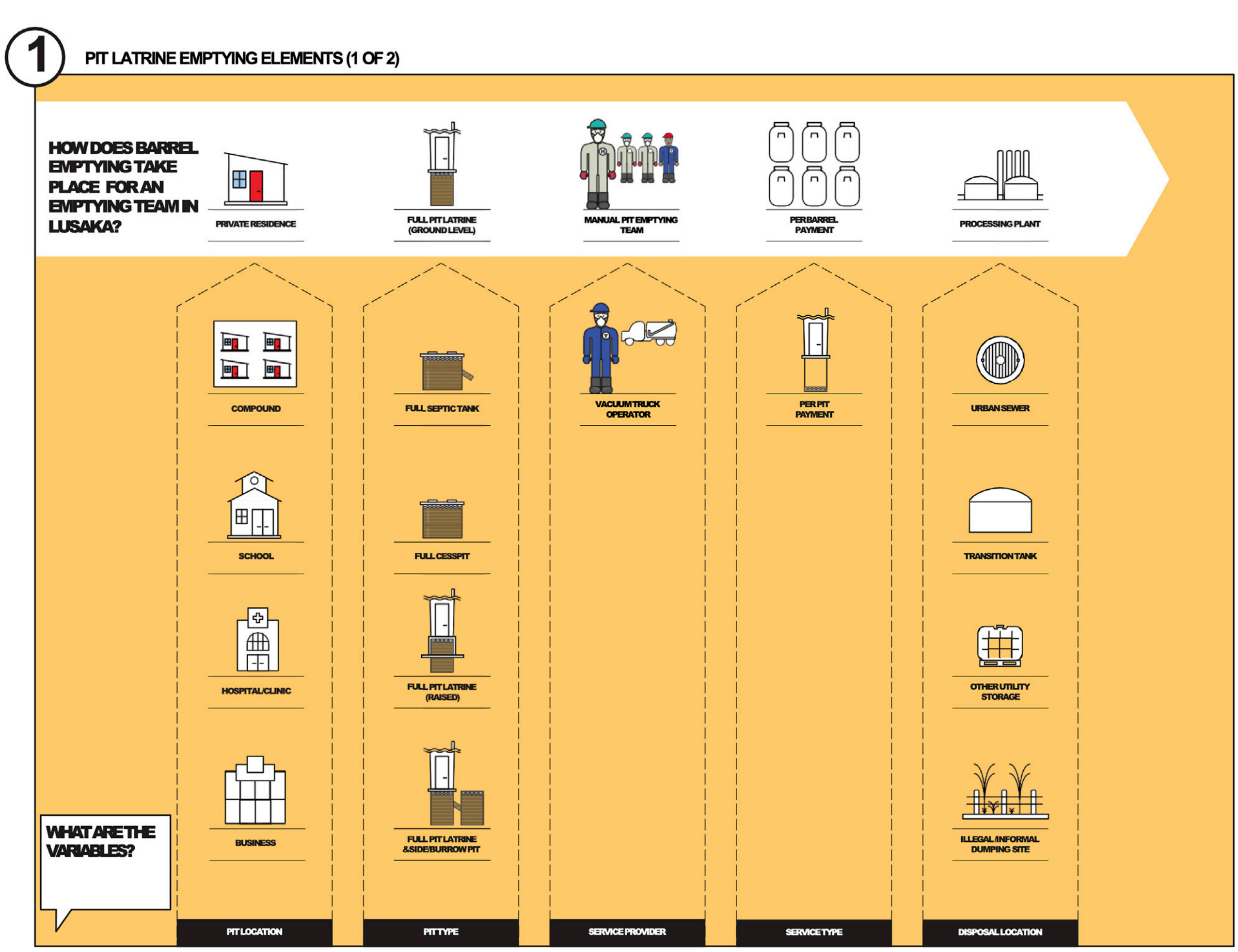

FIGURE 1
Excerpt of pit latrine emptying elements in manual pit latrine emptying. See Supplementary Material for the complete set.

putting on personal protective equipment, loading necessary equipment of the truck, travelling to the customer site, preparing pit emptying by removing the lid, starting a vacuum filling the vacuum truck, and then traveling to a wastewater treatment facility for proper sludge disposal (Figure 3).

3.1.3 Scenario 3: Vacuum truck emptying interrupted by a clog with improper disposal. Operator enters the truck for cleaning

Trash improperly disposed in latrines and septic tanks often interferes with mechanical emptying. The storyboard includes steps needed for unclogging (Figure 4). Sometimes sludge is disposed improperly in an open field instead of a treatment facility. This illustrated set also shows the process of fully cleaning a vacuum truck by having a worker enter the tank.

3.2 Qualitative risk analysis

3.2.1 Scenario 1: Manual emptying with proper disposal

Manual pit latrine emptying is one of the messiest processes as emptier are handling tools to directly remove trash and fecal sludge in the pit (Supplementary Table S1, steps J-L). However, this process tends to require a lot of physical and cognitive load, making the likelihood of facial touches low. In this illustrated scenario, we see that the higher score activities are when workers have contaminated hands but are relatively idle (Table 1), with the highest score after workers have completed emptying and are relatively inactive as they are signing off with the customer and transporting barrels of fecal sludge to the treatment plant.

Fecal aerosols are most likely generated during the pit emptying process (Table 2, steps H-M) and when the fecal

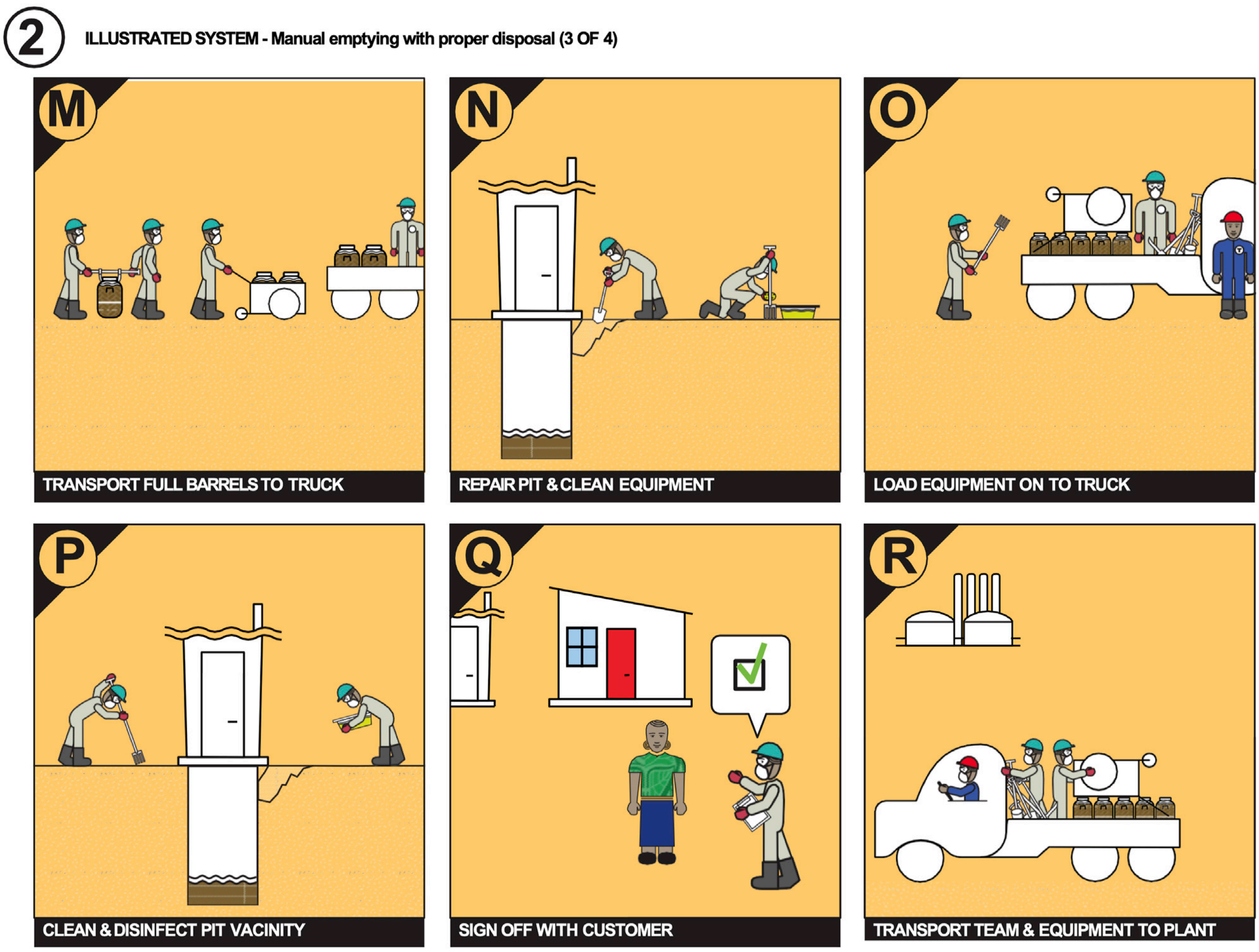

FIGURE 2
Excerpt of manual emptying with proper disposal. See Supplementary Material for the complete set. The panel labels correspond to the chronological labels used in the complete set.

sludge is transferred at the treatment plant for processing (Table 2, steps T-U). Both processes have workers close to sources of fecal aerosols, and the estimated 98-min process of pit emptying and 40 min disposal of the septage into the facility have the highest risk of inhaling aerosols.

3.2.2 Scenario 2: Vacuum truck emptying with proper disposal

Here, ingestion through indirect touches have a higher score when workers have completed pit latrine emptying and are in transit to the treatment plant (Table 3, steps S-U). With respect to aerosols the activities with the highest risk are when workers are inserting the hose for emptying (Table 4, steps I-Q) and when the workers are releasing septage into the treatment plant (Table 4, steps V-Z). Emptying takes about 1 h and the release of septage from the truck takes about 55 min.

3.2.3 Scenario 3: Vacuum truck emptying interrupted by a clog with improper disposal

With respect to indirect touches leading to ingestion of feces, emptying septage into an open field (Table 5, steps W-X) has a slightly elevated risk profile compared to emptying into a treatment facility (Table 3, steps W-X), as the act of emptying septage into a field has less cognitive load than emptying into a wastewater treatment plant.

Managing clogs in hoses adds more time to the pit emptying process, creating more opportunities for fecal aerosols. The emptying process (Table 6, steps I-T) is estimated at 95 min, on par with pit latrine emptying in this scenario (Supplementary Table S2, steps H-M). Emptying the septage into an open field and spending time to clean inside the truck also exposes emptiers to fecal aerosols for longer periods (Table 6, steps X-Z).

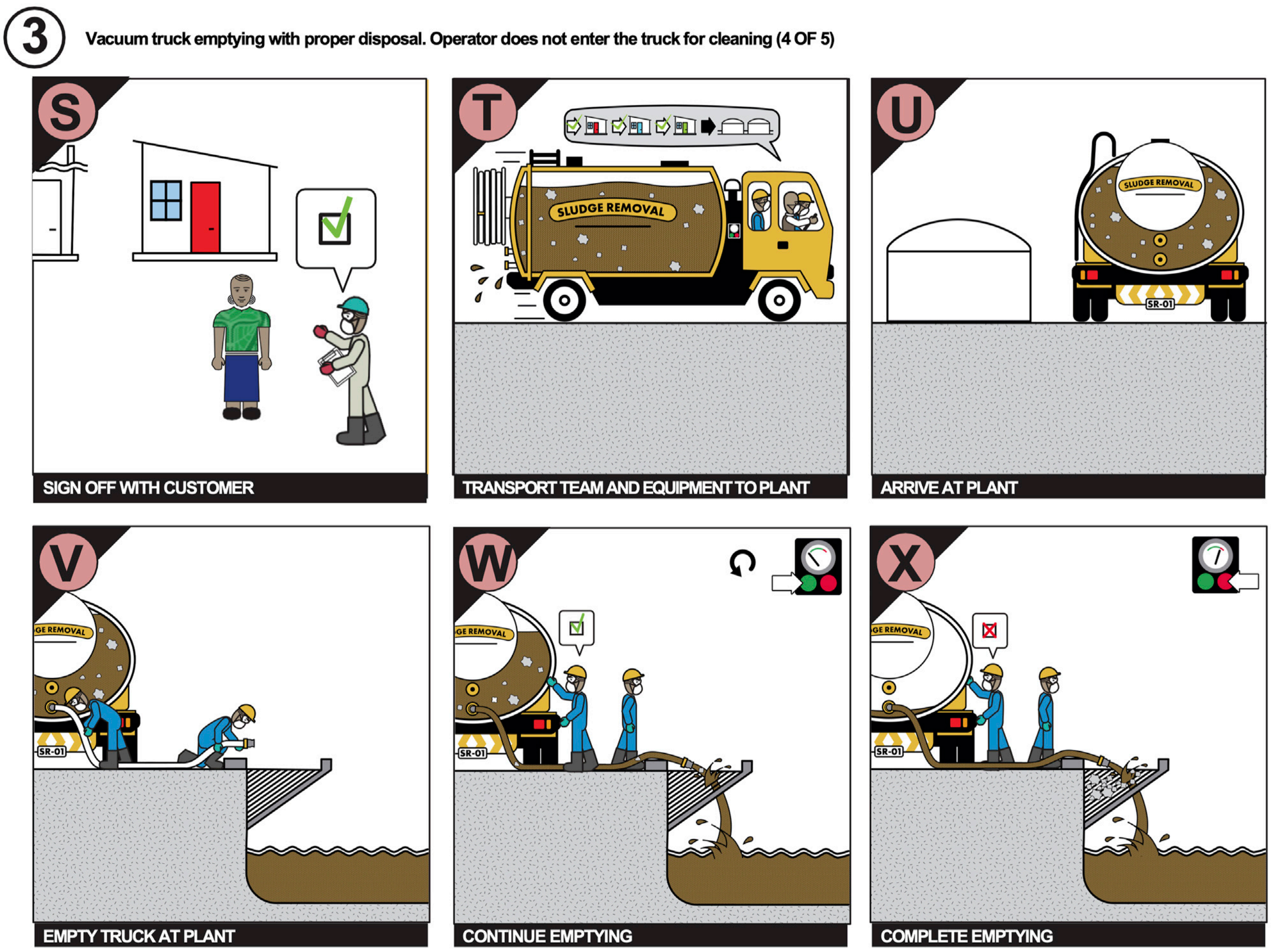

FIGURE 3
Excerpt of vacuum truck emptying with proper disposal. Operator does not enter the truck for cleaning. See Supplementary Material for the complete set. The panel labels correspond to the chronological labels used in the complete set.

4 Discussion

An illustrated system analysis has the same intent as an infographic—to clarify communication and improve information access—but goes deeper to create detailed visual communication of complexities and nuances of a system. A system analysis can have many branches of information and can zoom in and out of scale, depending on a design focus, budget, and time. Thus, one can use an illustrated system to add detail at any level and focus on a particular target of emphasis. In this study, we use the illustrated system to qualitatively analyze health risks to pit emptying workers, showing how the approach can be adjusted to fit a variety of scenarios. The mere exercise of putting together an illustration of the sanitation system along with establishing a rubric to examine exposure pathways of interest allows stakeholders to think through assumptions and mechanisms. It may highlight important steps, allowing groups to consider different design or operational approaches to safety interventions.

Here we examine the pathways of fecal aerosols and indirect ingestion *via* facial touches. While ingestion of feces can occur directly during pit latrine emptying, the mechanism can be subtle such as through face touches around perioral regions. There has also been recent attention towards the possibility of ingestion through fecal aerosols. Pit latrine emptiers in Malawi have been estimated to accidentally consume up to 0.4 g of feces a year through pit latrine emptying activities and inhale up to 6 g a year (Kumwenda et al., 2017). The estimated exposure dose of grams of fecal material along with dosage of *Ascaris*, *Taenia*, hookworms, *E. coli*, and *Salmonella* have been reported (Kumwenda et al., 2017).

Qualitative estimates on the likelihood of ingesting feces in different pit latrine emptying processes have been described (Stenström et al., 2011), but do not indicate steps that are

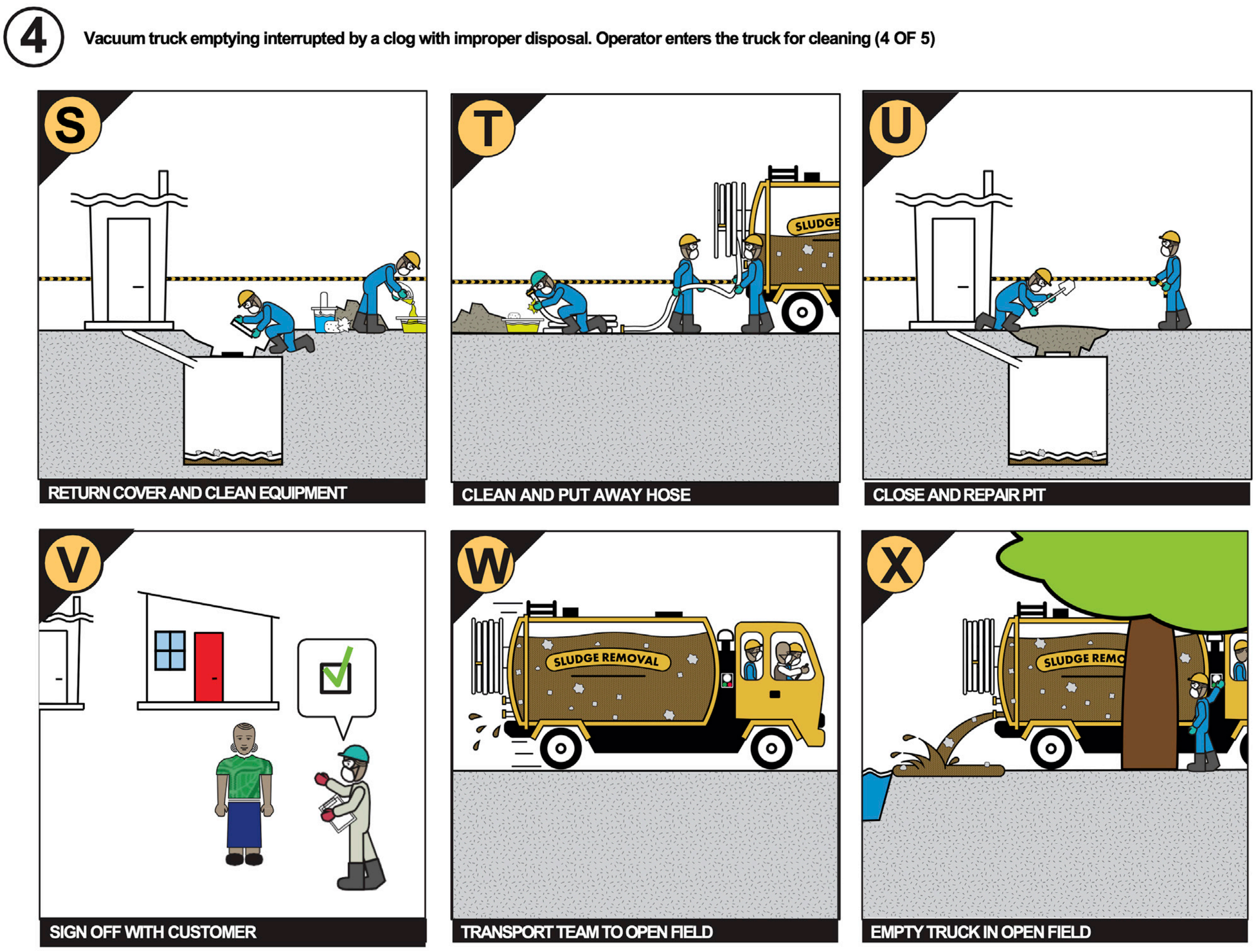

FIGURE 4
Excerpt of vacuum truck emptying interrupted by a clog with improper disposal. Operator enters the truck for cleaning. See Supplementary Material for the complete set. The panel labels correspond to the chronological labels used in the complete set.

TABLE 1 Scenario 1, Excerpt of facial touch risk scores for manual emptying with proper disposal. Solid lines between rows denotes to a break in steps. See Supplementary Material for the complete set.

Scenario 1: Manual emptying with proper disposal	Magnitude	Likelihood	Magnitude x likelihood	T: Time (minutes)
(A) Apply personal protective equipment	1	5	5	10
(B) Pickup/load equipment & team into truck	1	5	5	10
(C) Transport team and equipment to pit	1	5	5	30
(D) Find customer and request water	1	5	5	10
(Q) Sign off with customer	2	5	10	5
(R) Transport team & equipment to plant	2	5	10	30
(T) Empty barrels into trash sieve	3	2	6	10
(X) Remove personal protective equipment	1	5	5	5

TABLE 2 Scenario 1, Excerpt of fecal aerosol inhalation risk scores for manual emptying with proper disposal. Solid lines between rows denotes to a break in steps. See Supplementary Material for the complete set.

Scenario 1: Manual emptying with proper disposal	Magnitude	Likelihood	Magnitude x likelihood	T: Time (minutes)
(H) Dig hole into side of pit	4	4	16	10
(I) Create barrel filling spillway	4	4	16	8
(J) Fish trash from pit into barrel	4	5	20	20
(K) Close & clean barrel	4	5	20	20
(L) Scoop sludge into barrel	4	5	20	20
(M) Transport full barrels to truck	3	4	12	20
(T) Empty barrels into trash sieve	4	5	20	10
(U) Separate out trash into trash pile	4	5	20	20

TABLE 3 Scenario 2, Excerpt of facial touch risk scores for vacuum truck emptying with proper disposal. Operator does not enter the truck for cleaning. Solid lines between rows denotes to a break in steps. See Supplementary Material for the complete set.

Scenario 2: Vacuum truck emptying with proper disposal	Magnitude	Likelihood	Magnitude x likelihood	T: Time (minutes)
(A) Apply personal protective equipment	1	5	5	10
(B) Pickup/load equipment & team into truck	1	5	5	10
(C) Transport team and equipment to pit	1	5	5	30
(D) Find customer and request water	1	5	5	10
(O) Desludge hose	3	2	6	5
(S) Sign Off with customer	2	5	10	5
(T) Transport team and equipment to plant	2	5	10	30
(U) Arrive at plant	2	5	10	5
(W) Continue emptying	3	2	6	15
(X) Complete emptying	3	2	6	5

more prone to these more indirect routes. As an emptier works along the emptying process, the presence of fecal indicators such as *Staphylococcus aureus* and *E. coli* on work and household surfaces (i.e., walkways between pit latrines and handles on municipal vehicles) increases (Beukes and Schmidt, 2022). Wearing gloves does not always prevent hand contamination. In one study of pit latrine emptiers in Rwanda, hands were contaminated with *E. coli* nearly 2.5×10^2–4.8×10^3 CFU/hand after mechanically collecting waste despite wearing gloves (Sklar et al., 2021).

While the amount of fecal material on hands increases over the emptying process, the material needs to be transferred into the mouth for accidental ingestion. Touching of mucosal layers can occur frequently; when attending a lecture, students were found to have touched their face an average of 23 times per hour with 44% of them touching membranes such as the mouth (Kwok et al., 2015). While the frequency of face touches varies between individuals (Bischel et al., 2019), there is evidence indicating that hand touches are tied to cognitive load and activity level of hands. When people are asked to drive in conditions that require high physical and cognitive load, drivers had an average of 4.4 face touches an hour (FT/h). Under low cognitive load driving conditions there were 26.1 face touches with a large range in individual behaviors (anywhere between 5.1 and 90.7 FT/h) (Ralph et al., 2022). Facial touches decrease when people are asked to do activities that require active hands such as performing a small home improvement project versus a more passive activity such as listening to music (Lewis et al., 2021). Under video recording, sanitation workers who collected urine containers had relatively rare hand-mouth contact during collection while gloved, but after glove removal had facial touches 0.3 ± 0.7 times per hour during urine collection (Bischel et al., 2019). As with gloves, face masks do not completely mitigate accidental exposures. Under video observation, sanitation workers had approximately 13 ± 8 times per hour hand-to-face mask touches, and thus

TABLE 4 Scenario 2, Excerpt of fecal aerosol inhalation risk scores for vacuum truck emptying with proper disposal. Operator does not enter the truck for cleaning. Solid lines between rows denotes to a break in steps. See Supplementary Material for the complete set.

Scenario 2: Vacuum truck emptying with proper disposal	Magnitude	Likelihood	Magnitude x likelihood	T: Time (minutes)
(I) Insert hose	4	5	20	5
(J) Begin pumping	4	5	20	5
(K) Continue pumping	4	5	20	15
(L) Pit empty	4	5	20	5
(M) Stop pump	4	5	20	5
(N) Remove hose	4	5	20	5
(O) Desludge hose	4	5	20	5
(P) Return cover and clean equipment	4	5	20	10
(Q) Clean and put away hose	3	5	15	5
(V) Empty truck tank	4	5	20	5
(W) Continue emptying	4	5	20	15
(X) Complete emptying	4	5	20	5
(Y) Clean screen	4	5	20	10
(Z) Clean and disinfect truck and equipment	4	5	20	20

TABLE 5 Scenario 3. Excerpt of facial touch risk scores for vacuum truck emptying interrupted by a clog with improper disposal. Solid lines between rows denotes to a break in steps. Operator enters the truck for cleaning. See Supplementary Material for the complete set.

Scenario 3: Vacuum truck emptying interrupted by a clog with improper disposal	Magnitude	Likelihood	Magnitude x likelihood	T: Time (minutes)
(A) Apply personal protective equipment	1	5	5	10
(B) Pickup/load equipment & team into truck	1	5	5	10
(C) Transport team and equipment to pit	1	5	5	30
(D) Find customer and request water	1	5	5	10
(R) Desludge hose	3	2	6	5
(W) Transport team and equipment to open field	2	5	10	30
(X) Empty truck in open field	3	4	12	20
(BB) Remove personal protective equipment	1	5	5	5

inappropriate removal of PPE was included in models for infection risk for accidental exposure in urine collection and struvite production (Bischel et al., 2019).

Fecal aerosols have been reported in wastewater treatment plants, generated mainly through mechanical agitation such as splashing and aeration (Sánchez-Monedero et al., 2008). In wastewater bioaerosols, pathogens such as *Acinetobacter*, *Pseudomonas*, and *Micrococcus* have been detected, with long-term exposure having the potential to lead to chronic diseases (Yang et al., 2019). Recently, fecal based microbial genes were found in the bioaerosols in LMIC settings with inadequate sanitation infrastructure (Ginn et al., 2022). However, few of these studies measured viability, and even fewer studies connect pathogen viability to enteric pathogen exposure (Ginn et al., 2022).

There is evidence that pit latrine emptying activities can create bioaerosols; in one study of mechanical emptying, nearly 350 CFU m^{-3} for *E. coli* and 790 CFU m^{-3} for total coliforms were detected in air near pits being emptied, including the enterotoxigenic strain of *E. coli* (Farling et al., 2019). In our analysis, we directly relate the amount of mechanical disturbance in the process to higher production of bioaerosols, and inversely relate higher concentrations of aerosolized fecal indicator organisms to distance. Enteric pathogens can be found within 1 km of open wastewater canals in cities with poor sanitation (Ginn et al., 2021). Sampling of bioaerosols shows that fecal

TABLE 6 Scenario 3, Excerpt of fecal aerosol inhalation risk scores for vacuum truck emptying interrupted by a clog with improper disposal. Operator enters the truck for cleaning. Solid lines between rows denotes to a break in steps. See Supplementary Material for the complete set.

Scenario 3: Vacuum truck emptying interrupted by a clog with improper disposal	Magnitude	Likelihood	Magnitude x likelihood	T: Time (minutes)
(I) Insert hose	4	5	20	5
(J) Begin pumping	4	5	20	5
(K) Continue pumping	4	5	20	15
(L) Remove hose due to blockage	4	5	20	5
(M) Reverse pump	4	5	20	10
(N) Clear hose)	4	5	20	10
(O) Resume pumping sludge	4	5	20	15
(P) Empty pit	4	5	20	5
(Q) Remove hose	4	5	20	5
(R) Desludge hose	4	5	20	5
(S) Return cover and clean equipment	4	5	20	10
(T) Clean and put away hose	3	5	15	5
(X) Empty truck in open field	4	5	20	20
(Y) Enter inside truck for cleaning	4	5	20	5
(Z) Continue emptying truck	4	5	20	30

indicators are at higher concentrations within 10 m of open wastewater canals than distances greater than 10 m away (Rocha-Melogno et al., 2020).

Our analysis led to specific recommendations that in hindsight may be obvious; however, the illustrated systems highlight and clearly communicated these risks to workers. Example interventions include additional training on minimizing facial touches (when idle, or doing routine work that has low cognitive load). Cleaning hands should be emphasized, but especially in the context of going in and out of vehicles, such as the ride back from the emptying site. As hands and PPE are likely to be more contaminated over time, emptying teams should take care to properly remove PPE and properly disinfect hands and clothes prior to entering and leaving the transporting truck. Reducing mechanical disturbance of the sludge during the emptying process can help mitigate fecal aerosol production. This is of particular concern at not only the pit latrine emptying site but also the site of dumping. PPE such as masks should be seen as necessities and not simply for virtue signaling.

The framework we described here can be applied to a range of possible improvements within the sanitation system. The emptying team can visualize and consider the health and safety of workers using typical or new technologies for emptying pit latrines, such as the Gulper (e.g., Thye et al., 2011; Balasubramanya et al., 2016), a pedal-powered Gulper (Chipeta et al., 2017), a screw auger (Rogers et al., 2014; Sisco et al., 2017); and a trash excluder (Portiolli et al., 2021). By developing new illustrations (frames or "cards") specific to these technologies and re-using the current illustrations, new storyboards can be developed. The framework could also assist examining how to make pit latrine emptying safer from an ergonomic perspective, such as how workers lift, twist, and transfer equipment and collected sludge (Bleck and Wettberg, 2012). Illustrations can also show how pit latrine emptying and its different approaches could contribute to fecal contamination of nearby soils (Pickering et al., 2012). The illustrations can be used for multiple functions: documenting team learnings, clarifying internal and external communication, decreasing onboarding/learning time, and expediting comprehension. These could lead to savings in consulting budgets and help in creating a multi-use library of visual assets (applicable from manuals to infographics to annual reports). The process of creating an illustrated system analysis inherently teaches the co-creators a deep understanding of the system and raises expectations of team comprehension and alignment.

The fecal sludge management (FSM) sector can take advantage of illustrated system analysis, by clearly communicating nuanced FSM systems so that they could be comprehensible to and referenced by a much larger audience and used to spark innovation. We recognize the benefit that this library of graphics can provide for the public and make it freely available *via* CC-BY. Free and open-source software can be used by the public to adapt or generate their own diagrams and make their own scenarios.

5 Conclusion

Illustrated systems have multiple functions that can help the FSM sector. As tools for analysis, communication, comprehension, and aligning team values and objectives, illustrated systems are useful and have potential impact. In this study, we show how using Illustrated System Analysis and combining this with qualitative risk analysis can allow pit emptying teams to more clearly and quickly evaluate the different levels of risks associated with the different steps of their specific pit emptying process. We provide a freely available library of graphics that the FSM community can use and disseminate widely.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

JT: investigation, conceptualization, methodology, and writing; NW: conceptualization, investigation, methodology, and visualization. FD: conceptualization, formal analysis, funding acquisition, investigation, methodology, supervision, writing, and editing.

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Conflict of interest

NW was employed by the company Catapult Design.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.1033877/full#supplementary-material

References

Ashwin, C. (1984). Drawing, design and semiotics. *Des. Issues* 1, 42–52. doi:10.2307/1511498

Balasubramanya, S., Evans, B., Ahmed, R., Habib, A., Asad, N. S. M., Vuong, L., et al. (2016). Pump it up: Making single-pit emptying safer in rural Bangladesh. *J. Water Sanit. Hyg. Dev.* 6, 456–464. doi:10.2166/washdev.2016.049

Beukes, L. S., and Schmidt, S. (2022). Manual emptying of ventilated improved pit latrines and hygiene challenges - a baseline survey in a peri-urban community in KwaZulu-Natal, South Africa. *Int. J. Environ. Health Res.* 32, 1043–1054. doi:10.1080/09603123.2020.1823334

Bischel, H. N., Caduff, L., Schindelholz, S., Kohn, T., and Julian, T. R. (2019). Health risks for sanitation service workers along a container-based urine collection system and resource recovery value chain. *Environ. Sci. Technol.* 53, 7055–7067. doi:10.1021/acs.est.9b01092

Bleck, D., and Wettberg, W. (2012). Waste collection in developing countries – tackling occupational safety and health hazards at their source. *Waste Manag.* 32, 2009–2017. doi:10.1016/j.wasman.2012.03.025

Chipeta, W. C. C., Holm, R. H. H., Kamanula, J. F. F., Mtonga, W. E. E., and de los Reyes, F. L. (2017). Designing local solutions for emptying pit latrines in low-income urban settlements (Malawi). *Phys. Chem. Earth Parts A/B/C* 100, 336–342. doi:10.1016/j.pce.2017.02.012

Farling, S., Rogers, T., Knee, J. S., Tilley, E. A., Brown, J., and Deshusses, M. A. (2019). Bioaerosol emissions associated with pit latrine emptying operations. *Sci. TOTAL Environ.* 648, 1082–1086. doi:10.1016/j.scitotenv.2018.08.147

Gautam, M., Wankhade, K., Sarangan, G., and Sudhakar, S. (2021). Framework for addressing occupational safety of de-sludging operators: A study in two Indian cities. *J. Environ. Manage.* 289, 112243. doi:10.1016/j.jenvman.2021.112243

Ginn, O., Lowry, S., and Brown, J. (2022). A systematic review of enteric pathogens and antibiotic resistance genes in outdoor urban aerosols. *Environ. Res.* 212, 113097. doi:10.1016/j.envres.2022.113097

Ginn, O., Rocha-Melogno, L., Bivins, A., Lowry, S., Cardelino, M., Nichols, D., et al. (2021). Detection and quantification of enteric pathogens in aerosols near open wastewater canals in cities with poor sanitation. *Environ. Sci. Technol.* 55 (21), 14758–14771. doi:10.1021/acs.est.1c05060

Graham, J. P., and Polizzotto, M. L. (2013). Pit latrines and their impacts on groundwater quality: A systematic review. *Environ. Health Perspect.* 121, 521–530. doi:10.1289/ehp.1206028

Greene, N., Hennessy, S., Rogers, T. W., Tsai, J., and de los Reyes, F. L., III (2021). The role of emptying services in provision of safely managed sanitation: A classification and quantification of the needs of LMICs. *J. Environ. Manage.* 290, 112612. doi:10.1016/j.jenvman.2021.112612

Gurksi, T., Hennessy, S., Rogers, T., and Shaw, J. (2022). A practical guide to available pit-emptying technologies. FSM Alliance Available at: https://fsm-alliance.glueup.com/event/fsma-spotlights-a-practical-guide-to-available-pit-emptying-technologies-48207/ (Accessed August 20, 2022).

Haas, C. N. (2020). Quantitative microbial risk assessment and molecular biology: Paths to integration. *Environ. Sci. Technol.* 54, 8539–8546. doi:10.1021/acs.est.0c00664

Iwasa, J. H. (2022). Using animation to mediate scientific discourse. *Nat. Microbiol.* 7, 3. doi:10.1038/s41564-021-01024-5

Kumwenda, S., Msefula, C., Kadewa, W., Ngwira, B., and Morse, T. (2017). Estimating the health risk associated with the use of ecological sanitation toilets in Malawi. *J. Environ. Public Health* 2017, 1–13. doi:10.1155/2017/3931802

Kwok, Y. L. A., Gralton, J., and McLaws, M.-L. (2015). Face touching: A frequent habit that has implications for hand hygiene. *Am. J. Infect. Control* 43, 112–114. doi:10.1016/j.ajic.2014.10.015

Leach, T. (2022). Scientist or artist? Why not be both? *Nat. Microbiol.* 7, 4. doi:10.1038/s41564-021-00995-9

Lewis, R. C., Rauschenberger, R., and Kalmes, R. (2021). Hand-to-mouth and other hand-to-face touching behavior in a quasi-naturalistic study under controlled conditions. *J. Toxicol. Environ. Health A* 84, 49–55. doi:10.1080/15287394.2020.1830457

McGill, G. G. (2022). Knowledge synthesis through scientific visualization. *Nat. Microbiol.* 7, 185. doi:10.1038/s41564-021-01048-x

Mubatsi, J. B., Wafula, S. T., Etajak, S., Ssekamatte, T., Isunju, J. B., Kimbugwe, C., et al. (2021). Latrine characteristics and maintenance practices associated with pit latrine lifetime in an informal settlement in Kampala, Uganda. *J. Water Sanit. Hyg. Dev.* 11, 657–667. doi:10.2166/washdev.2021.032

Pickering, A. J., Julian, T. R., Marks, S. J., Mattioli, M. C., Boehm, A. B., Schwab, K. J., et al. (2012). Fecal contamination and diarrheal pathogens on surfaces and in soils among Tanzanian households with and without improved sanitation. *Environ. Sci. Technol.* 46, 5736–5743. doi:10.1021/es300022c

Portiolli, G. F., Rogers, T. W., Beckwith, W., Tsai, J., ole-MoiYoi, P., Wilson, N., et al. (2021). Development of trash exclusion for mechanized pit latrine emptying. *Environ. Sci. Water Res. Technol.* 7, 1714–1722. doi:10.1039/D1EW00383F

Ralph, F., Large, D. R., Burnett, G., Lang, A., and Morris, A. (2022). U can't touch this! Face touching behaviour whilst driving: Implications for health, hygiene and human factors. *Ergonomics* 65, 943–959. doi:10.1080/00140139.2021.2004241

Revitt, D. M., Lundy, L., and Fatta-Kassinos, D. (2021). Development of a qualitative approach to assessing risks associated with the use of treated wastewater in agricultural irrigation. *J. Hazard. Mat.* 406, 124286. doi:10.1016/j.jhazmat.2020.124286

Rocha-Melogno, L., Ginn, O., Bailey, E. S., Soria, F., Andrade, M., and Bergin, M. H. (2020). Bioaerosol sampling optimization for community exposure assessment in cities with poor sanitation: A one health cross-sectional study. *Sci. Total Environ.* 738, 139495. doi:10.1016/j.scitotenv.2020.139495

Rogers, T. W., de los Reyes, F. L., Beckwith, W. J., and Borden, R. C. (2014). Power Earth auger modification for waste extraction from pit latrines. *J. Water Sanit. Hyg. Dev.* 4, 72–80. doi:10.2166/washdev.2013.183

Rutayisire, B., Wolter, D., Kuria, N., and Sklar, R. (2022). Time and motion assessment of pit-emptying operations in Kigali, Rwanda. *J. Water Sanit. Hyg. Dev.* 12, 16–22. doi:10.2166/washdev.2021.079

Sánchez-Monedero, M. A., Aguilar, M. I., Fenoll, R., and Roig, A. (2008). Effect of the aeration system on the levels of airborne microorganisms generated at wastewater treatment plants. *Water Res.* 42, 3739–3744. doi:10.1016/j.watres.2008.06.028

Schulte, P. (2009). Qualitative risk characterization and management of occupational hazards: Control banding (CB). Available at: https://www.cdc.gov/niosh/docs/2009-152/pdfs/2009-152.pdf (Accessed August 18, 2022).

Sisco, T., Rogers, T., Beckwith, W., Chipeta, W., Holm, R., Buckley, C. A., et al. (2017). Trash removal methods for improved mechanical emptying of pit latrines using a screw auger. *J. Water Sanit. Hyg. Dev.* 7, 85–91. doi:10.2166/washdev.2017.106

Sklar, R., Zhou, Z., Ndayisaba, W., Muspratt, A., Fuhrmeister, E. R., Nelson, K., et al. (2021). Risk of adenovirus and *cryptosporidium* ingestion to sanitation workers in a municipal scale non-sewered sanitation process: A case study from kigali. *Rwanda. J. Water Sanit. Hyg. Dev.* 11, 570–578. doi:10.2166/washdev.2021.241

Stenström, T. A., Seidu, R., Ekane, N., and Zurbrügg, C. (2011). *Microbial exposure and health assessments in sanitation technologies and systems*. Stockholm: Stockholm Environment Institute.

Thye, Y. P., Templeton, M. R., and Ali, M. (2011). A critical review of technologies for pit latrine emptying in developing countries. *Crit. Rev. Environ. Sci. Technol.* 41, 1793–1819. doi:10.1080/10643389.2010.481593

World Health Organization (2018). *Guidelines on sanitation and health*. Geneva: World Health Organization.

World Health Organization (2015). *Sanitation safety planning: Manual for safe use and disposal of wastewater, greywater and excreta*. Geneva: World Health Organization.

Yang, K., Li, L., Wang, Y., Xue, S., Han, Y., and Liu, J. (2019). Airborne bacteria in a wastewater treatment plant: Emission characterization, source analysis and health risk assessment. *Water Res.* 149, 596–606. doi:10.1016/j.watres.2018.11.027

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Pathogens inactivation in nutrient recovery from urine: A review

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Urine source separation, a kind of new sewage management concept, has made great progress in technology development and application in the past 30 years. However, understanding of the potential microbial risks in reuse of urine-derived fertilizer products (UDFPs) in agriculture is still lacking. Outbreak of pandemic of Coronavirus Disease 2019 and more deadly disease caused by Monkeypox strongly sounds the alarm bell to the attention on pathogens in urine and their fate in UDFPs. Therefore, this study presented a comprehensive review on pathogens inactivation in nutrient recovery technologies. The review suggests that technologies using alkaline or heating treatment can effectively reduce pathogens in UDFPs. However, technologies with characteristics such as membrane rejection of nutrients or nutrient adsorption may even concentrate pathogens in their fertilizer products. Based on an overall assessment, connections of technologies and the pathogens inactivation in their UDFPs have been established. This would help to provide a perspective on development of urine treatment technology and management of microbial risks in reusing urine nutrients in agriculture.

KEYWORDS

urine source separation, nutrient recovery, pathogens inactivation, microbial risk, urine treatment

1 Introduction

Urine source separation, a novel concept of wastewater management, was proposed at the end of the 19th century (Larsen and Gujer, 1996). Human urine contains abundant amounts of macro-nutrients, accounting for approximately 79% of nitrogen, 49% of phosphorus, and 58% of potassium in household wastewater (Vinnerås et al., 2006). Resource recycling from urine benefits closing the loop of nutrients. This would provide a sustainable approach to ease the tension between the increasing demand of food and fertilizer and the shortage of nutrients while preventing water pollution (Larsen et al., 2016; Badeti et al., 2022). Thus, it could be an effective tool to help eradicating hunger and ensuring environmental sustainability in the Millennium Development Goals (MDGs) of

United Nations, and achieving zero hunger, clean water and sanitation, and sustainable cities and communities in the Sustainable Development Goals (SDGs).

Various technologies have been developed to reuse or recover nutrients from urine. This has been reviewed in several recent publications (Simha and Ganesapillai, 2017; Harder et al., 2019; Patel et al., 2020; Cheng et al., 2022; Liu et al., 2022). Moreover, dozens of pilot projects of urine source separation have been constructed and evaluated in schools, villages or modern buildings in both developed and developing countries (Zhang et al., 2015). Most of these technologies and projects mainly focus on the technical and economic efficiency of nutrient recycling while only a few studies reported the hygienic aspect of urine. Actually, urine is not sterile and it contains culture-positive microbiological communities (Hilt et al., 2014). Several bacterial and viral pathogens were detected in the source-separated urine collected at the eThekwini Water and Sanitation municipality in South Africa (Bischel et al., 2015). Users of toilet and urine-derived fertilizer product (UDFP) may be exposed to pathogens-carrying urine and UDFPs. Moreover, consumers also may be exposed to food fertilized with UDFPs. All these possible exposure pathways can bring health risks to people who may be infected through vehicleborne transmission defined as one of the indirect transmission modes (US Department of Health and Human Services, 2012).

Quantitative Microbial Risk Assessment (QMRA) has been used to assess the microbial risk in handling of urine and eating vegetables fertilized by urine (Hoglund et al., 2002; Ahmed et al., 2017; Bischel et al., 2019; Oishi et al., 2020). Typical pathogens examined included *Campylobacter jejuni*, Enterotoxigenic *Escherichia coli (E. coli)*, *Shigella* spp., *Cryptosporidium parvum* and rotavirus, etc. All these studies reported health risks to users, workers and consumers when pathogens-containing urine was collected, transported and handled without any pretreatment. Storage for 2–6 months is usually recommended for effective inactivation of pathogens in urine, which is caused by high alkaline pH and high free ammonia due to urea hydrolysis (World Health Organization (WHO), 2006; Vinnerås et al., 2008). Moreover, pathogens in urine can also be effectively inactivated through alkaline treatment by ash and lime (Randall et al., 2016; Senecal et al., 2018). However, up to date, there still lacks a connection of urine treatment to its effect on pathogens inactivation, which might make researchers ignore the microbial risks of urine source separation especially developing new technologies for urine treatment. Particularly, the pandemic of Coronavirus Disease 2019 (https://www.who.int/emergencies/diseases/novel-coronavirus-2019) and the outbreak of more deadly disease caused by Monkeypox (https://www.who.int/emergencies/situations/monkeypox-oubreak-2022) strongly reminds the possible microbial risks in the recycling of urine nutrients in agriculture.

Therefore, this study aimed to review the inactivation of pathogens in urine treatment technologies. Pathogens in urine reported in publications were summarized. The inactivation of pathogens in various technologies and UDFPs were evaluated based on a comprehensive review of publications. Then, an overall assessment was carried out to build a connection of urine treatment to its effect on pathogens inactivation. Finally, an outlook was proposed for the microbial risk management in urine source separation and nutrient recovery.

2 Pathogens in urine

Only a few publications reported pathogens detected in urine collected from toilets while many reported findings in urine collected from patients in medical research. Bacteria and viruses detected in urine in literature have been briefly summarized in Supplementary Table S1. Therefore, urine is not sterile. Possible approaches for pathogens introducing to urine were discussed as following.

2.1 Pathogens excretion with urine

Human urine forms by filtration of blood plasma through glomerular filtration barrier into nephron in kidneys (Rose, 1966). The barrier commonly has nanoscale pores while sizes of bacteria are approximately of micron scale (Goswami and Pugazhenthi, 2020). For example, the length and the diameter of *E. coli* is approximately 2 μm and 0.5 μm, respectively (Sherbet and Lakshmi, 1973). Thus, urine often does not contain bacteria. However, urine will be contaminated by pathogenic bacteria when infection occurs in the urinary system of patients. Studies have reported several pathogenic bacteria in urine, which often cause some clinical urinary tract infection and inflammation, such as *E. coli* (Hinata et al., 2004), *Proteus mirabilis, Pseudomonas aeruginosa* (Qiao et al., 2013), a variety of gram-negative and gram-positive bacteria (Shigemura et al., 2005). Sun et al. (2020) identified more than 10^5/ml of bacterial particles in clinical urine samples through analysis by mass spectrometry combined with UF–5000i flow cytometry, and the pathogens were all single microbial species (Sun et al., 2020). Chen et al. (2018) successfully detected *E. coli*, *Proteus mirabilis*, *Pseudomonas aeruginosa* and *Staphylococcus aureus* in urine samples, with the detection limit of 100 colony-forming unit (CFU)/mL, using multiplex recombinase polymerase chain reaction (Chen et al., 2018).

Infection of urinary system can also introduce viruses to urine similar as the introduction of bacteria. In addition, viruses usually range in size from 5 to 300 nm (Goldsmith and Miller, 2009) and most of them lies in the lower margin of the scale as summarized by (Goswami and Pugazhenthi, 2020). Thus, a part of viruses can pass through the glomerular filtration barrier in kidneys, thereby contaminating urine. For example, researchers reported that the diameter of SARS-CoV-2 ranged in 60–140 nm

(Zhu et al., 2020). The virus detection rate in the serum and urine samples collected from 74 COVID-19 patients were 2.8% (9/323) and 0.8% (2/247), with mean viral load of 1210 ± 1861 and 79 ± 30 copies/mL, respectively (Kim et al., 2020). Kim et al. (2020) did not report urinary system infection by SARS-CoV-2. This indicates that virus in serum passed through the barrier to urine. While the viral load in urine was low and the SARS-COV-2 could not be isolated from the virus-positive samples (Kim et al., 2020), the microbiological risk of viral infection still cannot be ruled out. In addition, researchers have found many types of viruses in urine, such as Zika virus (Wiwanitkit, 2016), SARS virus (Xu et al., 2005), dengue virus (Van den Bossche et al., 2015), BK virus (Konietzny et al., 2012), Rift Valley fever and yellow fever virus (Li M. et al., 2019), etc. Therefore, urine would inevitably contain pathogens due to pathogen permeation from serum and infection of urinary system when patients use toilets.

2.2 Fecal contamination

Besides urinal, urine diverting toilet, which is divided into two parts through a partition, is employed to collect urine separately from feces. This toilet is quite different from a conventional toilet, which may make users puzzled especially when there is insufficient instruction. Incorrect use or cleaning of the toilet may cause the feces to enter the urine, which is a common unavoidable phenomenon (Schonning et al., 2002). Moreover, insect vectors (e.g., mosquitoes and flies) can also be carriers of microbes from feces to urine. The detection of intestinal microbes such as *E. coli* in source-separated urine would be an evidence for the cross contamination by feces (An et al., 2020). A study found that the corresponding level of fecal contamination of urine samples in eco-villages was 38% and at public places (i.e., work places and schools) 58% of the urine samples were contaminated when the contamination was determined based on the content of fecal sterols (Schonning et al., 2002). Therefore, cross contamination of urine by feces can be confirmed to be another route to introduce pathogens to urine. Feces contain more than 100 different varieties of viruses, bacteria, and helminthes (Senecal et al., 2018). However, only a few kinds of bacteria have been detected in source-separated urine because of the lack of related studies.

Urine contamination by feces would enlarge the microbial risks of reusing urine in agriculture. As far as the SARS-COV-2 is concerned, it may replicate in human gastrointestinal tract, exist in fecal excrement for a certain period of time, and may have infectious pathogenicity (Senecal et al., 2018). Zhang et al. (2020) investigated the feces of 23 patients, 83% of those were positive and the average duration of virus shedding was 22 days. During this period, the average titer of virus in feces was 5,623 copies/mL, but the highest titer reached $10^{5.8}$ copies/mL at the peak (Zhang et al., 2020). Although the viral load in urine was quite low in the clinical study of sampling in aseptic environment (Kim et al., 2020), the viral load and its potential risk would increase a lot when urine was contaminated by feces in the field-scale projects of source separation. As such, cross contamination of feces is considered as a dominating risk of disease transmission when handling and reusing urine (Senecal et al., 2018). Therefore, due care should be taken in the design of new urine-diverting toilets, instructions of toilet use and training of urine collection users.

3 Pathogens in urine treatment and UDFPs

3.1 Direct use of urine after storage

Direct use of urine as liquid fertilizer is a commonly recommended simple approach for nutrient recycling from urine to agriculture. This has been successfully applied for the cultivation of microalgae (Adamsson, 2000; Golder et al., 2007), zooplankton (Adamsson, 2000) and various plants such as cucumbers (Heinonen-Tanski et al., 2007), lettuce, tomatoes (Adamsson, 2000; Mnkeni et al., 2008; Pradhan et al., 2009), okra (Akpan-Idiok et al., 2012), beet (Mnkeni et al., 2008; Pradhan et al., 2010a), pumpkin (Pradhan et al., 2010b), carrot (Mnkeni et al., 2008), maize (Guzha et al., 2005; Mnkeni et al., 2008; Antonini et al., 2012a), cabbage (Pradhan et al., 2007), water spinach (Yang et al., 2015), Lolium multiflorum Lam (Antonini et al., 2012a), wheat (Tidåker, 2003) and barley (Tidåker, 2003). However, the presence of pathogens may pose a potential risk for the users of fertilizer and the consumers of agriculture products. Particularly, the regrowth of some microorganisms such *E. coli* were even reported in fresh urine because of its appropriate pH and nutrients (Lahr et al., 2016; Ahmed et al., 2017).

To reduce the microbial risks of urine application, storage for 2–6 months is commonly recommended as a hygienic treatment method (Schonning, 2001; Jönsson et al., 2004; World Health Organization (WHO), 2006). Table 1 summarizes the inactivation of pathogens in urine after storage, including *Aeromonas hydrophila* (Höglund et al., 1998), Enterococci (Höglund et al., 2000), *Enterococcus faecalis* (Chandran et al., 2009; Nordin et al., 2013; Almeida et al., 2019), *E. coli* (Höglund et al., 1998; Höglund et al., 2000; Chandran et al., 2009; Wohlsager et al., 2010; Nordin et al., 2013; Ahmed et al., 2017; Zhou et al., 2017; Almeida et al., 2019; Oishi et al., 2020), fecal coliforms (Höglund et al., 2000; Wohlsager et al., 2010; Zhou et al., 2017; Almeida et al., 2019), fecal streptococci (Höglund, 2001; Wohlsager et al., 2010), human adenovirus (Decrey and Kohn, 2017), *Mycobacterium tuberculosis* (Vinnerås et al., 2011), *Mycobacterium* bovis (Vinnerås et al., 2011), *Pseudomonas aeruginosa* (Höglund, 2001), *Salmonella typhimurium* (Höglund et al., 1998; Vinnerås et al., 2008; Chandran et al., 2009; Wohlsager et al., 2010), *Salmonella senftenberg* (Höglund et al., 1998), sulphite reducing *Clostridia*

TABLE 1 A summary on the reduction of pathogens in storage of urine.

Urine	Temperature°C	Pathogens	Reduction		Days	References
			Description	Unit		
Diluted and undiluted	15–35	*Escherichia coli*	5.5 log10	CFU/mL	3–50	Ahmed et al. (2017)
		coliphage MS2	5.2 log10	PFU/mL	2–50	
Diluted	5–20	*Rhesus* rotavirus	90%	[a]	32–240	Höglund et al. (2002)
		Salmonella typhimurium			71–1466	
Diluted and undiluted	4–20	*Aeromonas hydrophila*	6 log10	CFU/mL	1–20	Höglund et al. (1998)
		Pseudomonas aeruginosa				
		Salmonella senftenberg				
		Salmonella typhimurium				
		Escherichia coli	1 log10	CFU/mL	1–14	
		Ascaris suum	15%–20%		0–21	
		faecal streptococci	1 log10	CFU/mL	6–19	
Diluted	4	*Cryptosporidium parvum* oocysts	90%		29	Höglund and Stenström, (1999)
Undiluted	20	*Ascaris suum* egg	1 log10-3 log10	Eggs/mL	24–90	Senecal et al. (2018)
		Salmonella typhimurium	1 log10-6 log10	CFU/mL	9–53	
		Enterococcus faecalis			26–155	
		Bacteriophages MS2		PFU/mL	1–6	
		Bacteriophages ΦX 174			29–175	
Diluted and undiluted	15–30	*Escherichia coli*	6.7 log10	CFU/mL	0–63	Chandran et al. (2009)
		Salmonella typhimurium	6.8 log10		7–49	
		Enterococcus faecalis	8.4 log10		0–69	
		coliphage MS2	8.6 log10	PFU/mL	7–42	
Diluted	21–24	*Ascaris suum* eggs	3 log10	Eggs/mL	1–10	Nordin et al. (2013)
		Enterococcus spp.	90%	[a]	7–10	
		Enterococcus faecalis			2	
		Salmonella typhimurium			0.1	
		Escherichia coli			0.1	
		enterobacteria phage MS2			8–16	
		coliphage ΦX 174			37–43	
		Salmonella typhimurium phage 28B			55–64	
Diluted and undiluted	4–30	total coliforms	3–5 log10	CFU/mL	0–90	Almeida et al. (2019)
		Escherichia coli	3–4 log 10			
		Enterobacteriaceae	5–6 log10			
		Enterococcus	4 log10			
		total staphylococci	6 log10			
Diluted and undiluted	27	total coliforms	5.4 log10	CFU/100 ml	0–28	Wohlsager et al. (2010)
		Escherichia coli	4 log10		0–28	
		Faecal *streptococci*	6.1 log10		0–56	
Diluted	60–70	fecal coliforms	3 log10	CFU/mL	0–1	Zhou et al. (2017)
		Escherichia coli	4.3 log10		0–3	
Diluted and undiluted	4–34	*Salmonella typhimurium*	90%	[a]	0–33	Vinnerås et al. (2008)
		Enterococcus faecalis			1–47	
		bacteriophages MS2			1–240	
		bacteriophages ΦX 174			5–150	
		bacteriophages 128			1–169	
Hydrolyzed	20	BK human polyomavirus	90%	[a]	0–9	Goetsch et al. (2018)
		bacteriophages T3			24–46	

(Continued on following page)

TABLE 1 (*Continued*) A summary on the reduction of pathogens in storage of urine.

Urine	Temperature°C	Pathogens	Reduction		Days	References
			Description	Unit		
		bacteriophages Qβ			0.3	
		bacteriophages MS2			0.4	
Diluted and undiluted	4–34	*Ascaris suum* eggs	99%	[a]	3–840	Nordin et al. (2009)
Diluted	4–22	*Mycobacterium tuberculosis*	90%	[a]	2–10	Vinnerås et al. (2011)

[a]The reference doesn't provide any information on the unit of pathogens tests.

(Höglund et al., 2000; Almeida et al., 2019), BK Human Polyomavirus (Goetsch et al., 2018), *Rhesus rotavirus* (Höglund et al., 2002), *Ascaris suum*, *Ascaris suum* egg (Nordin et al., 2009), and *Cryptosporidium parvum* oocysts (Höglund and Stenström, 1999). Furthermore, inactivation experiments sometimes used bacteriophage as virus surrogate, such as bacteriophage T3 (Goetsch et al., 2018), coliphage ΦX174 (Vinnerås et al., 2008; Nordin et al., 2013; Decrey and Kohn, 2017), coliphage MS2 (Chandran et al., 2009; Decrey et al., 2015; Ahmed et al., 2017; Decrey and Kohn, 2017), coliphage T4 (Decrey and Kohn, 2017), *Enterobacteria* phage MS2 (Vinnerås et al., 2008; Nordin et al., 2013), and *Salmonella typhimurium* phage 28B (Höglund et al., 2002; Vinnerås et al., 2008). Most of these pathogens were reduced to an acceptable limit after 6 months.

Several factors may respond for the pathogens inactivation, of which free ammonia (NH_3) induced by the hydrolysis of urea in the storage is considered as the dominating reason (Vinnerås et al., 2008). NH_3 is one of the most important basic species in stored urine inducing the genome cleavage *via* alkaline transesterification, which results in the inactivation of the single-stranded (ss)RNA viruses (Decrey et al., 2015). Based on the same mechanism, other bases (carbonate, phosphate, and hydroxide) should also be taken into account for the viruses inactivation (Decrey et al., 2015). Furthermore, high temperature and high pH can accelerate the inactivation because these two factors also determine the concentrations of NH_3 and other bases (Höglund et al., 1998; Höglund and Stenström, 1999; Hoglund et al., 2002; Vinnerås et al., 2008; Ahmed et al., 2017). For example, the inactivation rate constant K of *E. coli* increased from 0.20/d to 3.04/d at increasing temperature from 15°C to 35°C in storage of undiluted urine (Ahmed et al., 2017). 20°C or higher temperature was recommended for the current recommended storage time of 6 months (Vinnerås et al., 2008). Moreover, urine dilution brought by water flushing or pretreatment before fertilization (Jönsson et al., 2004) can decrease the concentration of NH_3, thereby slowing the pathogens inactivation and extending the storage time for hygienic treatment (Vinnerås et al., 2008).

Notably, the types of pathogens of which the inactivation was experimentally studied (Table 1) are far less than that detected in urine (Supplementary Table S1). The inactivation of pathogens will be surely determined by its type. For example, the mean time for 1 log10 reduction (t_{90}) of *S. typhimuriuma*, *Enterococcus Faecalis*, MS2, and ΦX174 was <0.1 d, <1.1 d, <1.6 d, and <5.7 d, respectively, during the storage of urine at 34°C (Vinnerås et al., 2008). Some pathogens were still in high concentrations and even enriched after several months of storage. The concentration of *Bacillus* spores did not decrease during the urine storage because some microorganisms in the sporulated form have a higher resistance (Almeida et al., 2019). Moreover, the growth of streptococci was even found in urine collecting pipes and tank (Höglund et al., 1998). In addition, heterogeneity among viruses in their susceptibility toward NH_3 is driven by the genome type. It is more difficult to inactivate the double-stranded (ds)RNA reovirus and *Rhesus rotavirus* as well as the dsDNA *Salmonella* phage 28B than ssRNA viruses (Decrey et al., 2015). Therefore, it is essential to carry out a comprehensive evaluation of the inactivation of possible pathogens particularly in areas with typical infectious diseases when urine was directly used as liquid fertilizer after storage.

In addition, several pretreatment methods were developed to accelerate the urea hydrolysis, which may accelerate the pathogens inactivation. These methods included dosage of urease (Kabdasli et al., 2006; Engelhardt et al., 2020), fecal incubation (Hotta and Funamizu, 2008), incubation of stale urine (Liu et al., 2008), increasing temperature (Liu et al., 2008) and microbial electrochemical current (Chen et al., 2017). However, incubation of fecal matter can simultaneously bring the contamination of urine by pathogens whether more pathogenic types or higher concentrations. As such, the pretreatment using fecal incubation should be re-considered taking the microbial risks into account.

3.2 Urine stabilization

Urea hydrolysis driven by the catalysis of urease occurred quickly in urine because many bacteria contaminated by feces or nature can produce urease (Udert et al., 2003a). More than half of urea hydrolyzed in the urine collecting pipes and storage tank (Udert et al., 2003b; 2003c). Although urea hydrolysis promotes the pathogens inactivation, it also brings the loss of nitrogen due to ammonia volatilization and the loss of phosphorus due to phosphate precipitation at alkaline pH. To inhibit urea hydrolysis, stabilization has been developed as a pretreatment before urine reuse or dewatering (Randall et al., 2016).

3.2.1 Acidification/alkalinization

Acidification (pH < 5 (Hellstrom et al., 1999; Saetta et al., 2020; Moharramzadeh et al., 2022)) or alkalinization (11 < pH < 13 (Randall et al., 2016)) can be used to inhibit the hydrolysis of urea due to the inactivation of urease-producing bacteria or urease. The inactivation of pathogens after urine acidification has been rarely reported maybe because the disinfection is not significant. By comparison, alkalinization of urine is considered as a promising method to inactivating pathogens as well as stabilizing urine (Randall et al., 2016). Lime is a common alkaline agent used for urine stabilization (Randall et al., 2016), sometimes combining with biochar (Simha et al., 2020a) and wood ash (Dutta and Vinnerås, 2016; Simha et al., 2020b). Pathogens inactivation in urine using lime has not been experimentally examined. However, lime is a well-known disinfection method for water and sewerage sludge because high pH was highly effective in the inactivation of pathogens (Bujoczek et al., 2002; Keller et al., 2004; Hansen et al., 2007). Moreover, bacteria *Enterococcus faecalis* and *Salmonella* spp. and bacteriophages MS2 and ΦX 174 were reduced to below the detection limit when urine was alkalized using wood ash after 4 d at 20°C (Senecal et al., 2018) while the mean time for t_{90} of *Enterococcus Faecalis*, MS2, and ΦX174 was 2.3, 15, and 12 d, respectively, during urine storage at 24°C (Vinnerås et al., 2008). Therefore, alkalinization would be much quicker and more effective than urine storage.

3.2.2 Chemical oxidation

Chemical oxidation using hydrogen peroxide or heat-activated peroxydisulfate could effectively inhibit urea hydrolysis due to the irreversible destruction of urease (Zhang et al., 2013; Lv et al., 2020). The two oxidants are normally used in disinfection of water (Jin et al., 2020; Xiao et al., 2020), providing a basis for pathogens inactivation of urine. However, chemical oxidation also brought the loss of nitrogen because of the oxidation of ammonium to nitrogen gas (Lv et al., 2020). This might limit the application of chemical oxidation for urine stabilization.

3.2.3 Biological nitrification

Urine after urea hydrolysis can also be stabilized through biological nitrification. Ammonium in hydrolyzed urine can be oxidized to nitrite or nitrate while the pH decreases to a weak acidic pH (i.e., 5–7) (Udert et al., 2003d; Feng et al., 2008; Jiang et al., 2011). This would reduce the volatilization of ammonia and the precipitation of phosphate salts. Furthermore, this produces a stabilized liquid fertilizer (Feng et al., 2008) or solid fertilizer when combining with distillation (Udert and Wächter, 2012; Fumasoli et al., 2016). However, the impact of nitrification on pathogens inactivation is not an interest even since nitrification was proposed for biological nitrogen removal from wastewater (Gujer, 2010). This means that biological nitrification may not be an effective technology on pathogens inactivation in urine. Notably, a recent study achieved the nitritation of urine in an acidic nitrifying bioreactor (Li et al., 2020). This may provide an opportunity to inactivate pathogens in urine because the product free nitrous acid is biocidal to a broad range of microorganisms (Jiang and Yuan, 2014) despite the target of nitritation was to obtain nitrite rather than recover nutrients from urine.

3.3 Dewatering urine to obtain concentrated fertilizer products

Despite being rich in nutrients, urine still has high content of water (approximately 97%) when urine is collected in a dry toilet. Urine will be further highly diluted when a water flushing toilet is used. Several dewatering technologies have been developed to concentrate urine to yield concentrated fertilizer products as well as clean water.

3.3.1 Membrane filtration

Urine can be dewatered to produce concentrated liquid fertilizer through membrane filtration including nanofiltration (Ray et al., 2020a; Courtney and Randall, 2022), reverse osmosis (Ek et al., 2006; Ray et al., 2020a; Courtney and Randall, 2022), forward osmosis (Zhang et al., 2014; Engelhardt et al., 2020; Jiang et al., 2022; Pocock et al., 2022), membrane distillation (Zhao et al., 2013; Volpin et al., 2019a; Khumalo et al., 2019) and electrodialysis (Brewster et al., 2017; Wang et al., 2017; De Paepe et al., 2018). Nutrients are rejected in the concentrate while water passes through the membrane filter to the other side in most of the filtration processes except the electrodialysis which concentrates nutrients in the permeate side.

Membrane filtration is a common technology to remove pathogens from water. The separation of bacteria and viruses from wastewater using polymeric and ceramic membrane has been summarized (Goswami and Pugazhenthi, 2020). The rejection of pathogens by filter mainly depends on the filter pore size due to the size exclusion mechanisms. Moreover, virus adsorption, electrostatic interaction and hydrophobic interaction also respond for the removal of pathogens from water (Goswami and Pugazhenthi, 2020). A nanofilter with pore size of 20 nm (Viresolve NFP filter, Millipore, United States) was employed to remove viruses from urine aiming to obtain virus free urokinase solution. The log reduction factors for porcine parvovirus (18–26 nm), human hepatitis A virus (25–30 nm), murine encephalomyocarditis virus (28–30 nm), bovine viral diarrhoea virus (40–60 nm), and bovine herpes virus (120–300 nm) were ≥4.86, ≥4.60, ≥6.87, ≥4.60, and ≥5.44, respectively (Kim et al., 2004). The rejection of pathogens by filter also means that pathogens would be concentrated in the liquid urine fertilizer. A recent study reported that concentration of urine can also lead to the inactivation of *E. coli* due to the high osmotic pressure under high salt contents (Oishi et al., 2020). 1-day storage was necessary for the safe reuse of 5-fold concentrated hydrolyzed urine whereas 91-h storage was required for non-concentrated urine when the initial numbers of *E. coli* were the same in these two urine solutions. However, the inactivation of pathogens might be inhibited due to the low concentration of free ammonia at low pH when acidification pretreatment was used to reduce the loss of ammonia to the water permeate (Tun et al., 2016; Xu et al., 2019a; Ray et al., 2020a).

Electrodialysis may pose an advantage than other membrane filtrations for dewatering urine. Nutrients were concentrated in the permeate side as the ionic species passed through selective ion-exchange membranes from the urine to the permeate side driven by an electric field (Pronk et al., 2006; De Paepe et al., 2018). Thus, pathogens would be retained in urine while yielding a pathogen free fertilizer product. However, this has not been examined by experiments.

Forward osmosis and membrane distillation were also employed to separate ammonia and urea from urine, producing ammonia- or urea-rich solution in the permeate side (Xu et al., 2019a; Ray et al., 2019; Ray et al., 2020b; Han et al., 2022). The N-rich solution would have low pathogen concentrations due to the rejection by the filter. Furthermore, a P-rich solid product could be obtained in a pretreatment using struvite precipitation before the filtration to avoid fouling on the membrane (Volpin et al., 2018; Volpin et al., 2019b). The combined processes successfully would achieve the recovery of N and P from urine. However, special attention should be paid to microbial risks of the struvite product formed in the urine with concentrated pathogens.

3.3.2 Evaporation/distillation

Urine can be passively evaporated at ambient temperature to produce concentrated fertilizer solution or solid fertilizer products (Bethune et al., 2014). The evaporation was further accelerated by solar irradiation (Antonini et al., 2012b; Bethune et al., 2015) or heating at 25–65°C (Dutta and Vinnerås, 2016; Senecal and Vinnerås, 2017; Simha et al., 2018; Simha et al., 2020a). The purpose of urine distillation at boiling temperature is mainly to obtain solid fertilizer products (Udert and Wächter, 2012; Fumasoli et al., 2016; Jiang et al., 2017). The boiling temperature even increased to 130.1°C when the salts in urine was highly concentrated following the distillation (Udert and Wächter, 2012). However, loss of the total ammonia was observed due to the volatilization of free ammonia during the evaporation of water (Bethune et al., 2014,2016). Therefore, stabilization pretreatment such as acidification (Jiang et al., 2017), alkalinization (Dutta and Vinnerås, 2016; Senecal and Vinnerås, 2017; Simha et al., 2018; Simha et al., 2020a) and nitrification (Udert and Wächter, 2012; Fumasoli et al., 2016) was usually employed prior to the evaporation or distillation process.

Several factors involved in the evaporation/distillation of urine can inactivate pathogens. High temperature is highly effective to inactivate pathogens as reported in the fields of waste composting or water disinfection (Chu et al., 2019; Hu et al., 2020). Moreover, Bethune et al. (2014) suggested that the urine-derived solid product was sterile because high salinity in the concentrated product might respond for the inactivation of microorganisms. In addition, solar thermal evaporation may further enhance the pathogen inactivation because sunlight radiation is considered as a unconventional disinfection technology to obtain safe drinking water (Chu et al., 2019). The inactivation of pathogens would be further enhanced when alkaline pretreatment was employed to inhibit the urea hydrolysis before evaporation/distillation. In an alkaline dehydration of urine using ash at 42°C, five fecal pathogens including *Ascaris suum*, *Enterococcus faecalis*, bacteriophages MS2 and ΦX 174, and *Salmonella* spp. were inactivated to below the detection limit within 10 d (Senecal et al., 2018), which met the World Health Organization (WHO) guidelines for the reuse of excreta (World Health Organization (WHO), 2006). Although acidification or biological nitrification may be not effective on the pathogen inactivation, the following evaporation/distillation can play a dominating role (Bischel et al., 2015).

The evaporation/distillation of urine can also produce clean water for reuse. Distillation at boiling temperature would also promise a sterile water product because boiling temperature is very efficient on disinfection (Chu et al., 2019). However, reclaimed water collected after evaporation at ambient temperature or high temperature around 35–65°C may still pose microbial risks. Pathogens in the concentrated fertilizer solution or the solid product may be inactivated by the synergistic effects of high salinity, pH and temperature. But single effect of temperature on the water disinfection may not act as effectively as on the solid product disinfection. Thus, the reuse of the reclaimed water after the evaporation/distillation of urine should be further addressed.

3.3.3 Freezing-thawing

Freeze crystallization can recover water in the form of ice from urine as well as concentrating the fertilizer solution. Low temperature ranges of −18 to −4°C were examined for freezing urine (Lind et al., 2001; Gulyas et al., 2004; Schmidt and Alleman, 2005; Ganrot et al., 2007a; Yu et al., 2007; Ganrot et al., 2008; Moharramzadeh et al., 2022). A thermodynamic model was further developed providing a theoretical understanding on obtaining solid salts and water from stored urine (Randall and Nathoo, 2018). After thawing, the reclaimed water and the concentrated fertilizer product can be obtained.

The influence of freezing and thawing on pathogens seems to be unclear. Freezing creates damage to cell structure of microorganisms (Sanin et al., 1994). It was found that the reduction of pathogenic bacteria (*Salmonella*), virus (Poliovirus) and parasites (*Ascaris suum* and *Cryptosporidium parvum*) was effectively achieved by freezing-thawing coupled with anaerobic digestion of sludge in a wastewater treatment plant, meeting the pathogen reduction requirements for sludge land disposal by US regulations (Sanin et al., 1994). Furthermore, freezing is widely used in food storage because of its negative effect on microbial community. For examples, storage for more than 3 days at −20°C can effectively inactivate *T. gondii* in contaminated meat (Alizadeh et al., 2018). However, freeze-drying is also considered as a common cryopreservation method to preserve pathogens because the ultra-low temperature can fix the cells in powder and nearly completely inhibit the cell metabolism (Perry, 1998). For example, the freeze-drying was sustainable for the long-term preservation of marine pathogen *V. anguillarum* (Yu et al., 2019). Furthermore, the stability and retention of infectivity of viruses was confirmed after frozen storage of foods, indicating negative effect on killing viruses (Sánchez and Bosch, 2016). In addition, it was reported that sublethally injured pathogens (*E. coli*) caused by freezing during food storage can recover after thawing, presenting a potential threat on food safety (Zhang R. et al., 2021). Therefore, the related publications can't show a clear understanding whether freeze-drying is bad or good to effectively deactivate pathogens in urine.

3.4 Extraction of nutrients from urine

3.4.1 Stripping-absorption of ammonia to obtain liquid N-products

Ammonia separated from urine by air (Behrendt et al., 2002; Basakcilardan-Kabakci et al., 2007; Antonini et al., 2011; Morales et al., 2013; Liu et al., 2015; Xu et al., 2017; Jagtap and Boyer, 2018; Jagtap and Boyer, 2020) or membrane stripping (Tarpeh et al., 2018a; Christiaens et al., 2019; Pradhan et al., 2019) can be absorbed in water or sulfate acid solution to yield liquid N-products such as ammonia water or ammonium sulfate solution. However, an autofluorescent *E. coli* spiked in the urine was also observed in the absorbent (Christiaens et al., 2019), which should be caused by the transfer of microorganisms from urine to the absorbent *via* aerosols induced by air stripping (Benami et al., 2016). This indicates potential microbial risks of using the ammonia absorbent products in agriculture. Alkalinization and heating is usually used to improve ammonia stripping efficiency from urine. pH >12 maintained by lime increased the removal efficiency by 8% for the stripping of pure urine at 30°C (Pradhan et al., 2017). Furthermore, high temperature ranging in 40°C–65°C could significantly increase the stripping efficiency because of the formation of more free ammonia (Pradhan et al., 2017; Wei et al., 2018; Tao et al., 2019; Tian et al., 2019). High pH and temperature would meanwhile benefit the inactivation of pathogens in urine influent as well as reducing the pathogens in absorbent.

Membrane stripping provide another approach to reduce the transfer of pathogens to absorbent. Free ammonia in the urine side pass through a gas permeate membrane (GPM) to the absorbent side. Pore size of the GPM commonly ranges in 0.1–0.59 μm (Tarpeh et al., 2018a; Xu et al., 2019a; Christiaens et al., 2019). As such, most pathogenic bacteria and some viruses would be rejected by the membrane, producing N-products with less pathogens in the permeate side. A study by Tarpeh et al. (2018a) confirmed that *E. coli* was not observed in the absorbent of a membrane stripping process when its concentration was $10^{8.00–8.78}$ events/mL in the urine feed. However, it was also found that very small microorganisms reported in urine (<0.1 μm) could pass through the membrane with an average measured pore size of 0.274 μm (Dong et al., 2011). Thus, stripping *via* hydrophobic GPM does not lead to a pathogens-free absorbent. Similar as that in the air stripping process, high pH and temperature intending for high ammonia transfer efficiency in membrane stripping (Xu et al., 2019a) would probably inactivate pathogens in the feed side and reduce the transfer of pathogens to the permeate side.

Concentrating ammonia using cation exchange membrane (CEM) in electrodialysis can increase the concentration of free ammonia before stripping (Christiaens et al., 2017; Tarpeh et al., 2018a; Christiaens et al., 2019). Tarpeh et al. (2018a) developed a novel process combining electrodialysis and membrane stripping to yield an *E. coli*-free fertilizer product from urine for potential safe reuse. Pore size of CEM ranges from 1.5 to 200 nm (Kononenko et al., 2017), which would benefit rejecting the transfer of pathogens with small sizes such as nanoscale viruses.

3.4.2 Adsorption of nutrients to obtain solid fertilizer products

Urea, ammonium, phosphate and potassium in urine can be adsorbed by various adsorbents such as activated carbon (Ganrot et al., 2007a), biochar (Bai et al., 2018; Xu et al., 2018; Xu et al., 2019b; Zhang X. et al., 2021), gastropod shell (Saliu et al., 2020), ion exchange resin (O'Neal and Boyer, 2013; O'Neal and Boyer, 2015; Tarpeh et al., 2017; Tarpeh et al., 2018b), layered double hydroxides (LDH) (Dox et al., 2019a; Dox et al., 2019b; Dox et al., 2022), magnetic $Fe_3O_4@ZrO_2$ nanoparticles (Guan et al., 2020a), metal organic frameworks (MOF) (Lin et al., 2015; Guan et al., 2020b), natural loess (Jiang et al., 2016), porous organic polymer (Zhang et al., 2020), wollastonite (Lind et al., 2000), zeolite (Ban and Dave, 2004; Beler-Baykal et al., 2004; Ganrot et al., 2007a; Leung et al., 2007; Ganrot et al., 2008; Baykal et al., 2009; Beler-Baykal et al., 2011; Huang et al., 2014; Xu S. et al., 2015; Mitrogiannis et al., 2018; Makgabutlane et al., 2020; Regmi and Boyer, 2020). Some of these adsorbents i.e., biochar, gastropod shell, natural loess, and zeolite after nutrient adsorption can be directly used as fertilizer in agriculture (Ganrot et al., 2008; Beler-Baykal et al., 2011; Xu S. et al., 2015; Jiang et al., 2016; Bai et al., 2018; Xu et al., 2018; Saliu et al., 2020; Zhang X. et al., 2021). Other adsorbents should be desorbed in solutions containing NaOH (Beler-Baykal et al., 2004; O'Neal and Boyer, 2015; Mitrogiannis et al., 2018; Guan et al., 2020a; Guan et al., 2020b), $NaHCO_3$ (Mitrogiannis et al., 2018; Dox et al., 2019a; Dox et al., 2019b), NaCl (Lin et al., 2015; O'Neal and Boyer, 2015; Mitrogiannis et al., 2018; Zhang et al., 2020), HCl (Mitrogiannis et al., 2018; Guan et al., 2020b), or H_2SO_4 (Tarpeh et al., 2017; Tarpeh et al., 2018b) to obtain phosphate-rich solution, after which a chemical precipitation process such as struvite precipitation was usually conducted to yield solid phosphate fertilizer easy to be collected and applied for agriculture. However, to our best knowledge, the behavior of urine pathogens during the nutrient adsorption has not been reported.

Normally, some adsorbents such as zeolites and biochar can uptake aquatic microorganisms, forming biofilm on the surface (Perez-Mercado et al., 2019; Wang et al., 2020). The uptake of microorganisms is mainly driven by weak electrostatic or binding forces to the carrier surface and the intra-grain and intra-crystallite pores (Lameiras et al., 2008). Experiments confirmed the uptake of fecal coliforms and *E. coli* from wastewater by clinoptilolite, a naturally occurring zeolite, with an active uptake of 3989 CFU/g and 2732 CFU/g, respectively (Ferronato et al., 2015). Furthermore, a correlation model based on experiments also showed that biochar filters could significantly remove bacteria and viruses with the reduction rate of ≥2 log10 and ≥1 log10, respectively, because these microbes were enriched on biochar due to adsorption (Perez-Mercado et al., 2019). This indicates that the microbial risks would even be magnified especially when the nutrient-enriched adsorbents are directly used as fertilizer in agriculture.

Various metal ions have been used as biocidal agents such as Ag, Zn, Cu, Ni, Co, Ti and Bi (Wyszogrodzka et al., 2016). Zeolite exchanged with Cu and Zn can be used as antimicrobial material for efficient disinfection of contaminated water with bacteria because it was effective to reduce the concentrations of *E. coli* and *Staphylococcus aureus* (Yao et al., 2019). This may provide a potential approach to reduce the microbial risks of nutrient-adsorbed solid fertilizer but pose a potential risk of heavy metals. Post treatment in an alkaline desorption solution may further inactivate pathogens adsorbed on adsorbents because alkaline treatment is effective in the disinfection of urine pathogens (Senecal et al., 2018). However, it is unclear that whether desorption of nutrients from adsorbents in acid solution could inactivate pathogens.

3.4.3 Chemical precipitation to obtain solid products

Chemical precipitation is a commonly reported approach to recover nutrients from urine by the formation of non-soluble phosphate salts. Struvite precipitation is the most concerned phosphorus recovery technology which can also simultaneously recover part of ammonium from urine (Krähenbühl et al., 2016; Zamora et al., 2017; Wei et al., 2018; Zheng et al., 2018; Aguado et al., 2019; Li P. et al., 2019; Pinatha et al., 2020; Oztekin et al., 2022). The precipitation of struvite-K, an analogue of struvite, can simultaneously recover phosphate and potassium from ammonium-depleted urine (Xu et al., 2011; Xu et al., 2012; Xu K. et al., 2015; Xu et al., 2017; Zhang et al., 2017; Zhang et al., 2018; Huang et al., 2019). Furthermore, phosphate can also be recovered by the precipitation of calcium phosphate (Pradhan et al., 2017). Finally, filtration and drying following the precipitation process is essential to obtain solid phosphate products. Struvite and struvite-K can be directly used as fertilizer in agriculture because they are both slow-release fertilizer while calcium phosphate is considered as a raw material for phosphate fertilizer industry (Ganrot et al., 2007b; Liu et al., 2020). There are standards for microbial risk management in industrial fertilizer (Ministry of Industry and Information Technology of the People's Republic of China, 2019). Therefore, this review mainly addresses the potential microbial risk of the recovered phosphate products which can be directly used in agriculture.

Decrey et al. (2011) found that the struvite precipitation process did not considerably inactivate the pathogen indicators phage ΦX174 and *Ascaris suum* eggs in the urine liquid fraction. The pH value during the struvite precipitation in urine was approximately 9 (Etter et al., 2011), which is similar as that in the storage process. This indicates that free ammonia formed at such alkaline pH can inactivate pathogens like that in the storage process. However, the reaction time for struvite formation was only 10 min in their study (Decrey et al., 2011). Some other studies used longer precipitation time ranging from 15 to 125 min (Ronteltap et al., 2007; Ronteltap et al., 2010; Liu et al., 2013), which is still much less that the storage time of 2–6 months (Jönsson et al., 2004; Vinnerås et al., 2008). As such, the pathogen inactivation can be neglected within such a short precipitation time. At a longer precipitation time of 24 h, the number of coliforms was reduced by 56% during the struvite precipitation at pH 9 in anaerobically digested chicken slurry (Muhmood et al., 2018). Furthermore, they also reported a greater reduction of coliforms (73%) at pH 10. The viability of spiked *E. coli* cells also significantly decreased during the struvite precipitation at pH of 11 in source-diverted blackwater (Yee et al., 2019). Non-etheless, optimum pH of the struvite precipitation was approximately 9 and higher pH decreased the struvite purity (Harada et al., 2006). Thus, high pH for effective pathogen inactivation may be suitable for precipitation of calcium phosphate rather than the struvite precipitation. Complete inactivation of *E. coli*, *Salmonella* enterica serovar typhymurium, and Porcine circovirus type 2 was achieved when removing phosphate from swine slurry at pH 10 using $Ca(OH)_2$ (Viancelli et al., 2015). The coliforms was also completely inactivated after 6 h of treatment using wood ash to remove phosphate from urban wastewater and landfill leachate at pH of 10.1–12.7 (Ivanković et al., 2014). In addition, the optimal pH in ranges of 10–11 for the precipitation of struvite-K (Xu et al., 2011; Xu et al., 2012; Xu K. et al., 2015) may also improve the pathogens inactivation in the liquid fraction despite this has not been reported.

It is essential to evaluate the pathogens in the solid nutrient product obtained from urine especially when the product is directly used as fertilizer. Pathogen indicators phage ΦX174 and *Ascaris suum* eggs were both detected in the struvite product filtered by nylon fabric while no considerable inactivation was observed in the precipitation process in urine (Decrey et al., 2011). There was no significant difference on concentration of phage ΦX174 in both the solid and the liquid fraction. However, the *Ascaris* eggs even accumulated by 100 fold within the solid product because the filter with irregular pore diameters of 18–240 μm rejected the *Ascaris* eggs having a size of 35–50 × 45–70 μm in the solid fractions. Bischel et al. (2016) also reported the accumulation of heterotrophs and total bacteria in the struvite product obtained by the filtration with nylon or cloth filters from urine. Non-etheless, these two publications cannot clearly display an actual behavior of the pathogens in the solid fraction of struvite precipitation because of the effect of filtration on the pathogens accumulation. Electrostatic attraction and repulsion may play an important role for behavior of pathogens in solid struvite. Struvite crystals are negatively charged with zeta-potential of −17.5 to −27.6 mV at pH from 8.5 to 10.5 (Le Corre et al., 2007). Yee et al. (2019) reported that the electrostatic attraction between *C. perfringens* with positive zeta potential of 0–3 mV and struvite particles increased the cell aggregation in the final solid product. However, there was an electrostatic repulsion between struvite and phage ΦX174 with isoelectric point of 6.6 (Michen and Graule, 2010) carrying negative surface charge at pH around 9 (Muhmood et al., 2018). Moreover, isoelectric points of most viruses ranged from 1.9 to 8.4 (Michen and Graule, 2010). Thus, these viruses would present negative surface charge in the struvite precipitation system of urine, indicating electrostatic repulsion between struvite and viruses.

Factors affecting the surface charge of struvite may change the adsorption of pathogens onto struvite particles. High concentration of residual Mg^{2+} lowered the negative charge of struvite which could lead to more adsorption of pathogens with low isoelectric point (Decrey et al., 2011). Coagulants and flocculants may also result in more adsorption of pathogens when they were used to promote the agglomeration of struvite crystals (Le Corre et al., 2007). The adsorption of pathogens would probably be enhanced during the precipitation of struvite on metal-modified biochar (Xu et al., 2018; Liu et al., 2020) or zeolite (Huang et al., 2014; Mitrogiannis et al., 2018) with positive surface charge. In addition, the tendency of bacteria growth on these carrier (Perez-Mercado et al., 2019; Wang et al., 2020) would further lead to accumulation of more pathogens in the struvite product.

Although there lacks understanding on the adsorption of pathogens on struvite and the following filtration rejects some pathogens with large size in the struvite filter cake, pathogens in the solid products can still be effectively inactivated in the following drying process (Bischel et al., 2016). Temperature and humidity were important factors determining the efficiency of pathogens inactivation. No significant inactivation of *Ascaris suum* eggs in struvite obtained from urine were observed at 5 and 20°C while the eggs was inactivated by more than 99% at 35–36°C after drying for 3 days (Decrey et al., 2011). Furthermore, inactivation of *Ascaris suum* eggs was only 1.2 log10 after 3 days drying at temperature of 35°C and relative humidity of 85% while it reached more than 2 log10 after 1 day of drying at temperature of 36°C and relative humidity of 36%. Thus, inactivation of *Ascaris suum* eggs in struvite drying was enhanced at low relative humidity (Decrey et al., 2011). Moreover, the reduction of phage ΦX174 in struvite was 0.03, 0.07 and 0.09 log10/day in the drying process at 5°C/85% (temperature/relative humidity), 20°C/93% and 5°C/35%, respectively. As such, its inactivation was enhanced at high temperatures and low relative humidity. Experimental results further showed that the inactivation of heterotrophic bacteria, total bacteria, *Enterococcus* spp. and *Salmonella typhimurium* accumulated in struvite from urine was also improved with increasing temperature for drying at a constant relative humidity (Bischel et al., 2016). The reduction of heterotrophs even reached 3 log10 at optimized drying conditions within 100 h. Therefore, drying, also as an essential process to obtain final solid struvite product, is recommended as an effective method for the disinfection of the final product. Experimental results confirmed that the concentrations of total coliforms and *E. coli* were under the detection limits when struvite formed in anaerobically digested chicken slurry was dried at 40°C without control of humidity for 48 h after a filtration using 0.45 μm membrane (Muhmood et al., 2018; Muhmood et al., 2019). Drying at higher temperature than the ambient temperature already examined in experiments will reasonably improve the pathogens inactivation of struvite product. However, this may also result in the loss of crystal water and ammonia in the struvite crystals due to its decomposition (Bhuiyan et al., 2008).

Drying struvite by sunlight is also an option especially for small-scale reactor. However, Decrey et al. (2011) found that no significant inactivation of phage ΦX174 or *Ascaris suum* eggs was observed when struvite was exposed to sunlight within 5 h at 31°C with relative humidity of <35%. The short exposure time may be one of the dominating reasons for ineffective inactivation. Exposure to sunlight will increase the temperature of struvite and accelerate the loss of struvite moisture, thereby theoretically introducing the disinfection of struvite. Moreover, sunlight radiation in ultraviolet range is known to be effective in pathogens inactivation (Chu et al., 2019). Therefore, struvite disinfection is expected to be realized to some extent for long time of exposure in sunlight.

TABLE 2 An overall assessment of pathogens inactivation in urine treatment technologies and the related UDFPs.

Technology				Nutrient recovered	UDFP	Inactivation[a]
Urine storage				Complete	Liquid urine	++
Urine stabilization						
	Acidification			Complete	Liquid urine	N.I.
	Alkalinization			Complete	Liquid urine	++
	Chemical oxidation			Complete	Liquid urine	++
	Biological nitrification			Complete	Liquid urine	N.I.
Urine dewatering						
	Membrane	Reverse osmosis		Complete	Liquid UDFP	– –
		Forward osmosis		Complete	Liquid UDFP	– –
		Nanofiltration		Complete	Liquid UDFP	– –
		Membrane distillation[c]		Complete	Liquid UDFP	++[b]
				P, K	Liquid UDFP	++[b]
		Electrodialysis		N, P		++
	Evaporation/ distillation			Complete	Liquid UDFP	++
					Solid UDFP	++
	Freezing			Complete	Liquid UDFP	N.I.
Nutrient extraction						
	Stripping-absorption	Air stripping		N	Liquid UDFP	++[b]
		Membrane stripping		N	Liquid UDFP	++
	Adsorption	Direct use		N	Solid UDFP	–
				P	Solid UDFP	–
				part of N, P	Solid UDFP	–
				P, K	Solid UDFP	–
		Alkaline desorption		N	Liquid UDFP	++
		Acidic desorption		N	Liquid UDFP	N.I.
				P	Liquid UDFP	N.I.
				part of N, P	Liquid UDFP	N.I.
				P, K	Liquid UDFP	N.I.
	Chemical precipitation	Calcium phosphate		P	Solid UDFP	N.I.
		Struvite		part of N, P	Solid UDFP	N.I.
		Struvite-K		P, K	Solid UDFP	N.I.
		Filtration/centrifugation separation	Direct use	P	Solid UDFP	– –
				part of N, P	Solid UDFP	– –
				P, K	Solid UDFP	– –

(Continued on following page)

TABLE 2 (*Continued*) An overall assessment of pathogens inactivation in urine treatment technologies and the related UDFPs.

Technology		Nutrient recovered	UDFP	Inactivation[a]
	Drying	P	Solid UDFP	++[d]
		part of N, P	Solid UDFP	+
		P, K	Solid UDFP	++
	Struvite decomposition and reuse	N	Liquid UDFP	++

[a]The symbol + means that pathogens can be positively inactivated while – presents the opposite effect. Higher number of symbols indicates strong effect. NI means none information.
[b]Treatment with heating or at alkaline pH.
[c]Membrane distillation can concentrate P and K or N, P and K, respectively, determined by the operation conditions.
[d]Struvite can only be dried at temperature <35°C while struvite-K and other phosphate salts can be dried at higher temperature.

Decomposition of struvite (Eq. 1) can release ammonia which can be recovered through absorption in water or acid solution and the solid decomposition product can be employed to remove ammonia from urine through the re-precipitation of struvite (Eq. 2) (Chen et al., 2020). The decomposition was commonly conducted in ranges of 100–150°C using calcination (Huang et al., 2016), ultrasound radiation (Huang et al., 2017), and microwave radiation (Chen et al., 2020), the latter two processes of which were even carried out in alkaline solution containing NaOH. High temperature and combination of alkaline condition would probably inactivate pathogens in struvite, thus promising clean products of solid struvite and liquid ammonia-rich solution.

$$MgNH_4PO_4 \cdot 6H_2O\,(s) \rightarrow MgHPO_4\,(s) + NH_3\,(g) + 6H_2O \tag{1}$$

$$MgHPO_4\,(s) + NH_3\,(aq) + 6H_2O \rightarrow MgNH_4PO_4 \cdot 6H_2O\,(s) \tag{2}$$

3.5 An overall assessment

Table 2 summarizes the overall assessment of pathogens inactivation in different urine treatment processes. Storage for 2–6 months was considered as an effective pretreatment technology to inactive pathogens when urine was used as liquid fertilizer (Schonning, 2001; Jönsson et al., 2004; World Health Organization (WHO), 2006). Urine dewatering and dehydration technologies are developed to obtain concentrated liquid fertilizer or solid fertilizer. Pathogens could be retained in concentrated urine fertilizer by membrane treatment using reverse osmosis, forward osmosis, and nanofiltration. This would bring strong negative effect on pathogens inactivation. However, electrodialysis may effectively remove pathogens because concentrated liquid fertilizer is obtained in the permeate side and pathogens are retained in the urine feed side. Moreover, membrane distillation should have strong positive effect on inactivating pathogens in concentrated urine fertilizer because of alkalinization or heating of urine feed. Evaporation under heating or distillation will probably yield sterile concentrated liquid or solid fertilizer products because high temperature is effective for pathogens inactivation.

Urine stabilization is commonly essential before urine dewatering to prevent loss of ammonia due to urea hydrolysis. Alkalinization can be used to enhance the pathogens inactivation as a pretreatment process, which may be particularly important for dewatering technologies without inactivation effect such as reverse osmosis, forward osmosis, nanofiltration and freezing. Pathogens would also be effectively inactivated by chemical oxidation. However, the effect of chemical oxidation on the characteristics of UDFPs is unclear. Moreover, it is also unclear whether acidification or biological nitrification can inactivate pathogens in urine. Thus, these two technologies would be suitable for urine stabilization before urine dewatering through membrane distillation, electrodialysis, evaporation and distillation while may be unsuitable prior to urine dewatering using reverse osmosis, forward osmosis, nanofiltration and freezing.

Absorption of ammonia by water or acid solution following stripping can recover N and yield liquid ammonia fertilizer. Air stripping with heating or at alkaline pH and membrane stripping would probably have strong positive effect on pathogens inactivation. Adsorption can recover specific nutrients from urine determined by the adsorbents' characteristics. However, direct use of the solid nutrients-enriched adsorbents in agriculture may pose microbial risks because pathogens may also be adsorbed on the UDFP. Alkaline desorption of nutrient from the solid UDFP to yield liquid fertilizer may be a promising post-treatment process to reduce the microbial risks. Nonetheless, alkaline desorption may be only suitable for ammonia recovery from urine. None information could be obtained on the pathogens inactivation through acidic desorption despite this post-treatment process can recover N, P and K in liquid UDFP. There lacks understanding on the inactivation of pathogens in the chemical precipitations of calcium phosphate, struvite, and struvite-K. However, the following filtration or centrifugation separation of precipitates from urine would retain pathogens in the solid UDFP. This may pose strong negative effect on pathogens inactivation in UDFP. Post-treatment through drying with heating could effectively inactivate pathogens in the solid UDFP. Moreover, recovery of total ammonia in urine through recycling use of struvite precipitation and decomposition may also yield sterile liquid ammonia fertilizer because of struvite decomposition with heating and alkaline treatment.

Combination of different processes is usually essential to extract N, P and K from urine. Adsorption and precipitation was combined to yielding solid N-P enriched UDFP (Lind et al., 2000; Ban and Dave, 2004; Ganrot et al., 2007a; Ganrot et al., 2008; Xu S. et al., 2015; Zheng et al., 2018). This combined processes would have negative effect on pathogens inactivation because each separated process has negative effect. Moreover, precipitation of struvite and stripping-absorption can be combined to recover N and P producing liquid ammonia fertilizer and solid struvite. Pathogens in the liquid ammonia fertilizer would be reduced because of heating and alkaline treatment of urine. However, the pathogens in struvite were determined by the order in the combination. Pathogens in urine can be inactivated in the stripping process. Thus, struvite obtained in a precipitation process following the stripping (Pradhan et al., 2017) would have lower contents of pathogens than that yielded in a precipitation process followed by stripping(Antonini et al., 2011; Morales et al., 2013; Wei et al., 2018; Tao et al., 2019; Yang et al., 2022; Zhang et al., 2022). However, pathogens in solid product obtained in combined processes of stripping and precipitation of struvite-K may be inactivated because the operating pH in this precipitation was approximately 11 which benefits pathogens inactivation (Xu et al., 2017). This indicates that more attention should be paid to the interaction effects of processes combination on pathogens inactivation in further studies.

It should be noted that this study has not reviewed the treatment technologies which are developed to remove pollutants or recover energy from urine. Biological processes including nitrification-denitrification (Udert et al., 2003d), partial nitrification-denitrification (Yao et al., 2017) and nitritation-anammox (Buergmann et al., 2011) can remove nitrogen from urine. Microbial electrolysis cell can remove organics in urine (Boggs et al., 2009; Barbosa et al., 2018; Barbosa et al., 2019). The removal of N and organics has been examined through electrochemical oxidation processes (Amstutz et al., 2012; Dbira et al., 2015; Zoellig et al., 2015; Zollig et al., 2017; Cotillas et al., 2018a; Dbira et al., 2019). Energy production has been achieved *via* microbial fuel cells (You et al., 2016; Salar-Garcia et al., 2017; Gajda et al., 2019; Sabin et al., 2022). Advanced oxidation processes including chemical oxidation (Sun et al., 2018; Li et al., 2022), photocatalytic oxidation (Zhang et al., 2016), and electrochemical oxidation (Antonin et al., 2015; Cotillas et al., 2018b) have been developed to remove micropollutants. Pathogens inactivation in these technologies has not been discussed in this review. Microbial risks in UDFPs should be paid more attention when these technologies are combined with nutrient recovery technologies.

In addition, only the pathogens inactivation in storage and alkaline stabilization has been experimentally examined. Most of the cases were assessed based on publications about their effects on pathogens inactivation in other fields rather than in urine treatment. Moreover, none information on the pathogens inactivation could be obtained when urine was treated using acidic stabilization, stabilization *via* biological nitrification, dewatering *via* freezing or desorption after nutrient adsorption. This means that systematic and meticulous research work is urgently needed to provide technical support for better and safe development of the concept of urine source separation. This is particularly important for achieving U.N. SDGs in developing countries and regions lacking sanitation.

4 Outlook on microbial risk management of urine source separation

Disinfection of UDFPs and agricultural products is essential if recovery technology can't effectively inactivate pathogens in urine and the fertilizer product. Conventional technologies including high-temperature sterilization, ultraviolet disinfection and chemical oxidation disinfection have been proved to be effective for product disinfection (US Centers for Disease Control and Prevention, 2008). Cooking agricultural products before eating will be preferred to reduce the microbial risk by consumers. However, few publications reported the disinfection of UDFPs. Due care should be taken if these disinfection technologies would affect the fertilizer characteristics in further studies.

Moreover, it is essential to set standards on pathogen limitations in UDFPs and technical standards from the aspect of microbial risk management. The related standards lacks despite the concept of urine source separation has been proposed for nearly 30 years. The WHO guidelines recommends that the number of *E. coli* in water is less than 10^4/100 ml in the reuse of water in drip irrigation (World Health Organization (WHO), 2006). The Environmental Protection Agency regulations suggest that the number of *E. coli* should be less than 10^2/100 ml in the reused water (Environmental Protection Agency, 2012). The maximum allowable concentration of bacteria is 1000 CFU/g in recycled organic waste fertilizer products following the European Animal By-Products Regulation (The European Parliament and of the Council, 2002). These regulations may provide references for

UDFPs which are also used for agriculture. However, this has to be addressed in further studies.

Effective inactivation of pathogens in UDFPs would reduce the microbial risk to farmworkers and consumers of agricultural products. However, urine collection and transportation can also bring health risk to users. It is commonly assumed that the direct accidental ingestion of urine was 1 ml per case in recycling of urine in agriculture (Hoglund et al., 2002; Ahmed et al., 2017). Non-etheless, a recent study found that indirect ingestion also played a role in the exposure of urine collection users to urine (Bischel et al., 2019). The indirect ingestion refers to hand to mouth contacts with pathogens when hands, skin and clothes are contaminated and then hands bring pathogens to mouth. Furthermore, operating struvite precipitation reactor also resulted in health risk due to direct and indirect contacts with pathogens-carrying substances (Bischel et al., 2019). This indicates that microbial risk in urine source separation should consider all possible exposure pathways besides the exposure to UDFPs. Therefore, it is recommended that personal protective equipment (facemasks, gloves, work clothes, etc.) is essential to reduce the exposure of urine collection users and farmworkers to urine and UDFPs.

5 Conclusion

Pathogens in source-separated urine can be introduced through two approaches including excretion with urine and fecal contamination. A summary on bacteria and viruses detected in urine confirms that urine is not sterile. Then, this study reviewed and evaluated pathogens inactivation in urine treatment technologies classified based on their UDFPs. Storage and alkaline stabilization have experimentally proved effective effects on pathogens inactivation of urine. Technologies including membrane distillation, electrodialysis, evaporation, distillation, air stripping, and membrane stripping should have positive effect on pathogens inactivation of UDFPs because alkaline treatment, high temperature and membrane separation in these technologies could reduce pathogens. However, pathogens might be concentrated when urine is dewatered using reverse osmosis, forward osmosis, and nanofiltration. Moreover, adsorption and precipitates separation using filtration and centrifugation may also present negative effect on pathogens inactivation in UDFPs. Non-etheless, post treatment through alkaline desorption, precipitates drying, and struvite decomposition and recycle would benefit the disinfection of UDFPs. Finally, an overall assessment was carried out to show a clear map of the connection of technologies and the pathogens inactivation in UDFPs. Based on the assessment, this review discussed the lack of experimental studies on pathogens inactivation in urine treatment and presented outlooks on development of new urine treatment technology and management of microbial risk in urine recycling in agriculture.

Author contributions

KX: investigation and writing—original draft. JLu and HL: investigation, writing—review and editing. JLi: conceptualization, writing—review and editing, funding acquisition. SC: conceptualization, writing—review and editing. MZ: writing—review and editing. CW: conceptualization.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.1056019/full#supplementary-material

References

Adamsson, M. (2000). Potential use of human urine by greenhouse culturing of microalgae (Scenedesmus acuminatus), zooplankton (Daphnia magna) and tomatoes (Lycopersicon). *Ecol. Eng.* 16 (2), 243–254. doi:10.1016/S0925-8574(00)00064-1

Aguado, D., Barat, R., Bouzas, A., Seco, A., and Ferrer, J. (2019). P-recovery in a pilot-scale struvite crystallisation reactor for source separated urine systems using seawater and magnesium chloride as magnesium sources. *Sci. Total Environ.* 672, 88–96. doi:10.1016/j.scitotenv.2019.03.485

Ahmed, W., Hamilton, K. A., Vieritz, A., Powell, D., Goonetilleke, A., Hamilton, M. T., et al. (2017). Microbial risk from source-separated urine used as liquid fertilizer in sub-tropical Australia. *Microb. Risk Anal.* 5 (SI), 53–64. doi:10.1016/j.mran.2016.11.005

Akpan-Idiok, A. U., Udo, I. A., and Braide, E. I. (2012). The use of human urine as an organic fertilizer in the production of okra (Abelmoschus esculentus) in South Eastern Nigeria. *Resour. Conservation Recycl.* 62, 14–20. doi:10.1016/j.resconrec.2012.02.003

Alizadeh, A. M., Jazaeri, S., Shemshadi, B., Hashempour-Baltork, F., Sarlak, Z., Plievar, Z., et al. (2018). A review on inactivation methods of Toxoplasma gondii in foods. *Pathogens Glob. Health* 112 (6), 306–319. doi:10.1080/20477724.2018.1514137

Almeida, J. A. S., Azevedo, A. L., Brett, M., Tadeu, A., Silva-Afonso, A., Costa, A., et al. (2019). Urine recovery at the building level. *Build. Environ.* 156, 110–116. doi:10.1016/j.buildenv.2019.04.006

Almeida, J. A. S., Azevedo, A. L., Brett, M., Tadeu, A., Silva-Afonso, A., Costa, A., et al. (2019). Urine recovery at the building level. *Build. Environ.* 156, 110–116. doi:10.1016/j.buildenv.2019.04.006

Amstutz, V., Katsaounis, A., Kapalka, A., Comninellis, C., and Udert, K. M. (2012). Effects of carbonate on the electrolytic removal of ammonia and urea from urine with thermally prepared IrO2 electrodes. *J. Appl. Electrochem.* 42 (9SI), 787–795. doi:10.1007/s10800-012-0444-y

An, X., Wang, J., Pu, Q., Li, H., Pan, T., Li, H., et al. (2020). High-throughput diagnosis of human pathogens and fecal contamination in marine recreational water. *Environ. Res.* 190, 109982. doi:10.1016/j.envres.2020.109982

Antonin, V. S., Santos, M. C., Garcia-Segura, S., and Brillas, E. (2015). Electrochemical incineration of the antibiotic ciprofloxacin in sulfate medium and synthetic urine matrix. *Water Res.* 83, 31–41. doi:10.1016/j.watres.2015.05.066

Antonini, S., Arias, M. A., Eichert, T., and Clemens, J. (2012a). Greenhouse evaluation and environmental impact assessment of different urine-derived struvite fertilizers as phosphorus sources for plants. *Chemosphere* 89 (10), 1202–1210. doi:10.1016/j.chemosphere.2012.07.026

Antonini, S., Paris, S., Eichert, T., and Clemens, J. (2011). Nitrogen and phosphorus recovery from human urine by struvite precipitation and air stripping in Vietnam. *Clean. Soil Air Water* 39 (12), 1099–1104. doi:10.1002/clen.201100036

Antonini, S., Phong, T. N., Arnold, U., Eichert, T., and Clemens, J. (2012b). Solar thermal evaporation of human urine for nitrogen and phosphorus recovery in Vietnam. *Sci. Total Environ.* 414, 592–599. doi:10.1016/j.scitotenv.2011.11.055

Badeti, U., Jiang, J., Almuntashiri, A., Pathak, N., Dorji, U., Volpin, F., et al. (2022). Impact of source-separation of urine on treatment capacity, process design, and capital expenditure of a decentralised wastewater treatment plant. *Chemosphere* 300, 134489. doi:10.1016/j.chemosphere.2022.134489

Bai, X., Li, Z., Zhang, Y., Ni, J., Wang, X., and Zhou, X. (2018). Recovery of ammonium in urine by biochar derived from faecal sludge and its application as soil conditioner. *Waste Biomass Valor.* 9 (9), 1619–1628. doi:10.1007/s12649-017-9906-0

Ban, Z., and Dave, G. (2004). Laboratory studies on recovery of N and P from human urine through struvite crystallisation and zeolite adsorption. *Environ. Technol.* 25 (1), 111–121. doi:10.1080/09593330409355443b

Barbosa, S. G., Peixoto, L., Soares, O. S. G. P., Pereira, M. F. R., Ter Heijne, A., Kuntke, P., et al. (2018). Influence of carbon anode properties on performance and microbiome of Microbial Electrolysis Cells operated on urine. *Electrochimica Acta* 267, 122–132. doi:10.1016/j.electacta.2018.02.083

Barbosa, S. G., Rodrigues, T., Peixoto, L., Kuntke, P., Alves, M. M., Pereira, M. A., et al. (2019). Anaerobic biological fermentation of urine as a strategy to enhance the performance of a microbial electrolysis cell (MEC). *Renew. Energy* 139, 936–943. doi:10.1016/j.renene.2019.02.120

Barzon, L., Pacenti, M., Franchin, E., Pagni, S., Martello, T., Cattai, M., et al. (2013). Excretion of West Nile virus in urine during acute infection. *J. Infect. Dis.* 208 (7), 1086–1092. doi:10.1093/infdis/jit290

Basakcilardan-Kabakci, S., Ipekoglu, A. N., and Talini, I. (2007). Recovery of ammonia from human urine by stripping and absorption. *Environ. Eng. Sci.* 24 (5), 615–624. doi:10.1089/ees.2006.0412

Baykal, B. B., Kocaturk, N. P., Allar, A. D., and Sari, B. (2009). The effect of initial loading on the removal of ammonium and potassium from source-separated human urine via clinoptilolite. *Water Sci. Technol.* 60 (10), 2515–2520. doi:10.2166/wst.2009.614

Behrendt, J., Arevalo, E., Gulyas, H., Niederste-Hollenberg, J., Niemiec, A., Zhou, J., et al. (2002). Production of value added products from separately collected urine. *Water Sci. Technol.* 46 (6-7), 341–346. doi:10.2166/wst.2002.0698

Beler-Baykal, B., Allar, A. D., and Bayram, S. (2011). Nitrogen recovery from source-separated human urine using clinoptilolite and preliminary results of its use as fertilizer. *Water Sci. Technol.* 63 (4), 811–817. doi:10.2166/wst.2011.324

Beler-Baykal, B., Bayram, S., Akkaymak, E., and Cinar, S. (2004). Removal of ammonium from human urine through ion exchange with clinoptilolite and its recovery for further reuse. *Water Sci. Technol.* 50 (6), 149–156. doi:10.2166/wst.2004.0371

Benami, M., Busgang, A., Gillor, O., and Gross, A. (2016). Quantification and risks associated with bacterial aerosols near domestic greywater-treatment systems. *Sci. Total Environ.* 562, 344–352. doi:10.1016/j.scitotenv.2016.03.200

Bercovici, M., Kaigala, G. V., Mach, K. E., Han, C. M., Liao, J. C., and Santiago, J. G. (2011). Rapid detection of urinary tract infections using isotachophoresis and molecular beacons. *Anal. Chem.* 83 (11), 4110–4117. doi:10.1021/ac200253x

Berger, J. R., Miller, C. S., Mootoor, Y., Avdiushko, S. A., Kryscio, R. J., and Zhu, H. (2006). JC virus detection in bodily fluids: Clues to transmission. *Clin. Infect. Dis.* 43 (1), e9–e12. doi:10.1086/504947

Bethune, D. N., Chu, A., and Ryan, M. C. (2014). Passive evaporation of source-separated urine from dry toilets: A lab study. *J. Water Sanit. Hyg. De.* 4 (4), 654–662. doi:10.2166/washdev.2014.058

Bethune, D. N., Chu, A., and Ryan, M. C. (2015). Passive evaporation of source-separated urine from dry toilets: Prototype design and field testing using municipal water. *J. Water, Sanitation Hyg. Dev.* 5 (3), 392–401. doi:10.2166/washdev.2015.158

Bethune, D. N., Chu, A., and Ryan, M. C. (2016). Passive evaporation of source-separated urine from dry toilets: UES optimization and dry product accumulation over time. *J. Water Sanit. Hyg. De.* 6 (1), 96–103. doi:10.2166/washdev.2016.103

Bhuiyan, M., Mavinic, D. S., and Koch, F. A. (2008). Thermal decomposition of struvite and its phase transition. *Chemosphere* 70 (8), 1347–1356. doi:10.1016/j.chemosphere.2007.09.056

Bischel, H. N., Caduff, L., Schindelholz, S., Kohn, T., and Julian, T. R. (2019). Health risks for sanitation service workers along a container-based urine collection system and resource recovery value chain. *Environ. Sci. Technol.* 53 (12), 7055–7067. doi:10.1021/acs.est.9b01092

Bischel, H. N., Duygan, B. D. O., Strande, L., Mcardell, C. S., Udert, K. M., and Kohn, T. (2015). Pathogens and pharmaceuticals in source-separated urine in eThekwini, South Africa. *Water Res.* 85, 57–65. doi:10.1016/j.watres.2015.08.022

Bischel, H. N., Schindelholz, S., Schoger, M., Decrey, L., Buckley, C. A., Udert, K. M., et al. (2016). Bacteria inactivation during the drying of struvite fertilizers produced from stored urine. *Environ. Sci. Technol.* 50 (23), 13013–13023. doi:10.1021/acs.est.6b03555

Boan, P., Hewison, C., Swaminathan, R., Irish, A., Warr, K., Sinniah, R., et al. (2016). Optimal use of plasma and urine BK viral loads for screening and predicting BK nephropathy. *BMC Infect. Dis.* 16, 342. doi:10.1186/s12879-016-1652-6

Boggs, B. K., King, R. L., and Botte, G. G. (2009). Urea electrolysis: Direct hydrogen production from urine. *Chem. Commun.* (32), 4859–4861. doi:10.1039/b905974a

Bonaldo, M. C., Ribeiro, I. P., Lima, N. S., Dos Santos, A. A., Menezes, L. S., da Cruz, S. O., et al. (2016). Isolation of infective Zika virus from urine and saliva of patients in Brazil. *PLoS Negl. Trop. Dis.* 10 (6), e0004816. doi:10.1371/journal.pntd.0004816

Brewster, T. E., Jermakka, J., Freguia, S., and Batstone, D. J. (2017). Modelling recovery of ammonium from urine by electro-concentration in a 3-chamber cell. *Water Res.* 124, 210–218. doi:10.1016/j.watres.2017.07.043

Buergmann, H., Jenni, S., Vazquez, F., and Udert, K. M. (2011). Regime shift and microbial dynamics in a sequencing batch reactor for nitrification and anammox treatment of urine. *Appl. Environ. Microbiol.* 77 (17), 5897–5907. doi:10.1128/AEM.02986-10

Bujoczek, G., Oleszkiewicz, J., Danesh, S., and Sparling, R. (2002). Co-processing of organic fraction of municipal solid waste and primary sludge--stabilization and disinfection. *Environ. Technol.* 23 (2), 227–241. doi:10.1080/09593332508618423

Chandran, A., Pradhan, S. K., and Heinonen-Tanski, H. (2009). Survival of enteric bacteria and coliphage MS2 in pure human urine. *J. Appl. Microbiol.* 107 (5), 1651–1657. doi:10.1111/j.1365-2672.2009.04353.x

Chen, J., Xu, Y., Yan, H., Zhu, Y., Wang, L., Zhang, Y., et al. (2018). Sensitive and rapid detection of pathogenic bacteria from urine samples using multiplex recombinase polymerase amplification. *Lab. Chip* 18 (16), 2441–2452. doi:10.1039/c8lc00399h

Chen, S., Yang, Y., Zheng, M., Cheng, X., Xu, K., and Dou, X. (2020). Thermal decomposition of struvite pellet by microwave radiation and recycling of its product to remove ammonium and phosphate from urine. *Environ. Res.* 188, 109774–109779. doi:10.1016/j.envres.2020.109774

Chen, X., Gao, Y., Hou, D., Ma, H., Lu, L., Sun, D., et al. (2017). The microbial electrochemical current accelerates urea hydrolysis for recovery of nutrients from source-separated urine. *Environ. Sci. Technol. Lett.* 4 (7), 305–310. doi:10.1021/acs.estlett.7b00168

Cheng, S., Long, J., Evans, B., Zhan, Z., Li, T., Chen, C., et al. (2022). Non-negligible greenhouse gas emissions from non-sewered sanitation systems: A meta-analysis. *Environ. Res.* 212, 113468. doi:10.1016/j.envres.2022.113468

Christiaens, M. E. R., Gildemyn, S., Matassa, S., Ysebaert, T., De Vrieze, J., and Rabaey, K. (2017). Electrochemical ammonia recovery from source-separated urine for microbial protein production. *Environ. Sci. Technol.* 51 (22), 13143–13150. doi:10.1021/acs.est.7b02819

Christiaens, M. E. R., Udert, K. M., Arends, J. B. A., Huysman, S., Vanhaecke, L., Mcadam, E., et al. (2019). Membrane stripping enables effective electrochemical ammonia recovery from urine while retaining microorganisms and micropollutants. *Water Res.* 150, 349–357. doi:10.1016/j.watres.2018.11.072

Chu, C., Ryberg, E. C., Loeb, S. K., Suh, M., and Kim, J. (2019). Water disinfection in rural areas demands unconventional solar technologies. *Acc. Chem. Res.* 52 (5), 1187–1195. doi:10.1021/acs.accounts.8b00578

Corman, V. M., Albarrak, A. M., Omrani, A. S., Albarrak, M. M., Farah, M. E., Almasri, M., et al. (2015). Viral shedding and antibody response in 37 patients with Middle East respiratory syndrome coronavirus infection. *Clin. Infect. Dis.* 62 (4), 477–483. doi:10.1093/cid/civ951

Cotillas, S., Lacasa, E., Saez, C., Canizares, P., and Rodrigo, M. A. (2018a). Disinfection of urine by conductive-diamond electrochemical oxidation. *Appl. Catal. B Environ.* 229, 63–70. doi:10.1016/j.apcatb.2018.02.013

Cotillas, S., Lacasa, E., Saez, C., Canizares, P., and Rodrigo, M. A. (2018b). Electrolytic and electro-irradiated technologies for the removal of chloramphenicol in synthetic urine with diamond anodes. *Water Res.* 128, 383–392. doi:10.1016/j.watres.2017.10.072

Courtney, C., and Randall, D. G. (2022). A hybrid nanofiltration and reverse osmosis process for urine treatment: Effect on urea recovery and purity. *Water Res.* 222, 118851. doi:10.1016/j.watres.2022.118851

Dbira, S., Bensalah, N., Ahmad, M. I., and Bedoui, A. (2019). Electrochemical oxidation/disinfection of urine wastewaters with different anode materials. *Materials* 12 (12548), 1254. doi:10.3390/ma12081254

Dbira, S., Bensalah, N., Bedoui, A., Caizares, P., and Rodrigo, M. A. (2015). Treatment of synthetic urine by electrochemical oxidation using conductive-diamond anodes. *Environ. Sci. Pollut. Res.* 22 (8), 6176–6184. doi:10.1007/s11356-014-3831-6

De Paepe, J., Lindeboom, R. E. F., Vanoppen, M., De Paepe, K., Demey, D., Coessens, W., et al. (2018). Refinery and concentration of nutrients from urine with electrodialysis enabled by upstream precipitation and nitrification. *Water Res.* 144, 76–86. doi:10.1016/j.watres.2018.07.016

Decrey, L., Kazama, S., Udert, K. M., and Kohn, T. (2015). Ammonia as an *in situ* sanitizer: Inactivation kinetics and mechanisms of the ssRNA virus MS2 by NH3. *Environ. Sci. Technol.* 49 (2), 1060–1067. doi:10.1021/es5044529

Decrey, L., and Kohn, T. (2017). Virus inactivation in stored human urine, sludge and animal manure under typical conditions of storage or mesophilic anaerobic digestion. *Environ. Sci. Water Res. Technol.* 3 (3), 492–501. doi:10.1039/c6ew00311g

Decrey, L., Udert, K. M., Tilley, E., Pecson, B. M., and Kohn, T. (2011). Fate of the pathogen indicators phage Phi X174 and *Ascaris suum* eggs during the production of struvite fertilizer from source-separated urine. *Water Res.* 45 (16), 4960–4972. doi:10.1016/j.watres.2011.06.042

Dong, Q., Nelson, D., Toh, E., Diao, L., Gao, X., Fortenberry, J., et al. (2011). The microbial communities in male first catch urine are highly similar to those in paired urethral swab specimens. *Plos One* 6 (5), e19709. doi:10.1371/journal.pone.0019709

Dox, K., Everaert, M., Merckx, R., and Smolders, E. (2019a). Optimization of phosphate recovery from urine by layered double hydroxides. *Sci. Total Environ.* 682, 437–446. doi:10.1016/j.scitotenv.2019.05.181

Dox, K., Martin, T., Houot, S., Merckx, R., and Smolders, E. (2022). Superior residual fertiliser value in soil with phosphorus recycled from urine in layered double hydroxides. *Sci. Rep.* 12, 8092. doi:10.1038/s41598-022-11892-4

Dox, K., Pareijn, R., Everaert, M., and Smolders, E. (2019b). Phosphorus recycling from urine using layered double hydroxides: A kinetic study. *Appl. Clay Sci.* 182, 105255. doi:10.1016/j.clay.2019.105255

Drosten, C., Seilmaier, M., Corman, V. M., Hartmann, W., Scheible, G., Sack, S., et al. (2013). Clinical features and virological analysis of a case of Middle East respiratory syndrome coronavirus infection. *Lancet Infect. Dis.* 13 (9), 745–751. doi:10.1016/s1473-3099(13)70154-3

Ducancelle, A., Legrand, M. C., Pivert, A., Veillon, P., Le Guillou-Guillemette, H., De Brux, M. A., et al. (2014). Interest of human papillomavirus DNA quantification and genotyping in paired cervical and urine samples to detect cervical lesions. *Arch. Gynecol. Obstet.* 290 (2), 299–308. doi:10.1007/s00404-014-3191-y

Dutta, S., and Vinnerås, B. (2016). Fertilizer from dried human urine added to ash and lime a potential product from eco-sanitation system. *Water Sci. Technol.* 74 (6), 1436–1445. doi:10.2166/wst.2016.324

Ek, M., Bergstrom, R., Bjurhem, J. E., Bjorlenius, B., and Hellstrom, D. (2006). Concentration of nutrients from urine and reject water from anaerobically digested sludge. *Water Sci. Technol.* 54 (11-12), 437–444. doi:10.2166/wst.2006.924

Eksi, F., Karsligil, T., Gundes, I., Saglam, M., Kirik, M. P., Budeyri, M. S., et al. (2018). Investigation of BK virus by real-time polymerase chain reaction in patients with allogeneic bone marrow transplantation. *Transplant. Proc.* 50 (5), 1510–1513. doi:10.1016/j.transproceed.2017.12.056

El Ansary, M., Abd Elhamid, S., Saadi, G., Ismail, W., Ibrahim, N., Bahaa El-Din, N., et al. (2016). Prevalence of polyoma BK virus infection among living-donor renal transplant recipients. *Transpl. Infect. Dis.* 18 (4), 529–537. doi:10.1111/tid.12557

Engelhardt, S., Vogel, J., Duirk, S. E., Moore, F. B., and Barton, H. A. (2020). Assessment of urea hydrolysis as a pretreatment strategy to improve total nitrogen rejection from urine using aquaporin-based membranes in forward osmosis. *J. Water Process Eng.* 34, 101135. doi:10.1016/j.jwpe.2020.101135

Environmental Protection Agency (2012). *Guidelines for water reuse*. USA: USEPA, Washington D.C.

Etter, B., Tilley, E., Khadka, R., and Udert, K. M. (2011). Low-cost struvite production using source-separated urine in Nepal. *Water Res.* 45 (2), 852–862. doi:10.1016/j.watres.2010.10.007

Feng, D. L., Wu, Z. C., and Xu, S. H. (2008). Nitrification of human urine for its stabilization and nutrient recycling. *Bioresour. Technol.* 99 (14), 6299–6304. doi:10.1016/j.biortech.2007.12.007

Ferronato, C., Vianello, G., and Antisari, L. V. (2015). Adsorption of pathogenic microorganisms, NH4+ and heavy metals from wastewater by clinoptilolite using bed laminar flow. *Clay Min.* 50 (1), 1–10. doi:10.1180/claymin.2015.050.1.01

Fumasoli, A., Etter, B., Sterkele, B., Morgenroth, E., and Udert, K. M. (2016). Operating a pilot-scale nitrification/distillation plant for complete nutrient recovery from urine. *Water Sci. Technol.* 73 (1), 215–222. doi:10.2166/wst.2015.485

Gajda, I., Greenman, J., Santoro, C., Serov, A., Atanassov, P., Melhuish, C., et al. (2019). Multi-functional microbial fuel cells for power, treatment and electro-osmotic purification of urine. *J. Chem. Technol. Biotechnol.* 94 (7), 2098–2106. doi:10.1002/jctb.5792

Ganrot, Z., Dave, G., Nilsson, E., and Li, B. (2007b). Plant availability of nutrients recovered as solids from human urine tested in climate chamber on *Triticum aestivum* L. *Bioresour. Technol.* 98 (16), 3122–3129. doi:10.1016/j.biortech.2007.01.003

Ganrot, Z., Dave, G., and Nilsson, E. (2007a). Recovery of N and P from human urine by freezing, struvite precipitation and adsorption to zeolite and active carbon. *Bioresour. Technol.* 98 (16), 3112–3121. doi:10.1016/j.biortech.2006.10.038

Ganrot, Z., Slivka, A., and Dave, G. (2008). Nutrient recovery from human urine using pretreated zeolite and struvite precipitation in combination with freezing-thawing and plant availability tests on common wheat. *Clean. Soil Air Water* 36 (1), 45–52. doi:10.1002/clen.200700074

Goetsch, H. E., Zhao, L., Gnegy, M., Imperiale, M. J., Love, N. G., and Wigginton, K. R. (2018). Fate of the urinary tract virus BK Human Polyomavirus in source-separated urine. *Appl. Environ. Microbiol.* 84 (7), e02374-17. doi:10.1128/AEM.02374-17

Golder, D., Rana, S., Sarkar, D., and Jana, B. B. (2007). Human urine is an excellent liquid waste for the culture of fish food organism, Moina micrura. *Ecol. Eng.* 30 (4), 326–332. doi:10.1016/j.ecoleng.2007.04.002

Goldsmith, C. S., and Miller, S. E. (2009). Modern uses of electron microscopy for detection of viruses. *Clin. Microbiol. Rev.* 22 (4), 552–563. doi:10.1128/CMR.00027-09

Goswami, K. P., and Pugazhenthi, G. (2020). Credibility of polymeric and ceramic membrane filtration in the removal of bacteria and virus from water: A review. *J. Environ. Manag.* 268, 110583. doi:10.1016/j.jenvman.2020.110583

Guan, T., Kuang, Y., Li, X., Fang, J., Fang, W., and Wu, D. (2020a). The recovery of phosphorus from source-separated urine by repeatedly usable magnetic Fe3O4@ZrO2 nanoparticles under acidic conditions. *Environ. Int.* 134, 105322. doi:10.1016/j.envint.2019.105322

Guan, T., Li, X., Fang, W., and Wu, D. (2020b). Efficient removal of phosphate from acidified urine using UiO-66 metal-organic frameworks with varying functional groups. *Appl. Surf. Sci.* 501, 144074. doi:10.1016/j.apsusc.2019.144074

Gujer, W. (2010). Nitrification and me – a subjective review. *Water Res.* 44 (1), 1–19. doi:10.1016/j.watres.2009.08.038

Gulyas, H., Bruhn, P., Furmanska, M., Hartrampf, K., Kot, K., Luttenberg, B., et al. (2004). Freeze concentration for enrichment of nutrients in yellow water from no-mix toilets. *Water Sci. Technol.* 50 (6), 61–68. doi:10.2166/wst.2004.0360

Guzha, E., Nhapi, I., and Rockstrom, J. (2005). An assessment of the effect of human faeces and urine on maize production and water productivity. *Phys. Chem. Earth Parts A/B/C* 30 (11-16), 840–845. doi:10.1016/j.pce.2005.08.028

Han, C., Yuan, X., Ma, S., Li, Y., Feng, Y., and Liu, J. (2022). Simultaneous recovery of nutrients and power generation from source-separated urine based on bioelectrical coupling with the hydrophobic gas permeable tube system. *Sci. Total Environ.* 824, 153788. doi:10.1016/j.scitotenv.2022.153788

Han, M. S., Seong, M. W., Kim, N., Shin, S., Im Cho, S., Park, H., et al. (2020). Virological assessment of hospitalized patients with COVID-2019. *Nature* 26 (10), 465–469. doi:10.1038/s41586-020-2196-x

Hanaoka, N., Ito, S., Konagaya, M., Nojiri, N., Yasuda, M., Fujimoto, T., et al. (2019). Infectious human adenoviruses are shed in urine even after disappearance of urethral symptoms. *PLoS One* 14 (3), e0212434. doi:10.1371/journal.pone.0212434

Hansen, J. J., Warden, P. S., and Margolin, A. B. (2007). Inactivation of adenovirus type 5, rotavirus Wa and male specific coliphage (MS2) in biosolids by lime stabilization. *Int. J. Env. Res. Pub. He.* 4 (1), 61–67. doi:10.3390/ijerph2007010010

Harada, H., Shimizu, Y., Miyagoshi, Y., Matsui, S., Matsuda, T., and Nagasaka, T. (2006). Predicting struvite formation for phosphorus recovery from human urine using an equilibrium model. *Water Sci. Technol.* 54 (8), 247–255. doi:10.2166/wst.2006.720

Harder, R., Wielemaker, R., Larsen, T. A., Zeeman, G., and Oberg, G. (2019). Recycling nutrients contained in human excreta to agriculture: Pathways, processes, and products. *Crit. Rev. Environ. Sci. Technol.* 49 (8), 695–743. doi:10.1080/10643389.2018.1558889

Heinonen-Tanski, H., Sjoblom, A., Fabritius, H., and Karinen, P. (2007). Pure human urine is a good fertiliser for cucumbers. *Bioresour. Technol.* 98 (1), 214–217. doi:10.1016/j.biortech.2005.11.024

Hellstrom, D., Johannson, E., and Grennberg, K. (1999). Storage of human urine: Acidification as a method to inhibit decomposition of urea. *Ecol. Eng.* 12 (3-4), 253–269. doi:10.1016/S0925-8574(98)00074-3

Hilt, E. E., Mckinley, K., Pearce, M. M., Rosenfeld, A. B., Zilliox, M. J., Mueller, E. R., et al. (2014). Urine is not sterile: Use of enhanced urine culture techniques to detect resident bacterial flora in the adult female bladder. *J. Clin. Microbiol.* 52 (3), 871–876. doi:10.1128/JCM.02876-13

Hinata, N., Shirakawa, T., Okada, H., Shigemura, K., Kamidono, S., and Gotoh, A. (2004). Quantitative detection of *Escherichia coli* from urine of patients with bacteriuria by real-time PCR. *Mol. Diagn.* 8 (3), 179–184. doi:10.1007/BF03260062

Höglund, C., Ashbolt, N., Stenström, T. A., and Svensson, L. (2002). Viral persistence in source-separated human urine. *Adv. Environ. Res.* 6 (3), 265–275. doi:10.1016/S1093-0191(01)00057-0

Höglund, C. (2001). *Evaluation of microbial health risks associated with the reuse of source-separated human urine*. Stockholm: Royal Institute of Technology.

Hoglund, C., Stenstrom, T. A., and Ashbolt, N. (2002). Microbial risk assessment of source-separated urine used in agriculture. *Waste Manag. Res.* 20 (2), 150–161. doi:10.1177/0734242X0202000207

Höglund, C., Stenström, T. A., Jönsson, H., and Sundin, A. (1998). Evaluation of faecal contamination and microbial die-off in urine separating sewage systems. *Water Sci. Technol.* 38 (6), 17–25. doi:10.2166/wst.1998.0232

Höglund, C., and Stenström, T. A. (1999). Survival of <i>Cryptosporidium parvum</i> oocysts in source separated human urine. *Rev. Can. Microbiol.* 45 (9), 740–746. doi:10.1139/cjm-45-9-740

Höglund, C., Vinnerås, B., Stenström, T. A., and Jönsson, H. (2000). Variation of chemical and microbial parameters in collection and storage tanks for source separated human urine. *J. Environ. Sci. Health Part A* 35 (8), 1463–1475. doi:10.1080/10934520009377047

Höglund, C., Vinnerås, B., Stenström, T. A., and Jönsson, H. (2000). Variation of chemical and microbial parameters in collection and storage tanks for source separated human urine. *J. Environ. Sci. Health Part A* 35 (8), 1463–1475. doi:10.1080/10934520009377047

Hotta, S., and Funamizu, N. (2008). Evolution of ammonification potential in storage process of urine with fecal contamination. *Bioresour. Technol.* 99 (1), 13–17. doi:10.1016/j.biortech.2006.12.001

Hu, X., Han, M., Wang, C., Yang, N., Wang, Y., Duan, E., et al. (2020). A short review of bioaerosol emissions from gas bioreactors: Health threats, influencing factors and control technologies. *Chemosphere* 253, 126737. doi:10.1016/j.chemosphere.2020.126737

Huang, H., Li, J., Li, B., Zhang, D., Zhao, N., and Tang, S. (2019). Comparison of different K-struvite crystallization processes for simultaneous potassium and phosphate recovery from source-separated urine. *Sci. Total Environ.* 651 (1), 787–795. doi:10.1016/j.scitotenv.2018.09.232

Huang, H., Liu, J., Xu, C., and Gao, F. (2016). Recycling struvite pyrolysate obtained at negative pressure for ammonia nitrogen removal from landfill leachate. *Chem. Eng. J.* 284, 1204–1211. doi:10.1016/j.cej.2015.09.080

Huang, H., Xiao, D., Pang, R., Han, C., and Ding, L. (2014). Simultaneous removal of nutrients from simulated swine wastewater by adsorption of modified zeolite combined with struvite crystallization. *Chem. Eng. J.* 256, 431–438. doi:10.1016/j.cej.2014.07.023

Huang, H., Zhang, P., Xiao, J., Xiao, D., and Gao, F. (2017). Repeatedly using the decomposition product of struvite by ultrasound stripping to remove ammonia nitrogen from landfill leachate. *Ultrason. Sonochemistry* 38, 622–628. doi:10.1016/j.ultsonch.2016.08.019

Hung, I. F. N., Cheng, V. C. C., Wu, A. K. L., Tang, B. S. F., Chan, K. H., Chu, C. M., et al. (2004). Viral loads in clinical specimens and SARS manifestations. *Emerg. Infect. Dis.* 10 (9), 1550–1557. doi:10.3201/eid1009.040058

Iseri, E., Biggel, M., Goossens, H., Moons, P., and van der Wijngaart, W. (2020). Digital dipstick: Miniaturized bacteria detection and digital quantification for the point-of-care. *Lab. Chip* 20 (23), 4349–4356. doi:10.1039/d0lc00793e

Ivanković, T., Hrenović, J., Itskos, G., Koukouzas, N., Kovačević, D., and Milenković, J. (2014). Alkaline disinfection of urban wastewater and landfill leachate by wood fly ash. *Arh. za Hig. rada i Toksikol.* 65 (4), 365–375. doi:10.2478/10004-1254-65-2014-2546

Jagtap, N., and Boyer, T. H. (2018). Integrated, multi-process approach to total nutrient recovery from stored urine. *Environ. Sci. Water Res. Technol.* 4 (10), 1639–1650. doi:10.1039/c8ew00004b

Jagtap, N. S., and Boyer, T. H. (2020). Urine collection in a multi-story building and opportunities for onsite recovery of nutrients and non-potable water. *J. Environ. Chem. Eng.* 8, 103964. doi:10.1016/j.jece.2020.103964

Jain, S., Su, Y. H., Su, Y. P., McCloud, S., Xue, R., Lee, T. J., et al. (2018). Characterization of the Hepatitis B virus DNA detected in urine of chronic Hepatitis B patients. *BMC Gastroenterol.* 18 (1), 40. doi:10.1186/s12876-018-0767-1

Jeong, H. W., Kim, S. M., Kim, H. S., Kim, Y. I., Kim, J. H., Cho, J. Y., et al. (2020). Viable SARS-CoV-2 in various specimens from COVID-19 patients. *Clin. Microbiol. Infect.* 26 (11), 1520–1524. doi:10.1016/j.cmi.2020.07.020

Jiang, F., Chen, Y., Mackey, H. R., Chen, G. H., and van Loosdrecht, M. C. M. (2011). Urine nitrification and sewer discharge to realize in-sewer denitrification to simplify sewage treatment in Hong Kong. *Water Sci. Technol.* 64 (3), 618–626. doi:10.2166/wst.2011.491

Jiang, G., and Yuan, Z. (2014). Inactivation kinetics of anaerobic wastewater biofilms by free nitrous acid. *Appl. Microbiol. Biotechnol.* 98 (3), 1367–1376. doi:10.1007/s00253-013-5031-6

Jiang, Q., Liu, J., Song, X., Qiu, Y., Xue, J., Shao, Y., et al. (2022). Energy efficient bioelectro-concentration and recovery system of nutrients from human urine by integrating forward osmosis. *Resour. Conservation Recycl.* 181, 106253. doi:10.1016/j.resconrec.2022.106253

Jiang, S., Wang, X., Yang, S., and Shi, H. (2016). Characteristics of simultaneous ammonium and phosphate adsorption from hydrolysis urine onto natural loess. *Environ. Sci. Pollut. Res.* 23 (3), 2628–2639. doi:10.1007/s11356-015-5443-1

Jiang, S., Wang, X., Yang, S., and Shi, H. (2017). Effect of initial pH and pH-adjusted acid on nutrient recovery from hydrolysis urine by combining acidification with evaporation-crystallization. *Environ. Sci. Pollut. Res.* 24 (4), 3872–3881. doi:10.1007/s11356-016-8052-8

Jin, Y., Shi, Y., Chen, Z., Chen, R., Chen, X., Zheng, X., et al. (2020). Combination of sunlight with hydrogen peroxide generated at a modified reticulated vitreous carbon for drinking water disinfection. *J. Clean. Prod.* 252, 119794. doi:10.1016/j.jclepro.2019.119794

Jones, D. L., Baluja, M. Q., Graham, D. W., Corbishley, A., McDonald, J. E., Malham, S. K., et al. (2020). Shedding of SARS-CoV-2 in feces and urine and its potential role in person-to-person transmission and the environment-based spread of COVID-19. *Sci. Total Environ.* 749, 141364. doi:10.1016/j.scitotenv.2020.141364

Jönsson, H., Richert Stinzing, A., Vinnerås, B., and Salomon, E. (2004). "Guidelines on the use of urine and faeces in crop production," in *EcoSanRes publications*. (Stockholm: EcoSanRes Publications).

Judice, C. C., Tan, J. J. L., Parise, P. L., Kam, Y. W., Milanez, G. P., Leite, J. A., et al. (2018). Efficient detection of Zika virus RNA in patients' blood from the

2016 outbreak in Campinas, Brazil. *Sci. Rep.* 8 (1), 4012. doi:10.1038/s41598-018-22159-2

Kabdasli, I., Tunay, O., Islek, C., Erdinc, E., Huskalar, S., and Tatli, M. B. (2006). Nitrogen recovery by urea hydrolysis and struvite precipitation from anthropogenic urine. *Water Sci. Technol.* 53 (12), 305–312. doi:10.2166/wst.2006.433

Kashi, A. H., De la Rosette, J., Amini, E., Abdi, H., Fallah-Karkan, M., and Vaezjalali, M. (2020). Urinary viral shedding of COVID-19 and its clinical associations: A systematic review and meta-analysis of observational studies. *medRxiv*. doi:10.1101/2020.05.15.20094920

Keller, R., Passamani-Franca, R. F., Cassin, S. T., and Goncalves, F. R. (2004). Disinfection of sludge using lime stabilisation and pasteurisation in a small wastewater treatment plant. *Water Sci. Technol.* 50 (1), 13–17. doi:10.2166/wst.2004.0005

Khumalo, N., Nthunya, L., Derese, S., Motsa, M., Verliefde, A., Kuvarega, A., et al. (2019). Water recovery from hydrolysed human urine samples via direct contact membrane distillation using PVDF/PTFE membrane. *Sep. Purif. Technol.* 211, 610–617. doi:10.1016/j.seppur.2018.10.035

Kim, I. S., Choi, Y. W., and Lee, S. R. (2004). Optimization and validation of a virus filtration process for efficient removal of viruses from urokinase solution prepared from human urine. *J. Microbiol. Biotechn.* 14 (1), 140–147.

Kim, J., Kim, H. M., Lee, E. J., Jo, H. J., Yoon, Y., Lee, N., et al. (2020). Detection and isolation of SARS-CoV-2 in serum, urine, and stool specimens of COVID-19 patients from the Republic of Korea. *Osong Public Health Res. Perspect.* 11 (3), 112–117. doi:10.24171/j.phrp.2020.11.3.02

Kim, J. M., Kim, H. M., Lee, E. J., Jo, H. J., Yoon, Y., Lee, N. J., et al. (2020). Detection and isolation of SARS-CoV-2 in serum, urine, and stool specimens of COVID-19 patients from the Republic of Korea. *Osong Public Health Res. Perspect.* 11 (3), 112–117. doi:10.24171/j.phrp.2020.11.3.02

Konietzny, R., Fischer, R., Ternette, N., Wright, C. A., Turney, B. W., Chakera, A., et al. (2012). Detection of BK virus in urine from renal transplant subjects by mass spectrometry. *Clin. Proteom.* 9 (1), 4. doi:10.1186/1559-0275-9-4

Kononenko, N., Nikonenko, V., Grande, D., Larchet, C., Dammak, L., Fomenko, M., et al. (2017). Porous structure of ion exchange membranes investigated by various techniques. *Adv. Colloid Interface Sci.* 246, 196–216. doi:10.1016/j.cis.2017.05.007

Krähenbühl, M., Etter, B., and Udert, K. M. (2016). Pretreated magnesite as a source of low-cost magnesium for producing struvite from urine in Nepal. *Sci. Total Environ.* 542, 1155–1161. doi:10.1016/j.scitotenv.2015.08.060

Lahr, R. H., Goetsch, H. E., Haig, S. J., Noe-Hays, A., Love, N. G., Aga, D. S., et al. (2016). Urine bacterial community convergence through fertilizer production: Storage, pasteurization, and struvite precipitation. *Environ. Sci. Technol.* 50 (21), 11619–11626. doi:10.1021/acs.est.6b02094

Lameiras, S., Quintelas, C., and Tavares, T. (2008). Biosorption of Cr (VI) using a bacterial biofilm supported on granular activated carbon and on zeolite. *Bioresour. Technol.* 99, 801–806. doi:10.1016/j.biortech.2007.01.040

Larsen, T. A., and Gujer, W. (1996). Separate management of anthropogenic nutrient solutions (human urine). *Water Sci. Technol.* 34 (3-4), 87–94. doi:10.2166/wst.1996.0420

Larsen, T. A., Hoffmann, S., Luthi, C., Truffer, B., and Maurer, M. (2016). Emerging solutions to the water challenges of an urbanizing world. *Science* 352 (6288), 928–933. doi:10.1126/science.aad8641

Le Corre, K. S., Valsami-Jones, E., Hobbs, P., Jefferson, B., and Parsons, S. A. (2007). Agglomeration of struvite crystals. *Water Res.* 41 (2), 419–425. doi:10.1016/j.watres.2006.10.025

Leung, S., Barrington, S., Wan, Y., Zhao, X., and El-Husseini, B. (2007). Zeolite (clinoptilolite) as feed additive to reduce manure mineral content. *Bioresour. Technol.* 98 (17), 3309–3316. doi:10.1016/j.biortech.2006.07.010

Li, J., Xu, K., Liu, T., Bai, G., Liu, Y., Wang, C., et al. (2020). Achieving stable partial nitritation in an acidic nitrifying bioreactor. *Environ. Sci. Technol.* 54, 456–463. doi:10.1021/acs.est.9b04400

Li, M., Wang, B., Li, L., Wong, G., Liu, Y., Ma, J., et al. (2019a). Rift Valley fever virus and yellow fever virus in urine: A potential source of infection. *Virol. Sin.* 34 (3), 342–345. doi:10.1007/s12250-019-00096-2

Li, P., Chen, L., Ding, Y., Tian, X., Guan, D., Zhang, Z., et al. (2019b). Phosphorus recovery from urine using cooling water system effluent as a precipitant. *J. Environ. Manag.* 244, 391–398. doi:10.1016/j.jenvman.2019.05.057

Li, Z., Zhang, R., and Sun, P. (2022). Simultaneous removal of phosphate and antibiotic from hydrolyzed urine by novel spherical particles. *Chemosphere* 300, 134637. doi:10.1016/j.chemosphere.2022.134637

Liao, J. C., Mastali, M., Gau, V., Suchard, M. A., Moller, A. K., Bruckner, D. A., et al. (2006). Use of electrochemical DNA biosensors for rapid molecular identification of uropathogens in clinical urine specimens. *J. Clin. Microbiol.* 44 (2), 561–570. doi:10.1128/JCM.44.2.561-570.2006

Lin, K. A., Chen, S., and Jochems, A. P. (2015). Zirconium-based metal organic frameworks: Highly selective adsorbents for removal of phosphate from water and urine. *Mater. Chem. Phys.* 160, 168–176. doi:10.1016/j.matchemphys.2015.04.021

Lind, B. B., Ban, Z., and Byden, S. (2000). Nutrient recovery from human urine by struvite crystallization with ammonia adsorption on zeolite and wollastonite. *Bioresour. Technol.* 73 (2), 169–174. doi:10.1016/S0960-8524(99)90157-8

Lind, B. B., Ban, Z., and Byden, S. (2001). Volume reduction and concentration of nutrients in human urine. *Ecol. Eng.* 16 (4), 561–566. doi:10.1016/S0925-8574(00)00107-5

Liu, B., Giannis, A., Zhang, J., Chang, V. W. C., and Wang, J. (2015). Air stripping process for ammonia recovery from source-separated urine: Modeling and optimization. *J. Chem. Technol. Biotechnol.* 90 (12), 2208–2217. doi:10.1002/jctb.4535

Liu, J., Zheng, M., Wang, C., Liang, C., Shen, Z., and Xu, K. (2020). A green method for the simultaneous recovery of phosphate and potassium from hydrolyzed urine as value-added fertilizer using wood waste. *Resour. Conservation Recycl.* 157, 104793. doi:10.1016/j.resconrec.2020.104793

Liu, X., Hu, Z., Zhu, C., Wen, G., Meng, X., and Lu, J. (2013). Influence of process parameters on phosphorus recovery by struvite formation from urine. *Water Sci. Technol.* 68 (11), 2434–2440. doi:10.2166/wst.2013.514

Liu, Y., He, L., Deng, Y., Zhang, Q., Jiang, G., and Liu, H. (2022). Recent progress on the recovery of valuable resources from source-separated urine on-site using electrochemical technologies: A review. *Chem. Eng. J.* 442, 136200. doi:10.1016/j.cej.2022.136200

Liu, Z. G., Zhao, Q. L., Wang, K., Lee, D. J., Qiu, W., and Wang, J. F. (2008). Urea hydrolysis and recovery of nitrogen and phosphorous as MAP from stale human urine. *J. Environ. Sci.* 20 (8), 1018–1024. doi:10.1016/S1001-0742(08)62202-0

Lv, Y., Li, Z., Zhou, X., Cheng, S., and Zheng, L. (2020). Stabilization of source-separated urine by heat-activated peroxydisulfate. *Sci. Total Environ.* 749, 142213. doi:10.1016/j.scitotenv.2020.142213

Madden, K., Janitell, C., Sower, D., and Yang, S. (2018). Prediction of BK viremia by urine viral load in renal transplant patients: An analysis of BK viral load results in paired urine and plasma samples. *Transpl. Infect. Dis.* 20 (5), e12952. doi:10.1111/tid.12952

Makgabutlane, B., Nthunya, L. N., Musyoka, N., Dladla, B. S., Nxumalo, E. N., and Mhlanga, S. D. (2020). Microwave-assisted synthesis of coal fly ash-based zeolites for removal of ammonium from urine. *RSC Adv.* 10 (4), 2416–2427. doi:10.1039/C9RA10114D

Michen, B., and Graule, T. (2010). Isoelectric points of viruses. *J. Appl. Microbiol.* 109 (2), 388–397. doi:10.1111/j.1365-2672.2010.04663.x

Ministry of Industry and Information Technology of the People's Republic of China (2019). *Limitation requirements of toxic and harmful substance in fertilizers*. GB 38400-2019).

Mitrogiannis, D., Psychoyou, M., Koukouzas, N., Tsoukalas, N., Palles, D., Kamitsos, E., et al. (2018). Phosphate recovery from real fresh urine by Ca(OH)(2) treated natural zeolite. *Chem. Eng. J.* 347, 618–630. doi:10.1016/j.cej.2018.04.102

Mnkeni, P. N. S., Kutu, F. R., Muchaonyerwa, P., and Austin, L. M. (2008). Evaluation of human urine as a source of nutrients for selected vegetables and maize under tunnel house conditions in the Eastern Cape, South Africa. *Waste Manag. Res.* 26 (2), 132–139. doi:10.1177/0734242x07079179

Moharramzadeh, S., Ong, S. K., Alleman, J., and Cetin, K. S. (2022). Stabilization and concentration of nitrogen in synthetic urine with peracetic acid and progressive freeze concentration. *J. Environ. Chem. Eng.* 10, 107768. doi:10.1016/j.jece.2022.107768

Morales, N., Boehler, M. A., Buettner, S., Liebi, C., and Siegrist, H. (2013). Recovery of N and P from urine by struvite precipitation followed by combined stripping with digester sludge liquid at full scale. *Water* 5 (3), 1262–1278. doi:10.3390/w5031262

Muhmood, A., Lu, J., Kadam, R., Dong, R., Guo, J., and Wu, S. (2019). Biochar seeding promotes struvite formation, but accelerates heavy metal accumulation. *Sci. Total Environ.* 652, 623–632. doi:10.1016/j.scitotenv.2018.10.302

Muhmood, A., Wu, S., Lu, J., Ajmal, Z., Luo, H., and Dong, R. (2018). Nutrient recovery from anaerobically digested chicken slurry via struvite: Performance optimization and interactions with heavy metals and pathogens. *Sci. Total Environ.* 635, 1–9. doi:10.1016/j.scitotenv.2018.04.129

Musso, D., Teissier, A., Rouault, E., Teururai, S., de Pina, J. J., and Nhan, T. X. (2016). Detection of chikungunya virus in saliva and urine. *Virol. J.* 13, 102. doi:10.1186/s12985-016-0556-9

Nomoto, H., Ishikane, M., Katagiri, D., Kinoshita, N., Nagashima, M., Sadamasu, K., et al. (2020). Handheld ultrasound devices: An emerging technology to reduce viral spread during the Covid-19 pandemic. *Am. J. Infect. Control* 48 (8), 968–969. doi:10.1016/j.ajic.2020.05.041

Nordin, A., Niwagaba, C., Jonsson, H., and Vinnerås, B. (2013). Pathogen and indicator inactivation in source-separated human urine heated by the sun. *J. Water Sanit. Hyg. De.* 3 (2), 181–188. doi:10.2166/washdev.2013.174

Nordin, A., Nyberg, K., and Vinnerås, B. (2009). Inactivation of Ascaris eggs in source-separated urine and feces by ammonia at ambient temperatures. *Appl. Environ. Microbiol.* 75 (3), 662–667. doi:10.1128/AEM.01250-08

Novazzi, F., Cassaniti, I., Piralla, A., Di Sabatino, A., Bruno, R., Baldanti, F., et al. (2020). Detection of the SARS-CoV-2 in different biologic specimens from positive patients with COVID-19, in Northern Italy. *Pediatr. Allergy Immunol.* 31 (S26), 72–74. doi:10.1111/pai.13366

O'Neal, J. A., and Boyer, T. H. (2013). Phosphate recovery using hybrid anion exchange: Applications to source-separated urine and combined wastewater streams. *Water Res.* 47 (14), 5003–5017. doi:10.1016/j.watres.2013.05.037

O'Neal, J. A., and Boyer, T. H. (2015). Phosphorus recovery from urine and anaerobic digester filtrate: Comparison of adsorption–precipitation with direct precipitation. *Environ. Sci. Water Res. Technol.* 1 (4), 481–492. doi:10.1039/C5EW00009B

Oishi, W., Kato, I., Hijikata, N., Ushijima, K., Ito, R., Funamizu, N., et al. (2020). Inactivation kinetics modeling of *Escherichia coli* in concentrated urine for implementing predictive environmental microbiology in sanitation safety planning. *J. Environ. Manag.* 268, 110672. doi:10.1016/j.jenvman.2020.110672

Olanrewaju, A. O., Ng, A., DeCorwin-Martin, P., Robillard, A., and Juncker, D. (2017). Microfluidic capillaric circuit for rapid and facile bacteria detection. *Anal. Chem.* 89 (12), 6846–6853. doi:10.1021/acs.analchem.7b01315

Oztekin, E., Colak, S., and Inan, H. (2022). Comparison of classic and chemometric methods used for phosphate removal from fresh human urine under optimum conditions. *Water sa.* 48 (3), 286–294. doi:10.17159/wsa/2022.v48.i3.3933

Pang, X. L., Martin, K., and Preiksaitis, J. K. (2008). The use of unprocessed urine samples for detecting and monitoring BK viruses in renal transplant recipients by a quantitative real-time PCR assay. *J. Virological Methods* 149 (1), 118–122. doi:10.1016/j.jviromet.2007.12.015

Patel, A., Mungray, A. A., and Mungray, A. K. (2020). Technologies for the recovery of nutrients, water and energy from human urine: A review. *Chemosphere* 259, 127372. doi:10.1016/j.chemosphere.2020.127372

Perez-Mercado, L. F., Lalander, C., Joel, A., Ottoson, J., Dalahmeh, S., and Vinnerås, B. (2019). Biochar filters as an on-farm treatment to reduce pathogens when irrigating with wastewater-polluted sources. *J. Environ. Manag.* 248, 109295. doi:10.1016/j.jenvman.2019.109295

Perry, S. F. (1998). Freeze-drying and cryopreservation of bacteria. *Mol. Biotechnol.* 9, 59–64. doi:10.1007/BF02752697

Pinatha, Y., Polprasert, C., and Englande, Jr. (2020). Product and cost perspectives of phosphorus recovery from human urine using solid waste ash and sea salt addition - a case of Thailand. *Sci. Total Environ.* 713 (136514), 136514. doi:10.1016/j.scitotenv.2020.136514

Pocock, J., Muzhingi, A., Mercer, E., Velkushnova, K., Septien, S., and Buckley, C. A. (2022). Water and nutrient recovery from stored urine by forward osmosis with an ammonium bicarbonate draw solution. *Front. Environ. Sci.* 10, 937456. doi:10.3389/fenvs.2022.937456

Pradhan, S. K., Holopainen, J. K., and Heinonen-Tanski, H. (2009). Stored human urine supplemented with wood ash as fertilizer in tomato (Solanum lycopersicum) cultivation and its impacts on fruit yield and quality. *J. Agric. Food Chem.* 57 (16), 7612–7617. doi:10.1021/jf9018917

Pradhan, S. K., Holopainen, J. K., Weisell, J., and Heinonen-Tanski, H. (2010a). Human urine and wood ash as plant nutrients for red beet (Beta vulgaris) cultivation: Impacts on yield quality. *J. Agric. Food Chem.* 58 (3), 2034–2039. doi:10.1021/jf9029157

Pradhan, S. K., Mikola, A., Heinonen-Tanski, H., and Vahala, R. (2019). Recovery of nitrogen and phosphorus from human urine using membrane and precipitation process. *J. Environ. Manag.* 247, 596–602. doi:10.1016/j.jenvman.2019.06.046

Pradhan, S. K., Mikola, A., and Vahala, R. (2017). Nitrogen and phosphorus harvesting from human urine using a stripping, absorption, and precipitation Process. *Environ. Sci. Technol.* 51 (9), 5165–5171. doi:10.1021/acs.est.6b05402

Pradhan, S. K., Nerg, A., Sjoeblom, A., Holopainen, J. K., and Heinonen-Tanski, H. (2007). Use of human urine fertilizer in cultivation of cabbage (*Brassica oleracea*)- Impacts on chemical, microbial, and flavor quality. *J. Agric. Food Chem.* 55 (21), 8657–8663. doi:10.1021/JF0717891

Pradhan, S. K., Pitkanen, S., and Heinonen-Tanski, H. (2010b). Fertilizer value of urine in pumpkin (Cucurbita maxima L.) cultivation. *AFSci.* 19 (1), 57–67. doi:10.2137/145960610791015032

Pronk, W., Biebow, M., and Boller, M. (2006). Electrodialysis for recovering salts from a urine solution containing micropollutants. *Environ. Sci. Technol.* 40 (7), 2414–2420. doi:10.1021/es051921i

Prusty, B. K., Kumar, A., Arora, R., Batra, S., and Das, B. C. (2005). Human papillomavirus (HPV) DNA detection in self-collected urine. *Int. J. Gynecol. Obstetrics* 90 (3), 223–227. doi:10.1016/j.ijgo.2005.06.004

Qiao, L., Chen, S., Yang, Y., Zhang, K., Zheng, B., Guo, H., et al. (2013). Characteristics of urinary tract infection pathogens and their *in vitro* susceptibility to antimicrobial agents in China: Data from a multicenter study. *Bmj Open* 3 (12), e004152. doi:10.1136/bmjopen-2013-004152

Qiao, L. D., Chen, S., Yang, Y., Zhang, K., Zheng, B., Guo, H. F., et al. (2013). Characteristics of urinary tract infection pathogens and their *in vitro* susceptibility to antimicrobial agents in China: Data from a multicenter study. *BMJ Open* 3 (12), e004152. doi:10.1136/bmjopen-2013-004152

Rahbar, M., Amiri, M., Poormand, G., Poortahmasebi, V., Karkhaneh, M. M., Jazayeri, A., et al. (2019). Simultaneous detection of opportunistic viral infections among renal transplant patients from Sina Hospital, Tehran. *Future Virol.* 14 (6), 419–426. doi:10.2217/fvl-2018-0192

Randall, D. G., Krahenbuhl, M., Kopping, I., Larsen, T. A., and Udert, K. M. (2016). A novel approach for stabilizing fresh urine by calcium hydroxide addition. *Water Res.* 95, 361–369. doi:10.1016/j.watres.2016.03.007

Randall, D. G., and Nathoo, J. (2018). Resource recovery by freezing: A thermodynamic comparison between a reverse osmosis brine, seawater and stored urine. *J. Water Process Eng.* 26, 242–249. doi:10.1016/j.jwpe.2018.10.020

Ray, H., Perreault, F., and Boyer, T. H. (2020b). Ammonia recovery from hydrolyzed human urine by forward osmosis with acidified draw solution. *Environ. Sci. Technol.* 54 (18), 11556–11565. doi:10.1021/acs.est.0c02751

Ray, H., Perreault, F., and Boyer, T. H. (2020a). Rejection of nitrogen species in real fresh and hydrolyzed human urine by reverse osmosis and nanofiltration. *J. Environ. Chem. Eng.* 8, 103993. doi:10.1016/j.jece.2020.103993

Ray, H., Perreault, F., and Boyer, T. H. (2019). Urea recovery from fresh human urine by forward osmosis and membrane distillation (FO-MD). *Environ. Sci. Water Res. Technol.* 5 (11), 1993–2003. doi:10.1039/c9ew00720b

Regmi, U., and Boyer, T. H. (2020). Ammonium and potassium removal from undiluted and diluted hydrolyzed urine using natural zeolites. *Chemosphere* 268, 128849. doi:10.1016/j.chemosphere.2020.128849

Ronteltap, M., Maurer, M., and Gujer, W. (2007). Struvite precipitation thermodynamics in source-separated urine. *Water Res.* 41 (5), 977–984. doi:10.1016/j.watres.2006.11.046

Ronteltap, M., Maurer, M., Hausherr, R., and Gujer, W. (2010). Struvite precipitation from urine - influencing factors on particle size. *Water Res.* 44 (6), 2038–2046. doi:10.1016/j.watres.2009.12.015

Rose, D. P. (1966). Excretion of xanthurenic acid in the urine of women taking progestogen-oestrogen preparations. *Nature* 210 (5032), 196–197. doi:10.1038/210196a0

Sabin, J. M., Leverenz, H., and Bischel, H. N. (2022). Microbial fuel cell treatment energy-offset for fertilizer production from human urine. *Chemosphere* 294 (133594), 133594. doi:10.1016/j.chemosphere.2022.133594

Saetta, D., Zheng, C., Leyva, C., and Boyer, T. H. (2020). Impact of acetic acid addition on nitrogen speciation and bacterial communities during urine collection and storage. *Sci. Total Environ.* 745, 141010. doi:10.1016/j.scitotenv.2020.141010

Salar-Garcia, M. J., Ortiz-Martinez, V. M., Gajda, I., Greenman, J., Hernandez-Fernandez, F. J., and Ieropoulos, I. A. (2017). Electricity production from human urine in ceramic microbial fuel cells with alternative non-fluorinated polymer binders for cathode construction. *Sep. Purif. Technol.* 187, 436–442. doi:10.1016/j.seppur.2017.06.025

Saliu, T. D., Ali, J., Ololade, I. A., and Oladoja, N. A. (2020). Preparation and characterization of a decentralized modular yellow water nutrient recovery system. *J. Environ. Manag.* 276, 111345. doi:10.1016/j.jenvman.2020.111345

Sánchez, G., and Bosch, A. (2016). "Survival of enteric viruses in the environment and food," in *Viruses in foods*. *Viruses in foods*. Editors S. M. Goyal and J. L. Cannon. 2nd ed (Springer), 367–392.

Sanin, F. D., Vesilind, P. A., and Martel, C. J. (1994). Pathogen reduction capabilities of freeze/thaw sludge conditioning. *Water Res.* 28 (11), 2393–2398. doi:10.1016/0043-1354(94)90055-8

Schmidt, J., and Alleman, J. (2005). Urine processing for water recovery via freeze concentration. *Trans. J. Aerosp.* 114 (1), 2005–013032. doi:10.4271/2005-01-3032

Schonning, C., Leeming, R., and Stenstrom, T. A. (2002). Faecal contamination of source-separated human urine based on the content of faecal sterols. *Water Res.* 36 (8), 1965–1972. doi:10.1016/S0043-1354(01)00427-4

Schonning, C. (2001). *Urine diversion – hygienic risks and microbial guidelines for reuse*.

Scutari, R., Piermatteo, L., Ciancio Manuelli, M., Iannetta, M., Salpini, R., Bertoli, A., et al. (2020). Long-term SARS-CoV-2 infection associated with viral dissemination in different body fluids including bile in two patients with acute cholecystitis. *Life* 10 (11), 302. doi:10.3390/life10110302

Senecal, J., Nordin, A., Simha, P., and Vinnerås, B. (2018). Hygiene aspect of treating human urine by alkaline dehydration. *Water Res.* 144, 474–481. doi:10.1016/j.watres.2018.07.030

Senecal, J., and Vinnerås, B. (2017). Urea stabilisation and concentration for urine-diverting dry toilets: Urine dehydration in ash. *Sci. Total Environ.* 586, 650–657. doi:10.1016/j.scitotenv.2017.02.038

Sherbet, G. V., and Lakshmi, M. S. (1973). Characterisation of *Escherichia coli* cell surface by isoelectric equilibrium analysis. *Biochimica Biophysica Acta - Biomembr.* 298 (1), 50–58. doi:10.1016/0005-2736(73)90008-4

Shigemura, K., Shirakawa, T., Okada, H., Tanaka, K., Kamidono, S., Arakawa, S., et al. (2005). Rapid detection and differentiation of Gram-negative and Gram-positive pathogenic bacteria in urine using TaqMan probe. *Clin. Exper. Med.* 4 (4), 196–201. doi:10.1007/s10238-004-0056-x

Si-Mohamed, A., Goff, J. L., Desire, N., Maylin, S., Glotz, D., and Belec, L. (2006). Detection and quantitation of BK virus DNA by real-time polymerase chain reaction in the LT-ag gene in adult renal transplant recipients. *J. Virological Methods* 131 (1), 21–27. doi:10.1016/j.jviromet.2005.06.025

Simha, P., and Ganesapillai, M. (2017). Ecological sanitation and nutrient recovery from human urine: How far have we come? A review. *Sustain. Environ. Res.* 27 (3), 107–116. doi:10.1016/j.serj.2016.12.001

Simha, P., Karlsson, C., Viskari, E., Malila, R., and Vinneras, B. (2020b). Field testing a pilot-scale system for alkaline dehydration of source-separated human urine: A case study in Finland. *Front. Environ. Sci.* 8 (570637). doi:10.3389/fenvs.2020.570637

Simha, P., Lalander, C., Nordin, A., and Vinnerås, B. (2020a13931). Alkaline dehydration of source -separated fresh human urine: Preliminary insights into using different dehydration temperature and media. *Sci. Total Environ.* 733, 139313. doi:10.1016/j.scitotenv.2020.139313

Simha, P., Senecal, J., Nordin, A., Lalander, C., and Vinnerås, B. (2018). Alkaline dehydration of anion-exchanged human urine: Volume reduction, nutrient recovery and process optimisation. *Water Res.* 142, 325–336. doi:10.1016/j.watres.2018.06.001

Su, L. C., Tian, Y. C., Chang, Y. F., Chou, C., and Lai, C. S. (2014). Rapid detection of urinary polyomavirus BK by heterodyne-based surface plasmon resonance biosensor. *J. Biomed. Opt.* 19 (1), 011013. doi:10.1117/1.JBO.19.1.011013

Sun, J., Zhu, A., Li, H., Zheng, K., Zhuang, Z., Chen, Z., et al. (2020). Isolation of infectious SARS-CoV-2 from urine of a COVID-19 patient. *Emerg. MICROBES Infect.* 9 (1), 991–993. doi:10.1080/22221751.2020.1760144

Sun, P., Li, Y., Meng, T., Zhang, R., Song, M., and Ren, J. (2018). Removal of sulfonamide antibiotics and human metabolite by biochar and biochar/H2O2 in synthetic urine. *Water Res.* 147, 91–100. doi:10.1016/j.watres.2018.09.051

Tao, W., Bayrakdar, A., Wang, Y., and Agyeman, F. (2019). Three-stage treatment for nitrogen and phosphorus recovery from human urine: Hydrolysis, precipitation and vacuum stripping. *J. Environ. Manag.* 249, 109435. doi:10.1016/j.jenvman.2019.109435

Tarpeh, W. A., Barazesh, J. M., Cath, T. Y., and Nelson, K. L. (2018a). Electrochemical stripping to recover nitrogen from source-separated urine. *Environ. Sci. Technol.* 52 (3), 1453–1460. doi:10.1021/acs.est.7b05488

Tarpeh, W. A., Udert, K. M., and Nelson, K. L. (2017). Comparing ion exchange adsorbents for nitrogen recovery from source-separated urine. *Environ. Sci. Technol.* 51 (4), 2373–2381. doi:10.1021/acs.est.6b05816

Tarpeh, W. A., Wald, I., Wiprachtiger, M., and Nelson, K. L. (2018b). Effects of operating and design parameters on ion exchange columns for nutrient recovery from urine. *Environ. Sci. Water Res. Technol.* 4 (6), 828–838. doi:10.1039/c7ew00478h

The European Parliament And Of The Council (2002). *The EU animal by-products regulation*. No. 1774.

Tian, X., Gao, Z., Feng, H., Zhang, Z., Li, J., and Wang, A. (2019). Efficient nutrient recovery/removal from real source-separated urine by coupling vacuum thermal stripping with activated sludge processes. *J. Clean. Prod.* 220, 965–973. doi:10.1016/j.jclepro.2019.02.181

Tidåker, P. (2003). *Life Cycle Assessment of grain production using source-separated human urine and mineral fertilizer*. Uppsala: Department of Agricultural Engineering, Swedish University of Agricultural Sciences.

Tun, L. L., Jeong, D., Jeong, S., Cho, K., Lee, S., and Bae, H. (2016). Dewatering of source-separated human urine for nitrogen recovery by membrane distillation. *J. Membr. Sci.* 512, 13–20. doi:10.1016/j.memsci.2016.04.004

Udert, K. M., Fux, C., Munster, M., Larsen, T. A., Siegrist, H., and Gujer, W. (2003d). Nitrification and autotrophic denitrification of source-separated urine. *Water Sci. Technol.* 48 (1), 119–130. doi:10.2166/wst.2003.0031

Udert, K. M., Larsen, T. A., Biebow, M., and Gujer, W. (2003a). Urea hydrolysis and precipitation dynamics in a urine-collecting system. *Water Res.* 37 (11), 2571–2582. doi:10.1016/S0043-1354(03)00065-4

Udert, K. M., Larsen, T. A., and Gujer, W. (2003b). Biologically induced precipitation in urine-collecting systems. *Water Sci. Technol. Water Supply* 3 (3), 71–78. doi:10.2166/ws.2003.0010

Udert, K. M., Larsen, T. A., and Gujer, W. (2003c). Estimating the precipitation potential in urine-collecting systems. *Water Res.* 37 (11), 2667–2677. doi:10.1016/S0043-1354(03)00071-X

Udert, K. M., and Wächter, M. (2012). Complete nutrient recovery from source-separated urine by nitrification and distillation. *Water Res.* 46 (2), 453–464. doi:10.1016/j.watres.2011.11.020

US Centers For Disease Control And Prevention (2008). *Guideline for disinfection and sterilization in healthcare facilities*. United States.

U. S. Department of Health and Human Services (2012). *Principles of epidemiology in public health practice*. 3rd ed. Atlanta, GA 30333: Centers for Disease Control and Prevention (CDC) Office of Workforce and Career Development, 1–62.

Van den Bossche, D., Cnops, L., and Van Esbroeck, M. (2015). Recovery of dengue virus from urine samples by real-time RT-PCR. *Eur. J. Clin. Microbiol. Infect. Dis.* 34 (7), 1361–1367. doi:10.1007/s10096-015-2359-0

Viancelli, A., Kunz, A., Fongaro, G., Kich, J. D., Barardi, C. R. M., and Suzin, L. (2015). Pathogen inactivation and the chemical removal of phosphorus from swine wastewater. *Water Air Soil Pollut.* 226 (8), 263. doi:10.1007/s11270-015-2476-5

Vinnerås, B., Bolske, G., Wahlstrom, H., and Albihn, A. (2011). Survival of *Mycobacterium tuberculosis* and Mycobacterium bovis in human urine. *Water Sci. Technol.* 63 (6), 1075–1080. doi:10.2166/wst.2011.344

Vinnerås, B., Nordin, A., Niwagaba, C., and Nyberg, K. (2008). Inactivation of bacteria and viruses in human urine depending on temperature and dilution rate. *Water Res.* 42 (15), 4067–4074. doi:10.1016/j.watres.2008.06.014

Vinnerås, B., Palmquist, H., Balmér, P., and Jönsson, H. (2006). The characteristics of household wastewater and biodegradable solid waste-A proposal for new Swedish design values. *Urban Water J.* 3 (1), 3–11. doi:10.1080/15730620600578629

Volpin, F., Chekli, L., Phuntsho, S., Cho, J., Ghaffour, N., Vrouwenvelder, J. S., et al. (2018). Simultaneous phosphorous and nitrogen recovery from source-separated urine: A novel application for fertiliser drawn forward osmosis. *Chemosphere* 203, 482–489. doi:10.1016/j.chemosphere.2018.03.193

Volpin, F., Chekli, L., Phuntsho, S., Ghaffour, N., Vrouwenvelder, J. S., and Shon, H. K. (2019a). Optimisation of a forward osmosis and membrane distillation hybrid system for the treatment of source-separated urine. *Sep. Purif. Technol.* 212, 368–375. doi:10.1016/j.seppur.2018.11.003

Volpin, F., Heo, H., Johir, M. A. H., Cho, J., Phuntsho, S., and Shon, H. K. (2019b). Techno-economic feasibility of recovering phosphorus, nitrogen and water from dilute human urine via forward osmosis. *Water Res.* 150, 47–55. doi:10.1016/j.watres.2018.11.056

Wang, R., Wang, X., Deng, C., Chen, Z., Chen, Y., Feng, X., et al. (2020). Partial nitritation performance and microbial community in sequencing batch biofilm reactor filled with zeolite under organics oppression and its recovery strategy. *Bioresour. Technol.* 305, 123031. doi:10.1016/j.biortech.2020.123031

Wang, Y., Geng, Y., Pan, X., and Sheng, G. (2017). *In situ* utilization of generated electricity for nutrient recovery in urine treatment using a selective electrodialysis membrane bioreactor. *Chem. Eng. Sci.* 171, 451–458. doi:10.1016/j.ces.2017.06.002

Wang, Y., Li, H., and Chen, B. (2016). Pathogen distribution and drug resistance of nephrology patients with urinary tract infections. *Saudi Pharm. J.* 24 (3), 337–340. doi:10.1016/j.jsps.2016.04.013

Wei, S. P., van Rossum, F., van de Pol, G. J., and Winkler, M. H. (2018). Recovery of phosphorus and nitrogen from human urine by struvite precipitation, air stripping and acid scrubbing: A pilot study. *Chemosphere* 212, 1030–1037. doi:10.1016/j.chemosphere.2018.08.154

Wiwanitkit, V. (2016). Urine-based molecular diagnosis of Zika virus. *Int. Urol. Nephrol.* 48 (12), 2023. doi:10.1007/s11255-016-1417-6

Wohlsager, S., Clemens, J., Nguyet, P. T., Rechenburg, A., and Arnold, U. (2010). Urine - a valuable fertilizer with low risk after storage in the tropics. *Water Environ. Res.* 82 (9), 840–847. doi:10.2175/106143010x12609736967125

Wohlsager, S., Clemens, J., Nguyet, P. T., Rechenburg, A., and Arnold, U. (2010). Urine--a valuable fertilizer with low risk after storage in the tropics. *Water Environ. Res.* 82 (9), 840–847. doi:10.2175/106143010x12609736967125

World Health Organization (WHO) (2006). *Guidelines for the safe use of the wastewater, excreta and grey water. Vol 2, Wastewater use in agriculture*. Geneva, Switzerland: WHO.

Wyszogrodzka, G., Marszałek, B., Gil, B., and Dorożyński, P. (2016). Metal-organic frameworks: Mechanisms of antibacterial action and potential applications. *Drug Discov. Today* 21 (6), 1009–1018. doi:10.1016/j.drudis.2016.04.009

Xiao, R., Bai, L., Liu, K., Shi, Y., Minakata, D., Huang, C., et al. (2020). Elucidating sulfate radical-mediated disinfection profiles and mechanisms of *Escherichia coli* and *Enterococcus faecalis* in municipal wastewater. *Water Res.* 173 (115552), 115552. doi:10.1016/j.watres.2020.115552

Xu, D., Zhang, Z., Jin, L., Chu, F., Mao, Y., Wang, H., et al. (2005). Persistent shedding of viable SARS-CoV in urine and stool of SARS patients during the convalescent phase. *Eur. J. Clin. Microbiol. Infect. Dis.* 24 (3), 165–171. doi:10.1007/s10096-005-1299-5

Xu, K., Glanton, V., Johnson, S. R., Beck-Sague, C. O. N. S. U. E. L. O., Bhullar, V., Ccandal, D. H., et al. (1998). Detection of neisseria gonorrhoeae infection by ligase chain reaction testing of urine among adolescent women with and without chlamydia trachomatis infection. *Sex. Transm. Dis.* 25 (10), 533–538. doi:10.1097/00007435-199811000-00007

Xu, K., Li, J., Zheng, M., Zhang, C., Xie, T., and Wang, C. (2015b). The precipitation of magnesium potassium phosphate hexahydrate for P and K recovery from synthetic urine. *Water Res.* 80, 71–79. doi:10.1016/j.watres.2015.05.026

Xu, K., Lin, F., Dou, X., Zheng, M., Tan, W., and Wang, C. (2018). Recovery of ammonium and phosphate from urine as value-added fertilizer using wood waste biochar loaded with magnesium oxides. *J. Clean. Prod.* 187, 205–214. doi:10.1016/j.jclepro.2018.03.206

Xu, K., Qu, D., Zheng, M., Guo, X., and Wang, C. (2019a). Water reduction and nutrient reconcentration of hydrolyzed urine via direct contact membrane distillation: Ammonia loss and its control. *J. Environ. Eng.* 145 (3), 04018144. doi:10.1061/(ASCE)EE.1943-7870.0001496

Xu, K., Wang, C., Liu, H., and Qian, Y. (2011). Simultaneous removal of phosphorus and potassium from synthetic urine through the precipitation of magnesium potassium phosphate hexahydrate. *Chemosphere* 84 (2), 207–212. doi:10.1016/j.chemosphere.2011.04.057

Xu, K., Wang, C., Wang, X., and Qian, Y. (2012). Laboratory experiments on simultaneous removal of K and P from synthetic and real urine for nutrient recycle by crystallization of magnesium-potassium-phosphate-hexahydrate in a draft tube and baffle reactor. *Chemosphere* 88 (2), 219–223. doi:10.1016/j.chemosphere.2012.02.061

Xu, K., Zhang, C., Dou, X., Ma, W., and Wang, C. (2019b). Optimizing the modification of wood waste biochar via metal oxides to remove and recover phosphate from human urine. *Environ. Geochem. Health* 41, 1767–1776. doi:10.1007/s10653-017-9986-6

Xu, K., Zhang, C., Li, J., Cheng, X., and Wang, C. (2017). Removal and recovery of N, P and K from urine via ammonia stripping and precipitations of struvite and struvite-K. *Water Sci. Technol.* 75 (1), 155–164. doi:10.2166/wst.2016.494

Xu, S., Luo, L., He, H., Liu, H., and Cui, L. (2015a). Nitrogen and phosphate recovery from source-separated urine by dosing with magnesite and zeolite. *Pol. J. Environ. Stud.* 24 (5), 2269–2275. doi:10.15244/pjoes/43611

Yam, W. C., Chan, K. H., Chow, K. H., Poon, L. L., Lam, H. Y., Yuen, K. Y., et al. (2005). Clinical evaluation of real-time PCR assays for rapid diagnosis of SARS coronavirus during outbreak and post-epidemic periods. *J. Clin. Virology* 33 (1), 19–24. doi:10.1016/j.jcv.2004.09.029

Yang, D., Zhang, J., Xie, M., Tong, X., Jiang, T., Yu, W., et al. (2022). An integrated hollow fiber membrane contactor and chemical precipitation to recover N, P and K from human urine wastewater. *J. Environ. Chem. Eng.* 10, 107844. doi:10.1016/j.jece.2022.107844

Yang, L., Giannis, A., Chang, V. W. C., Liu, B., Zhang, J., and Wang, J. (2015). Application of hydroponic systems for the treatment of source-separated human urine. *Ecol. Eng.* 81, 182–191. doi:10.1016/j.ecoleng.2015.04.013

Yao, G., Lei, J., Zhang, W., Yu, C., Sun, Z., Zheng, S., et al. (2019). Antimicrobial activity of X zeolite exchanged with Cu2+ and Zn2+ on *Escherichia coli* and *Staphylococcus aureus*. *Environ. Sci. Pollut. Res.* 26 (3), 2782–2793. doi:10.1007/s11356-018-3750-z

Yao, S., Chen, L., Guan, D., Zhang, Z., Tian, X., Wang, A., et al. (2017). On-site nutrient recovery and removal from source-separated urine by phosphorus precipitation and short-cut nitrification-denitrification. *Chemosphere* 175, 210–218. doi:10.1016/j.chemosphere.2017.02.062

Yee, R. A., Alessi, D. S., Ashbolt, N. J., Hao, W., Konhauser, K., and Liu, Y. (2019). Nutrient recovery from source-diverted blackwater: Optimization for enhanced phosphorus recovery and reduced co-precipitation. *J. Clean. Prod.* 235, 417–425. doi:10.1016/j.jclepro.2019.06.191

Yoon, J. G., Yoon, J., Song, J. Y., Yoon, S. Y., Lim, C. S., Seong, H., et al. (2020). Clinical significance of a high SARS-CoV-2 viral load in the Saliva. *J. Korean Med. Sci.* 35 (20), e195. doi:10.3346/jkms.2020.35.e195

You, J., Greenman, J., Melhuish, C., and Ieropoulos, I. (2016). Electricity generation and struvite recovery from human urine using microbial fuel cells. *J. Chem. Technol. Biotechnol.* 91 (3), 647–654. doi:10.1002/jctb.4617

Yu, T., Ma, J. Z., and Li, Q. (2007). Factors affecting ice crystal purity during freeze concentration process for urine treatment. *J. Harbin Inst. Technol.* 14 (5), 593–597.

Yu, Y., Zhang, Z., Wang, Y., Liao, M., Rong, X., Li, B., et al. (2019). Effects of different preservation methods on physicochemical property of marine pathogen Vibrio anguillarum. *J. Ocean. Univ. China* 18 (6), 1417–1426. doi:10.1007/s11802-019-4050-z

Zamora, P., Georgieva, T., Salcedo, I., Elzinga, N., Kuntke, P., and Buisman, C. J. N. (2017). Long-term operation of a pilot-scale reactor for phosphorus recovery as struvite from source-separated urine. *J. Chem. Technol. Biotechnol.* 92 (5), 1035–1045. doi:10.1002/jctb.5079

Zhang, B., Tian, S., and Wu, D. (2022). An integrated strategy for nutrient harvesting from hydrolyzed human urine as high-purity products: Tracking of precipitation transformation and precise regulation. *Sci. Total Environ.* 854, 158721. doi:10.1016/j.scitotenv.2022.158721

Zhang, C., Xu, K., Li, J., Wang, C., and Zheng, M. (2017). Recovery of phosphorus and potassium from source-separated urine using a fluidized bed reactor: Optimization operation and mechanism modeling. *Ind. Eng. Chem. Res.* 56 (11), 3033–3039. doi:10.1021/acs.iecr.6b04819

Zhang, C., Xu, K., Su, F., and Wang, C. (2015). Review on pilot projects of source separation system. *China Water & Wastewater* 31 (2), 28–33.

Zhang, C., Xu, K., Zheng, M., Li, J., and Wang, C. (2018). Factors affecting the crystal size of struvite-K formed in synthetic urine using a stirred reactor. *Ind. Eng. Chem. Res.* 57, 17301–17309. doi:10.1021/acs.iecr.8b03328

Zhang, J., She, Q., Chang, V. W. C., Tang, C. Y., and Webster, R. D. (2014). Mining nutrients (N, K, P) from urban source-separated urine by forward osmosis dewatering. *Environ. Sci. Technol.* 48 (6), 3386–3394. doi:10.1021/es405266d

Zhang, R., Lan, L., and Shi, H. (2021a). Sublethal injury and recovery of *Escherichia coli* O157:H7 after freezing and thawing. *Food control.* 120, 107488. doi:10.1016/j.foodcont.2020.107488

Zhang, R., Yang, Y., Huang, C., Zhao, L., and Sun, P. (2016). Kinetics and modeling of sulfonamide antibiotic degradation in wastewater and human urine by UV/H2O2 and UV/PDS. *Water Res.* 103, 283–292. doi:10.1016/j.watres.2016.07.037

Zhang, X., Gang, D. D., Sun, P., Lian, Q., and Yao, H. (2021b). Goethite dispersed corn straw-derived biochar for phosphate recovery from synthetic urine and its potential as a slow-release fertilizer. *Chemosphere* 262, 127861. doi:10.1016/j.chemosphere.2020.127861

Zhang, Y., Aguila, B., Ma, S., and Zhang, Q. (2020). Comparison of the use of functional porous organic polymer (POP) and natural material zeolite for nitrogen removal and recovery from source-separated urine. *J. Environ. Chem. Eng.* 8, 104296. doi:10.1016/j.jece.2020.104296

Zhang, Y., Li, Z., Zhao, Y., Chen, S., and Mahmood, I. B. (2013). Stabilization of source-separated human urine by chemical oxidation. *Water Sci. Technol.* 67 (9), 1901–1907. doi:10.2166/wst.2013.055

Zhao, Z., Xu, L., Shang, X., and Chen, K. (2013). Water regeneration from human urine by vacuum membrane distillation and analysis of membrane fouling characteristics. *Sep. Purif. Technol.* 118, 369–376. doi:10.1016/j.seppur.2013.07.021

Zheng, M., Xie, T., Li, J. Y., Xu, K., and Wang, C. W. (2018). Biochar as a carrier of struvite precipitation for nitrogen and phosphorus recovery from urine. *J. Environ. Eng.* 144 (10). doi:10.1061/(ASCE)EE.1943-7870.0001450

Zhou, X., Li, Y., Li, Z., Xi, Y., Nazim Uddin, S. M., and Zhang, Y. (2017). Investigation on microbial inactivation and urea decomposition in human urine during thermal storage. *J. Water, Sanit. Hyg. Dev.* 7 (3), 378–386. doi:10.2166/washdev.2017.142

Zhou, X., Li, Y., Li, Z., Xi, Y., Uddin, S. M. N., and Zhang, Y. (2017). Investigation on microbial inactivation and urea decomposition in human urine during thermal storage. *J. Water, Sanitation Hyg. Dev.* 7 (3), 378–386. doi:10.2166/washdev.2017.142

Zhu, N., Zhang, D., Wang, W., Li, X., Yang, B., Song, J., et al. (2020). A novel Coronavirus from patients with pneumonia in China, 2019. *N. Engl. J. Med.* 382 (8), 727–733. doi:10.1056/NEJMoa2001017

Zhu, Z., Liu, Y., Xu, L., Guan, W., Zhang, X., Qi, T., et al. (2015). Extra-pulmonary viral shedding in H7N9 Avian Influenza patients. *J. Clin. Virology* 69, 30–32. doi:10.1016/j.jcv.2015.05.013

Zoellig, H., Fritzsche, C., Morgenroth, E., and Udert, K. M. (2015). Direct electrochemical oxidation of ammonia on graphite as a treatment option for stored source-separated urine. *Water Res.* 69, 284–294. doi:10.1016/j.watres.2014.11.031

Zollig, H., Remmele, A., Morgenroth, E., and Udert, K. M. (2017). Removal rates and energy demand of the electrochemical oxidation of ammonia and organic substances in real stored urine. *Environ. Sci. Water Res. Technol.* 3 (3), 480–491. doi:10.1039/c7ew00014f

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Application of black soldier fly larvae in decentralized treatment of faecal sludge from pit latrines in informal settlements in Kampala city

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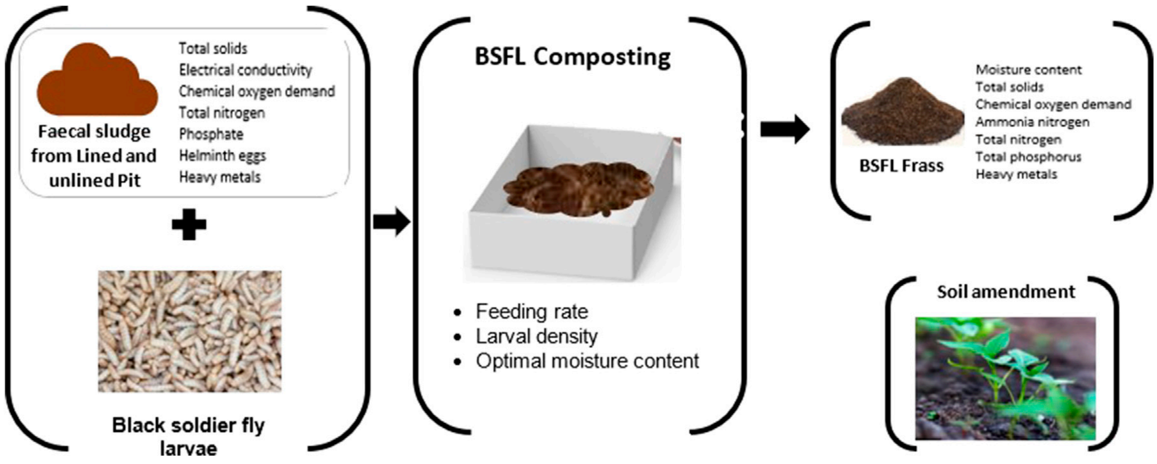
Introduction: Faecal sludge management (FSM) in urban areas of low-and middle-income countries (LMICs) is not properly implemented due to inaccessibility of sanitation facilities and high faecal sludge (FS) emptying costs, amongst others. Unlike in solid waste and fresh human excreta, use of black soldier fly larvae (BSFL) in treatment of FS from pit latrines - which are the most common sanitation facilities in urban areas of LMICs - has not yet been explored. Moreover, the optimal conditions for efficient FS degradation, such as moisture content, feeding rate and larval density are not yet well known. Against this backdrop, the overarching aim of this study was to determine the effectiveness of BSFL in treating FS under different conditions of moisture content, feeding rate and larval density. Also, the quality of residue left after treatment was assessed.

Methods: FS samples were collected from lined and unlined pit latrines in Bwaise I parish in Kampala, Uganda and experiments were set up to feed 10-day old larvae.

Results and Discussion: The optimum feeding rate, larval density and moisture content were found to be 50 mg/larvae/day, 1.33 larvae/cm^2 and 60%, respectively. The reduction efficiency at optimum conditions were 72% and 66% for FS from lined and unlined pit latrines, respectively. It was further noted that BSFL can feed on FS from pit latrines without dewatering it, hence there is no need for a dewatering unit. The properties of the residue left after treatment were within the allowable limit for use as compost except for helminth egg concentration. Thus, in informal urban settlements, BSFL can be applied for effective treatment of FS from pit latrines while generating good quality residue thereby providing an additional value chain in FSM.

KEYWORDS

black solider fly larvae, faecal sludge reduction, informal settlements, pit latrine faecal sludge, black solider fly, faecal sludge treatment, on-site sanitation system



GRAPHICAL ABSTRACT

1 Introduction

Globally, about half of the world's population make use of onsite sanitation systems for their sanitation needs (WHO/UNICEF, 2021). Majority of the urban population in Sub-Saharan Africa (SSA) use pit latrine (a form of onsite sanitation system) as their primary means of excreta disposal. In informal settlements (usually occupied by low-income earners), household pit latrines are mainly shared by a large number of people resulting in high filling rates (Nakagiri et al., 2015; Manga et al., 2022a). However, the management systems in place for the resulting accumulated faecal sludge (FS) are still challenging (Strande, 2014). FS comprises all liquid and semi-liquid contents of on-site sanitation systems, such as pit latrines, aqua privies and septic tanks. It is reported to be 10 to 100 times more concentrated in suspended and dissolved solids than wastewater (Heinss et al., 1998; Manga et al., 2016). FS can also vary in characteristics according to sources such as septic tanks, public toilets containment systems and pit latrines. In most cases, FS in pit latrines is thick and cannot be easily emptied with vacuum trucks (Semiyaga et al., 2022a). When emptied, FS from pit latrines can be treated at designated plants, where preliminary treatment involving removal of large amounts of solid wastes, silt, and the thick FS is often mixed with water (Semiyaga et al., 2022b). In addition, sedimentation in settling thickening tanks separate solid and liquid fractions; treatment of liquid fraction in waste stabilization ponds and drying of solid fractions on the sand bed are carried out (Manga et al., 2016; Manga et al., 2017). However, high emptying and transportation costs which cannot be met by the residents in informal settlements limit the effective management of FS. Consequently, these pit latrines are often opened up to discharge FS into the environment and drainage channels whenever it rains. This poses huge environmental and public health risks to the urban communities (Kulabako et al., 2010).

Application of decentralized (onsite) FS treatment facilities/ systems promotes initiatives which can allow FS to be emptied, treated and used at and/or near the point of generation leading to reduced transportation costs (Semiyaga et al., 2015). Several available options for decentralized treatment of FS such as composting, vermi-composting, anaerobic digestion, rendering have been applied for the treatment of FS (Cofie et al., 2009; Manga et al., 2021; Semiyaga, et al., 2022a; Manga et al., 2022b). However, these techniques have some limitations. For instance, composting is a slow process which may take months if not operated with aeration, turning as well as right environmental conditions (Manga et al., 2019). Vermi-composting has large space requirements and earthworms are usually very sensitive to salt contents in their feedstock (Munroe, 2007). A novel solution for FSM at a decentralized-scale such as the use of black soldier fly larvae (BSFL) could be a viable option under informal settlement conditions. BSF belongs to the family of *Stratiomyidae* and order of *Diptera* and thrives in both tropical and temperate regions worldwide (Singh and Kumari, 2019). The larvae is saprophytic and has powerful digestive enzymes which helps in breaking down various organic wastes (Liu et al., 2019; Cho et al., 2020); under ideal conditions, the larvae can significantly reduce the volume of organic waste by up to 50% or more (Gold et al., 2020). They also produce large quantities of larvae and prepupae which can be used as animal feed source as it is composed of protein and fat as high as 40% and 30%, respectively (Cummins et al., 2017; Nyakeri et al., 2019, Arnone et al., 2022). Also, their excruviae and the residue left after treatment (frass) can be used in the production of organic fertilizer (Webster et al., 2016; Beesigamukama et al., 2021).

Different kinds of organic waste such as pig manure, food waste, municipal waste have been used as substrates for treatment with BSFL and the optimal conditions for their treatment have also been investigated (Diener et al., 2011; Jucker et al., 2017; Manurung et al., 2016; Supriyatna et al., 2016). A few studies have reported treating of FS with BSFL, though these are not based on FS from pit latrines which are the most common sanitation facilities in informal settlements in SSA (Lalander et al., 2013; Nyakeri et al., 2019; Peguero et al., 2021). Pit latrine FS physicochemical and microbiological characteristics differ from other sanitation systems as it contains various types of solid wastes, chemicals for reducing pit content and smell and at times take long to be emptied. Indiscriminate use of different anal cleansing materials by pit latrine users make the FS characteristics from these facilities differ from the many studies done on sludge from septic tanks and fresh faecal matter. Also, some of these studies have been carried out in rural settings (Furlong et al., 2015) and the results cannot be transferred to the urban informal settlements where performance of the sanitation systems are affected by differences in user habits and high number of users. In the study by Furlong et al. (2015) in rural India, it was observed that smaller larvae density (2 kg/m^2) was more efficient in the degradation of organic matter than larger larvae density (4 kg/m^2). In urban slums of Kampala Uganda, the most common sanitation facilities are lined and unlined pit latrines. FS from pit latrines ranges from a slurry, to semi-solid paste (lined pit latrine) and at time a solid sludge (unlined pits) (Jördening and Winter 2005; Velkushanova and Strande, 2021). The unlined pit wall of most of these latrines allow infiltration and exfiltration of moisture. Since FS characteristics are known to influence the performance of BSFL (Diener et al., 2011; Banks et al., 2014), it is imperative that use of BSFL in treatment of FS from both lined and unlined pit latrines is studied. . Also, with the limited research in the use of BSFL for the treatment of FS, optimum conditions for factors such as moisture content, feeding rate and larval density which influence the efficiency of BSFL in treating FS are not yet well known. Specifically, not much is known about the production of BSFL frass from pit latrine FS. Knowledge gaps exist in the nutrient and microbial composition of BSFL frass from FS, its usage and benefits in agriculture and other cultivation related activities. To this end, the overarching aim of this study is to investigate the capacity of BSFL in treating FS from lined and unlined pit latrines in informal settings. Specifically, the study investigated: 1) suitability of FS from lined and unlined pit latrines as feedstock for BSFL; 2) optimal feeding rate, larval density, and moisture content for the treatment of FS with BSFL; 3) quality of the resulting residue and its suitability as organic fertilizer. The results are relevant in designing and implementing scalable and sustainable decentralized systems using BSFL within informal settlements. This can create additional value chain which can generate revenue for the sustenance of faecal sludge management chain in informal settlements.

2 Methodology

2.1 Study area

This study was carried out in Bwaise I Parish located in Kawempe division, Kampala Capital City in Uganda. Bwaise I has about 7,500 households with an average size of five people. The place is characterized by informal settlement patterns with very small plots, barely enough for the construction of both the living house and individual sanitation facilities (KCCA, 2015). This results in the inability of motorized vacuum trucks to access and empty full latrines. Bwaise I was selected based on the fact that residents rely heavily on shared pit latrines as the means of excreta disposal and contains both lined and unlined pit latrines.

2.2 Faecal sludge sampling strategy and preparation

The pit selection was carried out in collaboration with *Terikigana* Sanitation Services, an organization of local pit emptiers based in Kampala. They helped in identifying pit latrines that could be used in the study area. A total of 12 lined and 12 unlined pit latrines were purposively selected. The selection criteria included willingness of the latrine owners to participate in the study; availability of more than one stance per pit latrine so that residents could still access the latrine during periods of sampling; and the latrine facility had to be nearly full to provide sufficiently large quantity of FS content and depth for sampling (minimum sludge depth of 1.5 m). Due to the variation in the construction details of pit latrines and in turn, resulting faecal sludge characteristics, a clear distinction had to be made between lined and unlined pits.

From each pit, a total of four samples were taken from depths of 0.1 m, 0.5 m, 1.0 m and 1.5 m below the sludge surface using a multi-stage sampler reported in Semiyaga et al. (2017). One litre of FS was picked from each depth and collected in a container, where it was thoroughly mixed to obtain a composite sample. The collected composite samples were kept in labelled containers to easily differentiate them during analysis. At this point, the parameters of temperature and pH of the extracted FS were taken using a portable meter (Hach HQ30d flexi model). The samples were then preserved by storing at a temperature of 4°C in a cooling box and transported to the Public Health and Environmental Engineering (PH & EE) laboratory at Makerere University, Kampala Uganda for further analysis. Prior to BSFL experiments, FS samples were screened through a 5 mm sieve to remove extraneous materials such as clothes, pads, polythene bags, condoms, and bottles to remove materials which cannot be fed on by BSFL.

2.3 Collection of black soldier fly larvae

The BSFL used in the experiments were obtained from a colony at a private breeding place in Bombo Sub-County, Luwero district in Central Uganda; this was also the site for the experimental setup. One day old BSF eggs were collected from the colony using cardboards placed inside the BSF cage. The cardboards with the eggs were removed from the BSF cage and placed in a confined area for 3 days to allow the eggs hatch into larvae. The larvae and layer mash (which served as a food source for hatched larvae) were stored for 10 days. The 10-day old larvae were then separated from the feedstocks to be used in the experiments. 10-day old larvae were used in this study after the results of trial experiments showed the larvae to be more efficient in biodegrading FS than 6-day old larvae.

2.4 Characterization of faecal sludge and frass

In order to determine the suitability of FS as feedstock for BSFL as well as the suitability of the frass. he collected FS samples and the frass were analyzed for relevant physicochemical parameter. These parameters include: temperature, total solids (TS), electro-conductivity (EC), chemical oxygen demand (COD), total nitrogen (TN), phosphates, helminth eggs and heavy metals, such as copper (Cu), zinc (Zn), manganese (Mn), chromium (Cr), lead (Pb) and mercury (Hg). The values were compared with literature to examine if they fall within the range suitable for rearing BSFL. Moisture content was analyzed using gravimetric method, where a known mass of FS sample was heated in an oven at 105°C till it attained constant weight. The change in weight was then taken as a fraction of the initial wet sample volume (APHA-AWWWA-WEF, 2012). TS concentration was determined using gravimetric method by weighing an oven dried FS sample at 105°C till constant weight (24 h) and dividing by the measured volume of wet sample, expressed as g/L. Chemical Oxygen Demand (COD) was determined using closed reflux colorimetric method (APHA-AWWWA-WEF, 2012). Ammonium nitrogen (NH_4^+ -N) was determined using titrimetric method,

TABLE 1 Description of feeding rate and larval density used in experiment.

Feeding rate of FS (mg/larvae/day)	25			50			100			200		
Number of larvae (n)	100	200	400	100	200	400	100	200	400	100	200	400
Larval density (Larvae/cm^2)	0.67	1.33	2.67	0.67	1.33	2.67	0.67	1.33	2.67	0.67	1.33	2.67
FS quantity added to each box in (g)	25	50	100	50	100	200	100	200	400	200	400	800

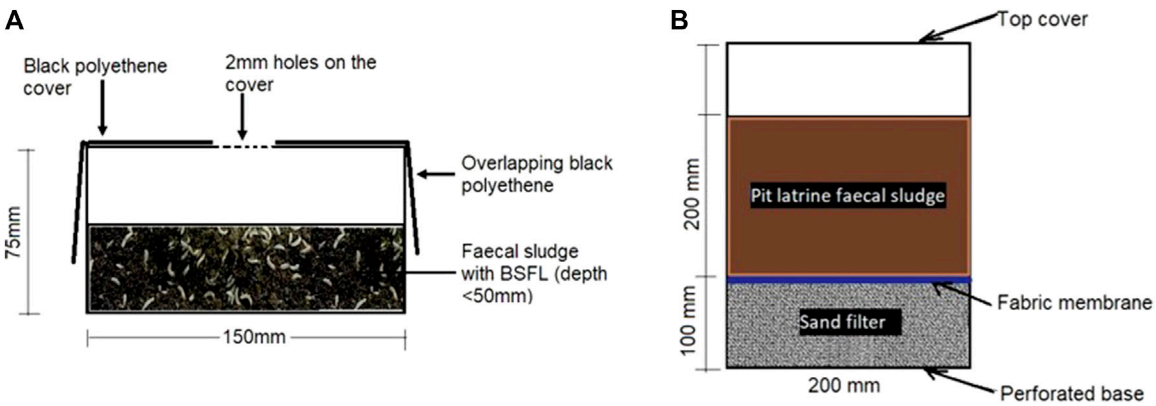


FIGURE 1
Experimental set up for: **(A)** feeding of black soldier fly larvae on faecal sludge from pit latrines; and **(B)** Dewatering of pit latrine faecal sludge using a locally made sand filter.

where samples were preliminarily distilled and then titrated with 0.002 NH_2SO_4 (APHA-AWWWA-WEF, 2012). Total Nitrogen (TN) was determined using Kjeldahl method where the samples was first digested in sulfuric acid (H_2SO_4) at 380 °C, followed by addition of excess sodium hydroxide solution. After this, they were distilled by passing them through boric solution and then back titrated using sodium hydroxide solution (Okalebo et al., 2002). Total phosphorous (TP) was determined using persulfate digestion using ascorbic acid.

Heavy metals (Cu, Mn, Zn, Cd, Cr, Pb, and Hg) were determined by atomic absorption spectroscopy (APHA-AWWWA-WEF, 2012). These metals were selected because they are metals which have the potential to harm soil organisms, plants, and animals through their entry into the food chain. This is due to the fact that the residue left after BSFL treatment can be used as soil conditioner and the prepupae as animal feed. The samples used for determining heavy metals were oven dried for 24 hr at 105°C, ground, sieved through 0.053 µm sieve and then digested with aqua regia solution. The resultant solutions were made to 50 mL by volume and aspirated using atomic absorption spectrophotometer (Agilent MY17180002 200 Series AA).

The number of helminth eggs was determined by examining them microscopically (Moodley et al., 2008). Each species of helminth eggs was enumerated separately and reported as total counts per gram of wet FS but the viability was not examined. Helminth eggs were selected because they are considered a very strong indicators for assessing health risks of BSFL due to their comparably long survival time and difficult elimination. Each parameter was analyzed for in triplicates.

2.5 Optimal feeding rate and larval density for black soldier fly larvae

In determining the optimum feeding rate and larval density, one factor experiments were carried out. The daily feeding rates of 25, 50, 100, and 200 mg/larva and larval density of 0.67, 1.33, and 2.67 larvae/cm^2 were used. These were selected basing on results of previous research (Fatchurochim et al., 1989; Diener et al., 2011; Banks et al., 2014; Nyakeri et al.,. 2019). The required quantity of FS in each container was prepared and measured using a weighing scale with accuracy of 0.1 g. The required quantity of feed to be added was calculated using the daily feeding rates, the number of larvae and a time period of 10 days, long enough to change to prepupae (Table 1). Feeding was carried out only once at the beginning of the experiment, since previous research has shown that feeding BSFL with a single lump amount of biomass leads to larger larvae and prepupae as well as microbial inactivation than feeding incrementally (Banks, et al., 2014; Lopes et al., 2020). In order to determine the impact of using BSFL for treating FS, controls were made for all treatment groups using equal quantities of FS without larvae.

The experiments were conducted in plastic containers of dimension 150 × 100 × 75 mm (Length x width x height) (Figure 1A). The depth of the feedstock in the container was maintained at 50 mm. A black polyethylene bag was placed between the box and lid to prevent oviposition by other flies and aid in darkening the interior container to avoid light interfering with BSFL feeding, since they dislike light. Tiny holes of 2 mm diameter were made on top (through the polyethylene) to allow air circulation. Air circulation is required to keep the waste temperature constant and

TABLE 2 Characteristics of FS from lined and unlined pit latrines in urban slums.

FS parameter	Unit	Lined pit latrine (n = 12)		Unlined pit latrine (n = 12)			Condition suitable for breeding BSFL
		Mean	Standard error	Mean	Standard error	*p*-value	
Temperature	°C	24.0	0.12	23.1	0.1	0.002*	10–40
pH		7.4	0.04	7.8	0.2	0.035*	5.25–8.94
Moisture content	%	90.2	0.15	81.4	0.4	0.000*	40–90
Total solid	g/L	128.6	8.51	344.8	79.4	0.010*	133–480
COD	mg/L	90,667	1244.00	90,400	435	0.844	50,000–150,000
Ammonium nitrogen	mg/L	90.3	0.33	240.0	2.50	0.000*	45–283
Total nitrogen	mg/L	2009	31.00	2746.0	34.0	0.000*	NA
Total phosphate	mg/L	1605	27.00	2063.0	57.0	0.000*	NA
Helminth eggs	No. per g	250	6.00	212.0	8.0	0.000*	NA
Copper	mg/L	84.6	0.53	38.2	0.26	0.000*	NA
Manganese	mg/L	32.3	0.27	37.6	0.32	0.000*	NA
Zinc	mg/L	414.6	3.75	190.8	3.12	0.020*	NA
Cadmium	mg/L	1.2	0.13	1.8	0.11	0.001*	NA
Chromium	mg/L	5.2	0.51	10.2	0.23	0.576	NA
Lead	mg/L	31.6	0.83	32.5	0.85	0.002*	NA
Mercury	mg/L	0.0	0.00	0.1	0.0	0.035*	NA

Note: *significant difference between FS, from lined and unlined pit latrine at $p \leq 0.05$ using independent samples *t*-test.

within the suitable range (25°C–30°C) for effective treatment of FS with BSFL (Pang et al., 2020). The experimental setup was on a raised platform and was protected from rain and direct sunlight using a tarpaulin. The experiment was run and closely monitored under ambient temperature conditions until 50% of the larvae reached prepupae stage, indicated by change of color from white to dark brown (Diener et al., 2011; Banks et al., 2014). The experiments were carried out as one factor experiments wherebt.

To examine the sole effect of degradation by BSFL, control experiments of FS from lined and unlined pit latrines were set up under similar conditions but without BSFL. After the experimental run, the prepupae were separated from the residue and the weight of each residue was measured using a weighing scale. The faecal sludge reduction (FSR) was then computed using Equation 1 (Beesigamukama et al., 2021).

$$\% FSR = \left(\frac{Initial\ weight - Final\ weight}{Initial\ weight}\right) X100 \tag{1}$$

2.6 Determination of optimal moisture content

The highest feeding rate and larval density in the previous experiments (Section 2.5) were subsequently used for determining optimal FS moisture content required by BSFL to efficiently reduce FS. Moisture content (MC) was varied by dewatering FS to 60% moisture content using a prefabricated sand filter. The 60% moisture content dewatered FS was later divided into three samples out of which two samples were rehydrated to 70%, and 80% moisture content. The moisture content ranges were selected based on the results of previous research on the effect of moisture content on BSFL survival, development time, and dry adult weight (Fatchurochim et al., 1989; Banks et al., 2014). To prevent the sand from mixing with FS, two layers of fabric mesh having about 2 mm opening were placed on top of the sand bed to separate FS from the sand (Figure 1B). The filtered water was collected inside a container placed below the filter and disposed of inside pit latrine.

The approach used in this study, *ex-situ* treatment, was preferred to *in situ* treatment (application of BSFL inside pit latrine) system due to the context of the study area. The area has high water table and is prone to flooding which make it very difficult to implement *in situ* treatment of FS by BSFL. Therefore, the study was geared towards reflecting conditions under decentralized FS treatment system, which is the most suitable option for such area, where FS is first emptied using most appropriate technology and then treated with BSFL.

2.8 Data analysis

Data analysis was carried out using Microsoft Excel 2010and Statistical Package for Social Sciences (SPSS) version 25.0 for Windows. Descriptive statistics (means and standard deviation) was used to describe the properties of FS from lined and unlined pit latrines. Independent sample *t*-test was used in investigating the differences in the mean values of the properties of lined and unlined

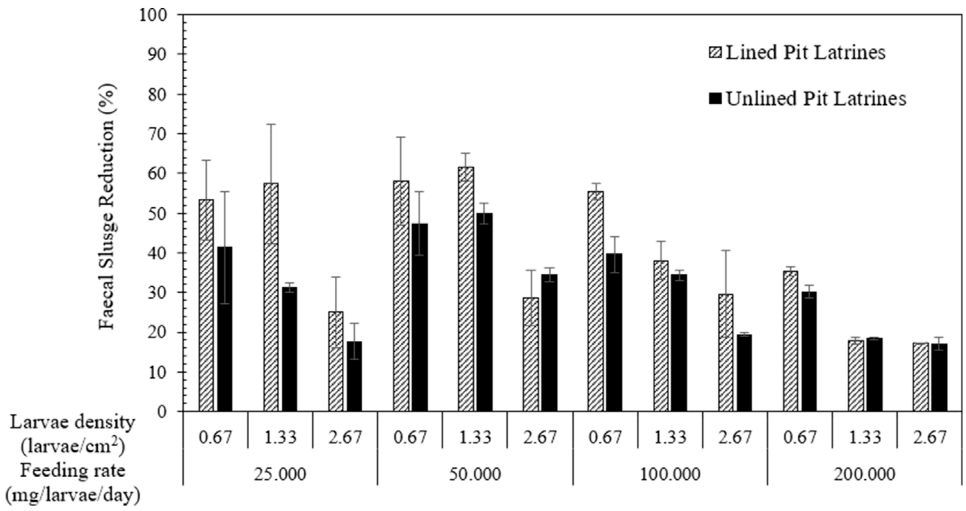


FIGURE 2
Percentage of faecal sludge reduction (FSR) with feeding rate (FR) and larvae density (LD) for FS from lined and unlined pit latrines.

pit latrines. It was also used to assess the differences between the properties of residue from both lined and unlined pit latrines and their corresponding control groups. The confidence interval used was 95%. Before analysis, all data were tested for normality and homogeneity of variance using the Shapiro-Wilk test and Levene's test in SPSS.

3 Results and discussion

3.1 Pit latrine FS characteristics and suitability in breeding BSFL

3.1.1 General pit latrine FS characteristics

The values of measured physico-chemical properties of FS from lined pit latrines are significantly different from those of FS from unlined pit latrines (p <0.05) except for COD (p = 0.844) and chromium (p = 0.576) (Table 2). Generally, the concentrations of heavy metals were higher in FS from unlined than lined pit latrines. However, some elements such as copper and zinc had higher concentration in lined than unlined pit latrines. The results also showed that FS from lined pit latrines had significantly higher helminth eggs per gram than unlined pit latrines.

Generally, the measured characteristics of FS is comparable to those found in previous studies within Kampala (Uganda) and other countries such as South Africa and Ghana (Banks et al., 2014; Chiposa et al., 2017; Semiyaga et al., 2017). However, the measured variation in characteristics between lined and unlined pit latrine FS can be attributed to the differences in the pit design, FS storage duration and toilet usage (Niwagaba et al., 2014). High moisture content from lined pit latrines FS can result from users disposing wastewater and grey water inside the pit latrines (Nakagiri et al., 2015). Unlike in unlined pit latrines, the lined wall of the latrines reduces exfiltration into the surrounding soils and hence wastewater and greywater disposed into the pit contribute to the higher moisture content observed in lined than unlined pit latrines.

The ratio of COD to TS was higher in lined than unlined pit latrines (733 and 262, respectively); hence, FS from lined pits contain more organic matter than FS from unlined pit latrines. This is vital when considering implementation of BSFL in a decentralized FS treatment plant as increase in organic content results in increase in FSR efficiency (Banks et al., 2014). The presence of heavy metals in FS from both lined and unlined latrines could have resulted from contamination due to large quantities of garbage (metallic building materials, cosmetic tins, detergents and paint tins) observed in most of the pit latrines. Studies on FS management in low income areas revealed that users of public toilets dispose solid wastes which contain metal compounds into the pit (Chiposa et al., 2017). High concentration of some metals such as copper and zinc in pit latrines could have also resulted from disposal of wastes which contain petrochemicals, contain cosmetics and leaching from solid waste damping sites since the study area has a lot of uncontrolled solid waste dumping (Tervahauta et al., 2014; Twinomucunguzi et al., 2022). The presence of lead (Pb) in the sludge could be as a result of disposal of materials such as lead-acid batteries, rubber and plastics into the pits (Appiah-Effah et al., 2014). The presence of heavy metals in FS has an impact on the use to which as they can accumulate in the larvae and prepupae of black soldier flies and consequently in the food chain (Attiogbe et al., 2019).

3.1.2 Suitability of pit latrine FS in breeding BSFL

The temperature (23°C–24°C), pH (7–8), TS (128.6–344.8 mg/L), COD (90,400–90,667 mg/L) and ammonia nitrogen (90–240 mg/L) of FS from both lined and unlined pit latrines are within the ranges suitable for effective decomposition by BSFL (temperature, 25°C–30°C (Shumo et al., 2019); pH, 6–10 (Ma et al., 2018); moisture content, 70–80% (Bortolini et al., 2020) (Table 2). These values indicate that FS from both lined and unlined pit latrines can be used to feed BSFL (Popa and Green, 2012; Lalander et al., 2013; Banks et al., 2014). Optimum feeding rate and larval density for FS from lined and unlined pit latrines.

Generally, for FS from both lined and unlined pit latrines, FSR tends to reduce with increase in larvae density (Figure 2). Highest FSR for FS from both lined (62% ± 3.5) and unlined pit latrines (50% ± 2.6) occurred at feeding rate of 50mg/larva/day and density of 1.33larva/cm^2 (Figure 2).

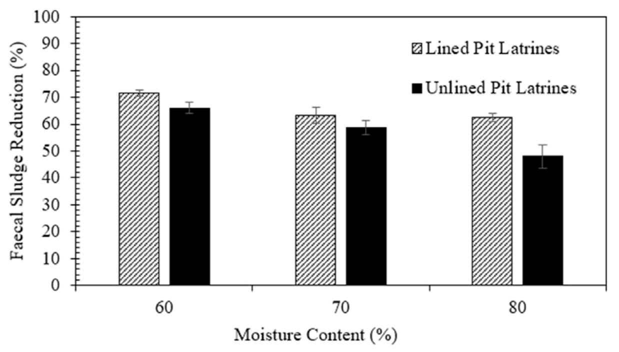


FIGURE 3
Faecal sludge reduction (FSR) ar different moisture content of both lined and unlined pit latrines.

Application of BSFL considerably reduced FS of pit latrines in volumes similar to those reported for other feedstocks: human faeces, 39.1–48.6% (Gold et al., 2020); food waste, 55.3 ± 4.1; fruit and vegetable waste, 46.7–60% (Giannetto et al., 2019). Optimum feeding rate of 50mg/larvae/day obtained in this study corresponds to previous findings by Fatchurochim et al. (1989), Banks et al. (2014) and Attiogbe et al., 2019. However, the highest larvae density of 200 (1.33larva/cm^2) is different from 400 larvae density previously reported by Banks et al. (2014). The results of the study also contradicts with the study of Diener et al. (2009) on reduction of municipal organic wastes using BSFL where 200 larvae density and 6-day old larvae had optimum decomposition at feeding rate of 100mg/larvae/day. Also, the study on dairy manure by Meyers et al. (2008) showed that use of two larvae/cm^2 density and 4-day old larvae at a feeding rate of 90mg/larvae/day resulted in maximum dry matter mass reduction of 58%. The aforementioned results imply that the reduction efficiency of biomass by BSFL depend on the interaction between factors, for example, effect of larval density is dependent on feeding rate (Parra Paz et al., 2015).

The highest FS reduction of 62% and 50% recorded in lined and unlined pit latrines, respectively, is within the range of 39–56% reported for cow manure and 50% for chicken manure (Sheppard et al., 1994; Diener et al., 2009), close to 57.5% reduction recorded by Banks et al. (2014), 65.3% recorded by Attiogbe et al. (2019) and 55.1% recorded by Lalander et al. (2014).

3.2 Moisture content variation and efficiency of BSFL in reducing faecal sludge

Generally, FSR decreased as moisture content increased from 60–80% (Figure 3). Also, at each moisture content, a higher FSR was recorded in FS from lined than unlined pit latrines; however, the differences were only statistically significant at 80% moisture content.

The reduction in FS with increase in moisture content can be attributed to lower evaporation rate for wetter FS. In addition, the fact that low moisture content favors microbial degradation of substrate (FS) to CO_2 resulting in efficient conversion of assimilated substrate into larval biomass (Bekker et al., 2021). The highest FSR was recorded at 60% moisture content in both FS types with reduction of 72 and 66% for lined and unlined pit latrines, respectively. Also, it is noted that even at high moisture content (70–80%), the FSR is still high. This implies that at highest larval density and feeding rate, BSFL can greatly reduce FS over a wider range of moisture due to high FS reduction recorded at both 70% and 80% moisture content in both types of FS (Figure 3). FSR of 50% obtained for FS from lined pit latrines at 90% moisture content when highest larval density and feeding rate is used confirms the ability of BSFL to reduce FS over a wide range of moisture content. This is advantageous in decentralized FSM since it allows FS with wide range of moisture content to be managed by BSFL, reducing the need for the dewatering stage.

The optimum moisture content of 60% obtained in this study is less than the 75% determined in the study by Banks et al. (2014) but is comparable to previous studies by Fatchurochim et al. (1989) where BSFL efficiently decomposed manure at moisture content ranging from 40 to 60%. Similar results were obtained in the studies by Diener et al. (2011) and Myers et al. (2008), where organic waste and chicken manure, respectively, were reduced efficiently at 60% moisture content by BSFL. This suggests that optimum moisture content of 60% obtained in this study is a value that can be applied for the treatment of different kinds of waste by BSFL. This moisture content value is also suitable for processing and quality of residue obtained after treatment with BSFL.

3.3 Characterization of the resulting residue

BSFL application resulted in significant differences (p <0.05) between some of the characteristics of the residue from both lined and unlined pit latrines and their corresponding control groups (Table 3). When FS from both lined and unlined pit latrines are compared to their corresponding control groups, it can be observed that there is significantly lower (p <0.05) COD concentration while ammonia nitrogen, total nitrogen and pH significantly increased (p < 0.05). There are no significant differences in moisture content, total phosphate, and helminth egg concentration between FS from both lined and unlined latrines and their corresponding control groups. However, significant difference (p = 0.000) was observed between the TS concentration in residue for FS from unlined pit latrine and its control group. There were no significant differences observed between the TS concentration in residue from FS for lined pit latrine and its corresponding control group (p = 0.399) (Table 3). Also, there was significant increase in the heavy metal concentration in the residues with BSFL in FS from both latrine types compared to the control, except mercury and lead which showed only significant differences in lined pit latrines (Table 3).

The lower COD levels in the residue when compared to the control can be attributed to the fact that BSFL accelerates decomposition of organic matter. The acceleration may be due to the respiratory action of micro-organisms in the intestine of BSFL as noted by Rehman et al. (2017). Substrates are degraded and homogenized by BSFL through muscular activities leading to surface increases for microbial action and reduction of organic matter (Prakash and Karmegam, 2010). The higher ammonia nitrogen content in the residue can be attributed to the fact that as decomposition occurs, a fraction of organic nitrogen in the influent material is transformed into ammonia. The higher ammonia nitrogen concentration in the residue also implies that the residue has higher fertilizer value than the control (Lalander et al., 2015). BSFL application resulted in significant pH increase (p <0.05) for both lined and unlined latrine FS residues, which is in line

TABLE 3 Characteristics of the residues of faecal sludge from lined and unlined pit latrines after BSFL treatment.

Physiochemical parameters	Unit	Lined pit latrine (n = 12)					Unlined pit latrine (n = 12)					Limit for use in composting
		BSFL present		Control lined			BSFL present		Control unlined			
		Mean	Standard error	Mean	Standard error	*p*-Value	Mean	Standard error	Mean	Standard error	*p*-Value	
Temperature	0C	23.70	0.115	23.27	0.120	0.060	23.03	0.2	23.50	0.115	0.049	–
pH		8.54	0.037	8.10	0.036	0.001	8.43	0.1	8.04	0.042	0.005	6–8.5
Moisture content	%	59.40	0.110	59.55	0.105	0.000	58.67	0.9	58.77	0.419	0.893	40–60
Total solid	g/g	0.497	0.0	0.697	0.0	0.399	0.539	0.0	0.853	0.0	0.000	–
COD	mg/g	92.800	0.1	99.967	0.1	0.000	88.433	0.1	96.367	0.2	0.000	>0.400
Ammonium nitrogen	mg/g	0.247	0.0	0.161	0.0	0.000	0.479	0.0	0.348	0.0	0.000	–
Total nitrogen	mg/g	1.799	0.0	1.668	0.0	0.000	1.897	0.0	1.712	0.0	0.000	0.5–4%
Total phosphate	mg/g	2.138	0.1	2.183	0.1	0.497	2.205	0.0	2.203	0.0	0.828	0.5–1.5%
Helminth eggs	No. per g	27	3	16	2	0.060	22	1.0	23	0.6	0.126	1
Copper	mg/g	0.153	0.0	0.118	0.0	0.000	0.050	0.0	0.081	0.0	0.001	0.070–0.600
Manganese	mg/g	0.425	0.0	0.493	0.0	0.000	0.409	0.0	0.453	0.0	0.001	
Zinc	mg/g	0.337	0.0	0.538	0.0	0.000	0.250	0.0	0.186	0.0	0.000	0.210–4.000
Cadmium	mg/g	0.003	0.0	0.002	0.0	0.001	0.001	0.0	0.002	0.0	0.008	0.000–0.010
Chromium	mg/g	0.032	0.0	0.028	0.0	0.026	0.036	0.0	0.035	0.0	0.009	0.070–0.200
Lead	mg/g	0.051	0.0	0.034	0.0	0.001	0.042	0.0	0.043	0.0	0.802	0.070–1.000
Mercury	mg/g	0.000	0.0	0.000	0.0	0.477	0.000	0.0	0.000	0.0	0.349	0.000–0.010

Note: significant difference between FS, from lined and unlined pit latrine and their corresponding control groups occur at $p \leq 0.05$ using independent samples *t*-test.

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with previous studies (Popa and Green, 2012; Lalander et al., 2013; Banks et al., 2014). The increase in pH for the residue can be explained by the fact that ammonia is produced from organic nitrogen during decomposition while in the liquid, ammonia acquires hydrogen ions from the water to produce hydroxide and ammonium ions; the hydroxide ions leads to increase in pH (Lalander et al., 2014). In addition, it was noted that there was no significant reduction in the amount of helminth eggs in the residue with and without BSFL. A similar finding was also reported by Lalander et al. (2014) who noted that BSFL did not have impact on reduction of helminths egg content. However, BSFL has been reported to be effective in removing *E. coli* and *salmonella* (Siddiqui et al., 2022). Since the persistence of helminth eggs presents high risk to workers using the residue, there is need for further treatment of residue prior to use.

In relation to the application of the residue as compost in agriculture, all the characteristics of the residue are within the acceptable limit, except for helminth eggs. Based on WHO guideline, the viable helminth eggs content of the finished compost product must not exceed 1 egg count per gram (WHO, 2006), but this study registered exceedingly 27 and 22 counts per gram for FS residue from lined and unlined pit latrines, respectively. In addition, the pH of the residue (8.34–8.54) is within the range suitable for optimum plant growth (7.0–8.5) (Surendra et al., 2020). This implies that the residue requires further treatment before application in agriculture.

4 Conclusion

This study has shown that BSFL can reduce FS volume from both lined and unlined pit latrines by about 60–72% under best conditions. This implies that BSFL can be used in effectively treating FS from pit latrines irrespective of lining conditions. In addition, the high removal efficiency means that it can be incorporated with other less biodegradable feedstock (i.e., brewery waste) for co-digestion by BSFL to achieve stable decomposition.

From this study, it was noted that under best conditions, FS from pit latrine with moisture content as high as 90% can be effectively treated with BSFL; reduction efficiency of 50% was obtained in the study. This indicates that BSFL can be applied in the treatment of FS from informal settlements without need for a prior dewatering step. This reduces the cost associated with processing and treatment of FS and this extra cost can be applied to other parts of faecal sludge management chain.

The properties of the residue obtained in this study shows the suitability for application as compost in agricultural fields. Also, the results of the study show that the residue contains micronutrients (zinc and copper) which are either non detected or in small amount for organic compost. Thus, addition of the residue to agricultural fields will supply the soil with micronutrients needed for its physiological and metabolic processes.

This study showed that employing BSFL for FS treatment can significantly reduce the FS volume and also produce residue of good quality. Hence, the BSFL can be used as a high-efficiency transformation agent for converting FS into stable compost especially in developing countries, where adopting technical devices for composting can be expensive and difficult to manipulate. However, there are still some unanswered questions which provide basis for future research in the following areas:

- There is need for more studies to determine how the age of larvae influences its ability to effectively decompose FS.
- The highest dose of residue to be applied to the soil needs to be determined as excess application can have adverse effect on plants.
- Since the residue odour may adversely affect its use, there is a need to investigate the odour control methods in the BSF treatment process.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

RT: Conceptualization; methodology; formal analysis; investigation; resources; writing-original draft preparation; visualization; SS: Conceptualization; methodology; formal analysis; investigation; resources; writing-original draft preparation; visualization; and supervisiosn. CN: Formal analysis; investigation; writing-review and editing; visualization; and supervision. AN: Formal analysis; investigation; writing-review and editing; visualization. JS: Formal Analysis; investigation; writing-review and editing; visualization. CM: Formal analysis; investigation; writing-review and editing; visualization. MM: Conceptualization; Methodology; Investigation; Resources; Formal Analysis; Writing-Review and Editing and Supervision. All authors read and approved the final manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

APHA-AWWWA-WEF (2012). *Standards Methods for the examination of water and wastewater, 20th Edition*. Washington D.C., USA: American Public Health Association, American Water Works Association, and Water and Environment Federation Publication. ISBN 0-87553-047-8.

Appiah-Effah, E., Nyarko, K. B., Gyasi, S. F., and Awuah, E. (2014). Faecal sludge management in low income areas: A case study of three districts in the ashanti region of Ghana. *J. Water Sanit. Hyg. Dev.* 4, 189–199. doi:10.2166/washdev.2014.126

Attiogbe, F. K., Ayim, N. Y. K., and Martey, J. (2019). Effectiveness of black soldier fly larvae in composting mercury contaminated organic waste. *Sci. Afr.* 6, e00205. doi:10.1016/j.sciaf.2019.e00205

Banks, I. J., Gibson, W. T., and Cameron, M. M. (2014). Growth rates of black soldier fly larvae fed on fresh human faeces and their implication for improving sanitation. *Trop. Med. Int. Health* 19 (1), 14–22. doi:10.1111/tmi.12228

Beesigamukama, D., Mochoge, B., Korir, N. K., Fiaboe, K., Nakimbugwe, D., Khamis, F. M., et al. (2021). Low-cost technology for recycling agro-industrial waste into nutrient-rich organic fertilizer using black soldier fly. *Waste Manag.* 119, 183–194. doi:10.1016/j.wasman.2020.09.043

Bekker, N. S., Heidelbach, S., Vestergaard, S. Z., Nielsen, M. E., Riisgaard-Jensen, M., Zeuner, E. J., et al. (2021). Impact of substrate moisture content on growth and metabolic performance of black soldier fly larvae. *Waste Manag.* 127, 73–79. doi:10.1016/j.wasman.2021.04.028

Bortolini, S., Macavei, L. I., Saadoun, J. H., Foca, G., Ulrici, A., Bernini, F., et al. (2020). Hermetia illucens (L.) larvae as chicken manure management tool for circular economy. *J. Clean. Prod.* 262, 121289. doi:10.1016/j.jclepro.2020.121289

Chiposa, R., Holm, R. H., Munthali, C., Chidya, R. C., and de los Reyes, F. L., III (2017). Characterization of pit latrines to support the design and selection of emptying tools in peri-urban Mzuzu, Malawi. *J. Water, Sanitation Hyg. Dev.* 7 (1), 151–155. doi:10.2166/washdev.2017.096

Cho, S., Kim, C. H., Kim, M. J., and Chung, H. (2020). Effects of microplastics and salinity on food waste processing by black soldier fly (Hermetia illucens) larvae. *J. Ecol. Environ.* 44 (1), 7–9. doi:10.1186/s41610-020-0148-x

Cofie, O., Kone, D., Rothenberger, S., Moser, D., and Zubruegg, C. (2009). Co-composting of faecal sludge and organic solid waste for agriculture: Process dynamics. *Water Res.* 43 (18), 4665–4675. doi:10.1016/j.watres.2009.07.021

Cummins, V. C., Jr, Rawles, S. D., Thompson, K. R., Velasquez, A., Kobayashi, Y., Hager, J., et al. (2017). Evaluation of black soldier fly (Hermetia illucens) larvae meal as partial or total replacement of marine fish meal in practical diets for Pacific white shrimp (Litopenaeus vannamei). *Aquaculture* 473, 337–344. doi:10.1016/j.aquaculture.2017.02.022

Diener, S., Zurbrügg, C., and Tockner, K. (2009). Conversion of organic material by black soldier fly larvae: Establishing optimal feeding rates. *Waste Manag. Res.* 27 (6), 603–610. doi:10.1177/0734242x09103838

Diener, S., Zurbrügg, C., Gutiérrez, F. R., Nguyen, D. H., Morel, A., Koottatep, T., et al. (2011). Black soldier fly larvae for organic waste treatment-prospects and constraints. *Proc. WasteSafe* 2, 13–15. Available online: https://www.eawag.ch/fileadmin/Domain1/Abteilungen/sandec/publikationen/SWM/BSF/Black_soldier_fly_larvae_for_organic_waste_treatment.pdf (Accessed on 20 October, 2022).

Fatchurochim, S., Geden, C. J., and Axtell, R. C. (1989). Filth by (Diptera) oviposition and larval development in poultry manure of various moisture levels. *J. Entomol. Sci.* 24, 224–231. doi:10.18474/0749-8004-24.2.224

Furlong, C., Gibson, W. T., Templeton, M. R., Taillade, M., Kassam, F., Crabb, G., et al. (2015). The development of an onsite sanitation system based on vermifiltration: The 'tiger toilet. *J. Water, Sanitation Hyg. Dev.* 5 (4), 608–613. doi:10.2166/washdev.2015.167

Giannetto, A., Oliva, S., Ceccon Lanes, C. F., de Araujo Pedron, F., Savastano, D., Baviera, C., et al. (2019). Hermetia illucens (Diptera: Stratiomydae) larvae and prepupae: Biomass production, fatty acid profile and expression of key genes involved in lipid metabolism. *J. Biotechnol.* 307, 44–54. doi:10.1016/j.jbiotec.2019.10.015

Gold, M., Cassar, C. M., Zurbrügg, C., Kreuzer, M., Boulos, S., Diener, S., et al. (2020). Biowaste treatment with black soldier fly larvae: Increasing performance through the formulation of biowastes based on protein and carbohydrates. *Waste Manag.* 102, 319–329. doi:10.1016/j.wasman.2019.10.036

Heinss, U., Larmie, S. A., and Strauss, M. (1998). *Solids separation and pond systems for the treatment of septage and public toilet sludges in tropical climate—lessons learnt and recommendations for preliminary design*. EAWAG/SANDEC Report No. 05/98.

Jördening, H.-J., and Winter, J. (2005). *Environmental biotechnology: Concepts and applications*. Germany: Wiley-VCH Verlag GmbH.

Jucker, C., Erba, D., Leonardi, M. G., Lupi, D., and Savoldelli, S. (2017). Assessment of vegetable and fruit substrates as potential rearing media for hermetia illucens (Diptera: Stratiomyidae) larvae. *Environ. Entomol.* 46, 1415–1423. doi:10.1093/ee/nvx154

KCCA (2015). *Kampala capital city authority (KCCA) strategic plan 2014/15-2018/19*. Available at: https://www.kcca.go.ug/uDocs/KCCA-STRATEGIC-PLAN-2014-19.pdf.

Kulabako, R. N., Nalubega, M., Wozei, E., and Thunvik, R. (2010). Environmental health practices, constraints, and possible interventions in peri-urban settlements in developing countries–a review of Kampala, Uganda. *Int. J. Environ. health Res.* 20 (4), 231–257. doi:10.1080/09603120903545745

Lalander, C., Diener, S., Magri, M. E., Zurbrügg, C., Lindström, A., and Vinnerås, B. (2013). Faecal sludge management with the larvae of the black soldier fly (Hermetia illucens)-from a hygiene aspect. *Sci. total Environ.* 458 (460), 312–318. doi:10.1016/j.scitotenv.2013.04.033

Lalander, C. H., Fidjeland, J., Diener, S., Eriksson, S., and Vinnerås, B. (2014). High waste-to-biomass conversion and efficient Salmonella spp. reduction using black soldier fly for waste recycling. *Agron. Sustain. Dev.* 35, 261–271. doi:10.1007/s13593-014-0235-4

Lalander, C. H., Komakech, A. J., and Vinnerås, B. (2015). Vermicomposting as manure management strategy for urban small-holder animal farms – Kampala case study. *Waste Manag.* 39, 96–103. doi:10.1016/j.wasman.2015.02.009

Liu, C., Wang, C., and Yao, H. (2019). Comprehensive resource utilization of waste using the black soldier fly (hermetia illucens (L.)) (Diptera: Stratiomyidae). *Animals* 9, 349. doi:10.3390/ani9060349

Lopes, I. G., Lalander, C., Vidotti, R. M., and Vinnerås, B. (2020). Reduction of bacteria in relation to feeding regimes when treating aquaculture waste in fly larvae composting. *Front. Microbiol.* 11, 1616. doi:10.3389/fmicb.2020.01616

Ma, J., Lei, Y., Rehman, K. U., Yu, Z., Zhang, J., Li, W., et al. (2018). Dynamic effects of initial pH of substrate on biological growth and metamorphosis of black soldier fly (Diptera: Stratiomyidae). *Environ. Entomol.* 47 (1), 159–165. doi:10.1093/ee/nvx186

Manga, M., Evans, B. E., Camargo-Valero, M. A., and Horan, N. J. (2016). Effect of filter media thickness on the performance of sand drying beds used for faecal sludge management. *Water Sci. Technol.* 74 (12), 2795–2806. doi:10.2166/wst.2016.451

Manga, M., Evans, B., Camargo-Valero, M. A., and Horan, N. (2016). "The Fate of Helminth eggs during the Co-composting of Faecal Sludge with Chicken Feathers and Market waste," in 13th IWA Specialized Conference on Small Water and Wastewater Systems (SWWS) and 5th IWA Specialized Conference on Resources-Oriented Sanitation (ROS), Aegli Zoppiou, Athens—Greece, September 14–16, 2016. Available at: https://eprints.whiterose.ac.uk/132633/

Manga, M. (2017). *The feasibility of Co-composting as an upscale treatment method for faecal sludge in urban Africa*. Leeds, UK: University of Leeds. Available at: http://etheses.whiterose.ac.uk/16997/ (Accessed October 12, 2022).

Manga, M., Camargo-Valero, M. A., and Evans, B. E. (2019). Inactivation of viable Ascaris eggs during faecal sludge co-composting with chicken feathers and market waste. *Desalin. Water Treat.* 163, 347–357. doi:10.5004/dwt.2019.24494

Manga, M., Camargo-Valero, M. A., Anthonj, C., and Evans, B. E. (2021). Fate of faecal pathogen indicators during faecal sludge composting with different bulking agents in tropical climate. *Int. J. Hyg. Environ. Health* 232, 113670. doi:10.1016/j.ijheh.2020.113670

Manga, M., Kolsky, P., Rosenboom, J. W., Ramalingam, S., Sriramajayam, L., Bartram, J., et al. (2022a). Public health performance of sanitation technologies in Tamil nadu, India: Initial perspectives based on E. Coli release. *Int. J. Hyg. Environ. Health* 243, 113987. doi:10.1016/j.ijheh.2022.113987

Manga, M., Evans, B. E., Ngasala, T. M., and Camargo-Valero, M. A. (2022b). Recycling of faecal sludge: Nitrogen, carbon and organic matter transformation during Co-composting of faecal sludge with different bulking agents. *Int. J. Environ. Res. public health* 19 (17), 10592. doi:10.3390/ijerph191710592

Manurung, R., Supriatna, A., and Esyanthi, R. R. (2016). Bioconversion of Rice straw waste by black soldier fly larvae (Hermetia illucens L.): Optimal feed rate for biomass production. *J. Entomol. Zool. Stud.* 4, 1036–1041. Available online: https://www.entomoljournal.com/archives/2016/vol4issue4/PartK/4-3-163-796.pdf (Accessed on October 15, 2022)

Moodley, P., Archer, C., and Hawksworth, D. (2008). *Standard Methods for the Recovery and Enumeration of helminth ova in wastewater, sludge, compost and urine-diversion waste in South-Africa*. WRC Report No. TT322/08. South Africa: Water Research Comission.

Munroe, G. (2007). Manual of on-farm vermicomposting and vermiculture. *Org. Agri. Cent. Can.* 39, 40. Available online: https://www.eawag.ch/fileadmin/Domain1/Abteilungen/sandec/E-Learning/Moocs/Solid_Waste/W4/Manual_On_Farm_Vermicomposting_Vermiculture.pdf (Accessed November 2, 2022)

Myers, H. M., Tomberlin, J. K., Lambert, B. D., and Kattes, D. (2008). Development of black soldier fly (Diptera: Stratiomyidae) larvae fed dairy manure. *Environ. Entomol.* 37, 11–15. doi:10.1093/ee/37.1.11

Nakagiri, A., Kulabako, R. N., Nyenje, P. M., Tumuhairwe, J. B., Niwagaba, C. B., and Kansiime, F. (2015). Performance of pit latrines in urban poor areas: A case of Kampala, Uganda. *Habitat Int.* 49, 529–537. doi:10.1016/j.habitatint.2015.07.005

Niwagaba, C. B., Mbéguéré, M., and Strande, L. (2014). *Faecal sludge quantification, characterisation and treatment objectives. In faecal sludge management: System approach for implementation and operation*. London: IWA Publishing, 19–43. Available at: http://www.eawag.ch/forschung/sandec/publikationen/ewm/dl/fsm_book.pdf Accessed Feb 2016.

Nyakeri, E. M., Ayieko, M. A., Amimo, F. A., Salum, H., and Ogola, H. J. O. (2019). An optimal feeding strategy for black soldier fly larvae biomass production and faecal sludge reduction. *J. Insects as Food Feed* 5 (3), 201–213. doi:10.3920/JIFF2018.0017

Okalebo, J. R., Gathua, K. W., and Woomer, P. L. (2002). *Laboratory methods of soil and plant analysis: A working manual second edition*, 21. Sacred Africa, Nairobi, 25–26.

Pang, W., Hou, D., Chen, J., Nowar, E., Li, Z., Hu, R., et al. (2020). Reducing greenhouse gas emissions and enhancing carbon and nitrogen conversion in food wastes by the black soldier fly. *J. Environ. Manag.* 260, 110066. doi:10.1016/j.jenvman.2020.110066

Parra Paz, A. S., Carrejo, N. S., and Gómez Rodríguez, C. H. (2015). Effects of larval density and feeding rates on the bioconversion of vegetable waste using black soldier fly larvae hermetia illucens (L.), (Diptera: Stratiomyidae). *Waste Biomass Valorization* 6 (6), 1059–1065. doi:10.1007/s12649-015-9418-8

Peguero, D. A., Mutsakatira, E. T., Buckley, C. A., Foutch, G. L., and Bischel, H. N. (2021). Evaluating the microbial safety of heat-treated fecal sludge for black soldier fly larvae production in South Africa. *Environ. Eng. Sci.* 38 (5), 331–339. doi:10.1089/ees.2020.0272

Popa, R., and Green, T. R. (2012). Using black soldier fly larvae for processing organic leachates. *J. Econ. Entomology* 105 (2), 374–378. doi:10.1603/ec11192

Prakash, M., and Karmegam, N. (2010). Dynamics of nutrients and microflora during vermicomposting of mango leaf litter (Mangifera indica) using Perionyx ceylanensis. *Int. J. Glob. Environ. Issues* 10 (3–4), 339–353. doi:10.1504/IJGENVI.2010.037275

Rehman, K., Rehman, A., Cai, M., Zheng, L., Xiao, X., Somroo, A. A., et al. (2017). Conversion of mixtures of dairy manure and soybean curd residue by black soldier fly larvae (Hermetia illucens L.). *J. Clean. Prod.* 154, 366–373. doi:10.1016/j.jclepro.2017.04.019

Semiyaga, S., Okure, M. A., Niwagaba, C. B., Katukiza, A. Y., and Kansiime, F. (2015). Decentralized options for faecal sludge management in urban slum areas of sub-saharan Africa: A review of technologies, practices, and end-uses. *Resour. Conservation Recycl.* 104, 109–119. doi:10.1016/j.resconrec.2015.09.001

Semiyaga, S., Okure, M. A. E., Niwagaba, C. B., Nyenje, P. M., and Kansiime, F. (2017). Dewaterability of faecal sludge and its implications on faecal sludge management in urban slums. *Int. J. Environ. Sci. Technol.* 14 (1), 151–164. doi:10.1007/s13762-016-1134-9

Semiyaga, S., Bamuhimbise, G., Apio, S. C., Kinobe, J. R., Nkurunziza, A., Lukooya, N. B., et al. (2022a). Adequacy of vacuum and non-vacuum technologies for emptying faecal sludge from informal settlements of Kampala City. *Habitat Int.* 125, 102596. doi:10.1016/j.habitatint.2022.102596

Semiyaga, S., Nakagiri, A., Niwagaba, C. B., and Manga, M. (2022b). "Application of anaerobic digestion in decentralized faecal sludge treatment plants," in *Anaerobic Biodigesters for human waste treatment.* Editors M. K. Meghvansi and A. K. Goel (Environmental and Microbial Biotechnology) Singapore: Springer Nature Singapore, 263–281. doi:10.1007/978-981-19-4921-0_14

Sheppard, D. C., Newton, G. L., Thompson, S. A., and Savage, S. (1994). A value added manure management system using the black soldier fly. *Bioresour. Technol.* 50 (3), 275–279. doi:10.1016/0960-8524(94)90102-3

Shumo, M., Khamis, F. M., Tanga, C. M., Fiaboe, K. K. M., Subramanian, S., Ekesi, S., et al. (2019). Influence of temperature on selected life-history traits of black soldier fly (Hermetia illucens) reared on two common urban organic waste streams in Kenya. *Animals* 9, 79. doi:10.3390/ani9030079

Siddiqui, S. A., Ristow, B., Rahayu, T., Putra, N. S., Yuwono, N. W., Mategeko, B., et al. (2022). Black soldier fly larvae (BSFL) and their affinity for organic waste processing. *Waste Manag.* 140, 1–13. doi:10.1016/j.wasman.2021.12.044

Singh, A., and Kumari, K. (2019). An inclusive approach for organic waste treatment and valorisation using black soldier fly larvae: A review. *J. Environ. Manag.* 251 (1), 109569. doi:10.1016/j.jenvman.2019.109569

Strande, L. (2014). "The global situation," in *Faecal Sludge Management - systems approach implementation and operation*. Editors L. Strande, M. Ronteltap, and D. Brdjanovic (London, UK: IWA Publishing), 1–14.

Supriyatna, A., Manurung, R., and Esyanti, R. R. (2016). Growth of black soldier larvae fed on cassava peel wastes, an agriculture waste. *J. Entomol. Zool. Stud.* 4, 161–165. Available at: https://multisite.itb.ac.id/sithdev/wp-content/uploads/sites/386/2018/01/Growth-of-black-soldier-larvae-fed-on-cassava-peel-1.pdf (Accessed November 1, 2022).

Surendra, K. C., Tomberlin, J. K., van Huis, A., Cammack, J. A., Heckmann, L. H. L., and Khanal, S. K. (2020). Rethinking organic wastes bioconversion: Evaluating the potential of the black soldier fly (Hermetia illucens (L.)) (Diptera: Stratiomyidae) (BSF). *Waste Manag.* 117, 58–80. doi:10.1016/j.wasman.2020.07.050

Tervahauta, T., Rani, S., Leal, L. H., Buisman, C. J., and Zeeman, G. (2014). Black water sludge reuse in agriculture: Are heavy metals a problem? *J. Hazard. Mater.* 274, 229–236. doi:10.1016/j.jhazmat.2014.04.018

Twinomucunguzi, F. R., Nyenje, P. M., Semiyaga, S., Kebirungi, P., Kulabako, R. N., and Kansiime, F. (2022). Antibiotics in shallow groundwater underlying urban informal settlements in developing countries: Influence of on-site sanitation practices and risk assessment. *Urban Water J.* 10, 1–13. doi:10.1080/1573062X.2022.2059688

Velkushanova, K., and Strande, L. (2021). *Faecal sludge properties and considerations for characterisation*. Available at: https://www.eawag.ch/fileadmin/Domain1/Abteilungen/sandec/publikationen/EWM/FS_Methods_Book/Ch02.pdf.

Webster, C. D., Rawles, S. D., Koch, J. F., Thompson, K. R., Kobayashi, Y., Gannam, A. L., et al. (2016). Bio-Ag reutilization of distiller's dried grains with solubles (DDGS) as a substrate for black soldier fly larvae, *Hermetia illucens*, along with poultry by-product meal and soybean meal, as total replacement of fish meal in diets for Nile tilapia, *Oreochromis niloticus*. *Oreochr. Aquac. Nutr.* 22, 976–988. doi:10.1111/anu.12316

WHO (2006). *WHO guidelines for the safe use of wastewater, excreta and greywater. Volume 1: Policy and regulatory aspects*. France: WHO.

WHO/UNICEF (2021). *Progress on household drinking water, sanitation and hygiene 2000-2020: Five years into the SDGs, joint water supply, & sanitation monitoring programme*. Available at: http://apps.who.int/bookorders.

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Sustainability assessment of rural toilet technology based on the unascertained measure theory

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Upgrading toilets in rural areas is an effective way to protect public health and reduce environmental pollution. Although there are studies on rural toilets, the sustainable performance of rural toilets in developing areas is considerably less understood. The study aims to build a sustainability assessment model of rural toilet technology to support the local government in upgrading rural toilets. The unascertained measure theory is integrated into the model to quantify the sustainability performance of rural toilet technology in three dimensions: economy, service and management, and environment. A case study of Honghai Village, Inner Mongolia, China, is conducted to verify the reliability of the sustainability assessment model. The results indicate that the sustainability performance of the three-compartment septic tank toilet technology is good in Honghai Village. The results are consistent with the situation of the three-compartment septic tank toilets in the village, which verifies the model's validity. This study can help local government significantly upgrade rural toilets and improve the living standards of rural residents.

KEYWORDS

rural toilet, separate toilet, sustainability assessment, unascertained measure theory, case study

1 Introduction

Toilets are essential to human wellbeing. However, according to the United Nations, at least 892 million people currently practice open defecation, most living in rural areas (United Nations, 2022). And many rural residents use toilets that cannot properly treat human waste. In China, 45% of the human waste produced by rural households is not properly treated, 79% of which is used as fertilizer and 12% is discharged directly into the environment (Zhou et al., 2022). Lack of toilets and inadequate toilet treatment capacity contribute to an increasing risk of transmission of infectious diseases and induce poverty (Akaishi et al., 2021; Dancer et al., 2021). More than 3,60,000 children die yearly from water and sanitation-related diarrheal diseases (Ignacio et al., 2018). In order to reduce the health and environmental threats posed by human waste, many governments have tried to upgrade the toilets in rural areas. The Chinese government has implemented a "toilet revolution" policy since 2015, working to improve toilets in rural areas (Cheng et al., 2018).

To guide the upgrading of toilets, the researchers have conducted studies on toilet technology assessment. Liu et al. (2021) focused on the microbial safety and antibiotic resistance of using open composting toilets and green composting toilets. In the Philippines, Zakaria et al. (2018) evaluated the service capacity of smart toilets. They found the smart toilets can monitor usage data for immediate maintenance and can save 97% of water usage compared to conventional toilets. Hill et al. (2013)

argued the reliability of the urine-diverting vermicomposting toilets by adopting the Solvita compost stability and maturity test. In Hong Kong, Liu et al. (2019) focused on the environmental impacts of the seawater toilet flushing (SWTF) system. They compared the environmental performance of five types of toilets using life cycle assessment (LCA). The result revealed that SWFT systems have excellent environmental performance, and can significantly reduce CO_2 emissions. Some studies have discussed the performance of toilet technology from both an economic and environmental perspective. Devkota et al. (2015) evaluated the environmental and economic performance of rainwater flushing toilets using LCA. The results showed that rain-flush toilets could significantly reduce energy consumption and greenhouse gas emissions. Anand and Apul (2011) evaluated the economic and environmental performance of potable water-flushed toilets, rain-flushed toilets, and composting toilets. The results indicated that rain-flushed and composting toilets are more efficient in saving energy and reducing CO_2 emissions. Shi et al. used cost-benefit analysis and LCA to analyze the economic and environmental performance of resource-oriented toilets and conventional toilets. The results suggested that resource-oriented toilets are better suited for rural use than traditional toilets in terms of cost, energy, and resources. Gao et al. (2017) used the economic net present value method to analyze the energy consumption and greenhouse gas emission impacts of rural toilet systems under five scenarios. Zhu et al. (2021) used the analytic hierarchy process (AHP) and LCA to construct an evaluation index system for public toilet technology in terms of economic, social, and environmental benefits. The correlational studies have focused more on the economic, technical and environmental performance of toilets (Gao et al., 2017; Fu et al., 2022; Tembhurkar et al., 2022; Fu et al., 2023). Few studies have considered the impact of residents when focusing on the sustainable performance of rural toilets. Unlike urban areas, rural residents are more deeply involved in the construction, management and maintenance of private toilets. The sustainable benefits of rural toilet technology can only be realized when the toilets can be accepted and maintained by rural residents. Accordingly, this study aims to construct an assessment model that reveals the sustainability performance of toilet technology in rural areas. The research objectives include: 1) Build sustainability assessment indexes of rural toilet technology; 2) Establish the sustainability assessment model of rural toilet technology; 3) A case was used to verify the effectiveness of the sustainability assessment model of rural toilet technology.

The remainder of the paper is structured as follows. Section 2 builds the sustainability assessment index system for rural toilet technology; Section 3 introduces the research methodology and constructs rural toilet technology sustainability assessment model (RTTSAM) based on unascertained measure theory (UMT); Section 4 shows the results of sustainability assessment of rural toilet technology in the case study and discusses the main findings; Section 5 includes the conclusion and the implication of the study.

2 Material and methods

2.1 Establishment of the sustainability assessment indexes for rural toilet technology

2.1.1 Establishment of sustainability assessment indexes

Through literature review and site survey in rural areas, a total of 16 indexes were finally obtained (Devkota et al., 2015; Gao et al., 2017; Shi et al., 2018; Zhu et al., 2021). These indexes were divided into three dimensions: economy, service and management, and environment (Table 1). Among them, five indexes belong to economic dimension, 6 indexes belong to service and management dimension, and 5 indexes belong to service and management dimension.

The economic dimension covers the indexes related to the costs of toilet upgrading. The construction cost index and the equipment cost index focus on the cost of the toilets. The ancillary facility cost index refers to the cost of supporting equipment required for the operation, such as the cost of water supply pipes, sewage pipes, etc. The operation and maintenance cost index cover the costs incurred for the use and maintenance of toilets. The policy support index focuses on the impact of the support policies on the cost of toilet upgrading.

The services and management dimension focus on the service performance of the toilets and the maintenance needs of the toilets. The treatment effect index and treatment capacity index reflect the capacity of the toilet to treat human waste. The convenience index, safety index, and durability index refer to the quality of toilet services. Besides, the operation and maintenance requirement index measures the intensity of toilet operation and maintenance requirements.

The environmental dimension refers to the impact of toilet technology on the environment. Since the treated human waste can be used as fertilizer, it can reduce the environmental impact of human waste while providing economic benefits to rural residents. Therefore, the study uses the waste reuse index to reflect the ability of toilet technology to reuse human waste. The water conservation index measures the ability of toilet technology to save water. The performance of toilets is critical for rural residents with inadequate water supply systems or in arid areas. The energy conservation index, noise control index, and odor control index measure the impact of toilets on energy, noise, and odor, respectively. The sustainability assessment indexes of rural toilet technology are shown in Figure 1.

TABLE 1 Index grading standards.

Grade	Grade I	Grade II	Grade III	Grade IV	Grade V
Situation	Very high	High	Average	Low	Very low
Standard	(9.0, 10)	(8.0, 9.0)	(7.0, 8.0)	(6.0, 7.0)	(0, 6.0)

2.1.2 Determination of the index grading standards

This study determines the index grading standards through literature review and consulting experts. They are divided into five grades. The assessment grading space is $G = \{G_1, G_2, G_3, G_4, G_5\}$. The specific classification standards are shown in Table 1.

2.2 Establishment of the RTTSAM

2.2.1 Unascertained measure theory

The UMT is an uncertainty information theory proposed by Wang (1990). It can quantitatively analyze uncertainty factors effectively and reliably. There is uncertainty in evaluating sustainability indexes for rural toilet technology due to subjective perception of experts (Xing et al., 2022). Therefore, the study adopts the UMT to establish a sustainability assessment model of rural toilet technology.

Suppose that the assessment object $T = \{T_1, T_2, \cdots, T_n\}$, each assessment object has m assessment indexes, and the assessment index $V = \{V_1, V_2, \cdots, V_m\}$. If t_{ij} represents the measured value of

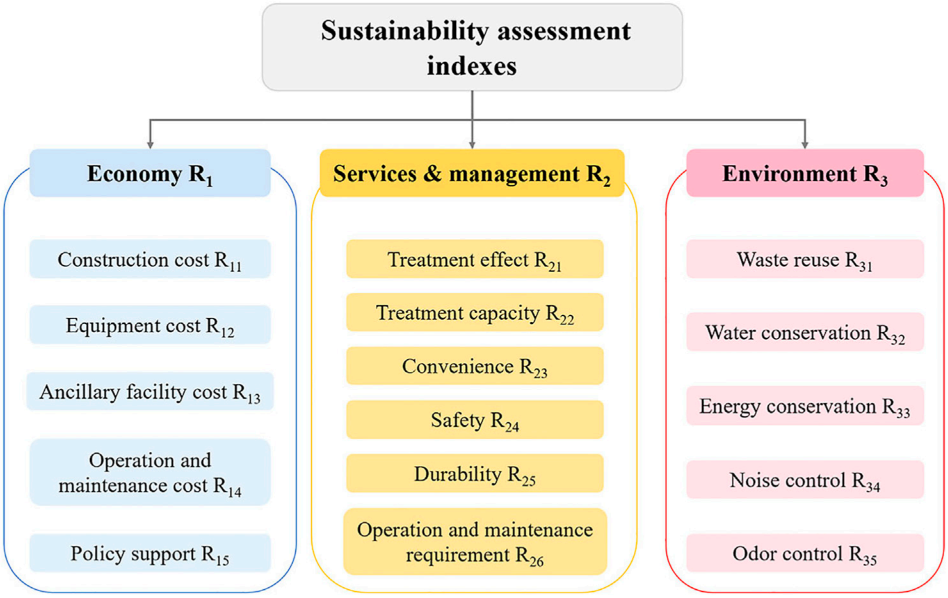

FIGURE 1
Sustainability assessment indexes of the rural toilet technology.

the i-th assessment object T_i for the j-th assessment index V_j, then T_i can be expressed as an m-dimensional vector $T_i = (t_{i1}, t_{i2}, \cdots, t_{im})$. Suppose that the assessment grade space $G = \{G_1, G_2, \cdots, G_P\}$, where G_k is the rating value of T_{ij}. If the k-th grade is higher than the $k+1$-th grade in the sustainability assessment process, it is denoted as $G_k > G_{k+1}$. If $G_1 > G_2 > \cdots > G_p$ or $G_1 < G_2 < \cdots < G_p$ is satisfied, then $G = \{G_1, G_2, \cdots, G_P\}$ is an ordered segmentation class of assessment space G.

2.2.2 Single-index unascertained measure

If $\mu_{ijk} = \mu(t_{ij} \in G_k)$ represents the degree to which the measured value t_{ij} belongs to the k-th assessment grade G_k, then

$$0 \le \mu\left(t_{ij} \in G_k\right) \le 1 \,(i = 1, 2, \cdots, n;\, j = 1, 2, \cdots, m;\, k = 1, 2, \cdots, p;) \quad (1)$$

$$\mu\left(t_{ij} \in G_k\right) = 1 \,(i = 1, 2, \cdots, n;\, j = 1, 2, \cdots, m) \quad (2)$$

$$\mu\left|t_{ij} \in \overset{k}{\underset{l=1}{G_k}}\right| = \sum_{l=1}^{k} \mu\left(t_{ij} \in G_l\right) \;(k = 1, 2, \cdots, p) \quad (3)$$

Equation 1 is called "unboundedness," Eq. 2 is "normalization", and Eq. 3 is "additivity." If μ satisfies the Eqs 1–3, then μ is called the unascertained measure. In general, the construction methods of single index measure functions include linear, exponential, parabolic, and sinusoidal. And the restriction conditions of Eqs 1–3 must be satisfied.

Based on the single-index measure function $(i = 1, 2, \cdots, n;\, j = 1, 2, \cdots, m;\, k = 1, 2, \cdots, p)$, the measured value μ_{ijk} of each index of the assessment object T_i can be obtained, and $(\mu_{ijk})_{m\times p}$ is defined the single-index measure matrix as follows:

$$\left(\mu_{ijk}\right)_{m\times p} = \begin{bmatrix} \mu_{i11} & \mu_{i12} \cdots & \mu_{i1p} \\ \mu_{i21} & \mu_{i22} \cdots & \mu_{i2p} \\ \vdots & \vdots \quad \ddots & \vdots \\ \mu_{im1} & \mu_{im2} \cdots & \mu_{imp} \end{bmatrix} \quad (4)$$

Based on the definition of the single-index measure function and the index grading standards in Table 1, the single-index unascertained measure function is determined. The function studied in this paper is linear, and the single-index unascertained measure function is made as follows:

$$\mu_{ij1} = \begin{cases} 0 & x_{ij} \le 8.5 \\ \dfrac{x_{ij} - 8.5}{1.0}, & 8.5 < x_{ij} \le 9.5 \\ 1 & x_{ij} > 9.5 \end{cases} \quad (5)$$

$$\mu_{ij2} = \begin{cases} 0 & x_{ij} \le 7.5 \text{ or } x_{ij} > 9.5 \\ \dfrac{x_{ij} - 7.5}{1.0}, & 7.5 < x_{ij} \le 8.5 \\ \dfrac{9.5 - x_{ij}}{1.0} & 8.5 < x_{ij} \le 9.5 \end{cases} \quad (6)$$

$$\mu_{ij3} = \begin{cases} 0 & x_{ij} \le 6.5 \text{ or } x_{ij} > 8.5 \\ \dfrac{x_{ij} - 6.5}{1.0}, & 6.5 < x_{ij} \le 7.5 \\ \dfrac{8.5 - x_{ij}}{1.0} & 7.5 < x_{ij} \le 8.5 \end{cases} \quad (7)$$

$$\mu_{ij4} = \begin{cases} 0 & x_{ij} \le 3.0 \text{ or } x_{ij} > 7.5 \\ \dfrac{x_{ij} - 3.0}{1.0}, & 3.5 < x_{ij} \le 6.5 \\ \dfrac{7.5 - x_{ij}}{1.0} & 6.5 < x_{ij} \le 7.5 \end{cases} \quad (8)$$

$$\mu_{ij5} = \begin{cases} 1 & x_{ij} \le 3.0 \\ \dfrac{x_{ij} - 3.0}{1.0}, & 3.0 < x_{ij} \le 6.5 \\ 0 & x_{ij} \ge 6.5 \end{cases} \quad (9)$$

Based on Eqs 5–9, the single-index unascertained measure function is expressed graphically, as shown in Figure 2.

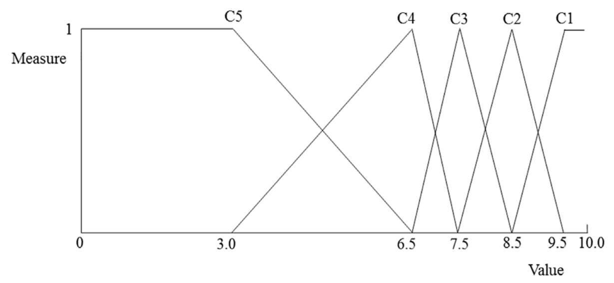

FIGURE 2
The single-index unascertained measure function.

2.2.3 Determination of indexes weights by AHP method

Analytic Hierarchy Process (AHP) method is proposed by Satty et al. and can solve complex multi-objective and multi-criteria decision problems using less quantitative information (Saaty, 1980). This study used the AHP approach to determine the index weight. The specific steps of AHP approach to determine the index weight are as follows.

(1) Establishment of the hierarchical structure.

The hierarchical structure of sustainability assessment of rural toilet technology is shown in Figure 1.

(2) Construction of the judgment matrix.

The judgment matrix A is represented as follows:

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{10}$$

where a_{ij} refers to a qualified pairwise comparison for indexes of the same level. 1-9 point scale method was used to obtain the value of the a_{ij} (see Supplementary Schedule S1), thus where a_{ij} takes the values of 1-9, 1/2-1/9.

(3) Calculation the weight of indexes.

1) Normalized judgment matrix A

$$a'_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \, (i = 1, 2, \cdots, n; j = 1, 2, \cdots, m) \tag{11}$$

2) Add the normalized matrix by rows, then

$$w' = \sum_{j=1}^{n} a'_{ij} (i = 1, 2, \cdots n) \tag{12}$$

3) Normalizing the vectors $w' = (w'_1, w'_2, \cdots, w'_n)^T$,

$$w_i = \frac{w'_i}{\sum_{j=1}^{n} w'_j} \quad (i = 1, 2, \cdots n) \tag{13}$$

The obtained eigenvector is $w = (w_1, w_2, \cdots, w_n)^T$.

4) Calculating the largest eigenvalue of the judgment matrix $\lambda_{\max}$ with the Eq. 14

$$\lambda_{\max} = \frac{\sum_{i=1}^{n} (Aw)_i}{nw_i} \tag{14}$$

where is the i-th element of the vector obtained by multiplying matrix A with weight vector w.

5) Calculating the consistency index (C.I.) with the Eq. 15.

$$\text{C.I.} = \frac{\lambda_{\max} - n}{n - 1} \tag{15}$$

where n is the number of the indexes in the judgment matrix.

6) Calculating the consistency ratio (C.R.) with the Eq. 16.

$$\text{C.R.} = \frac{\text{C.I.}}{\text{R.I.}} \tag{16}$$

where R.I. is the random index shown in Supplementary Schedule S2. If C.R. > 0 and C.R. < 0.1, judgment matrix A is considered to meet the requirements of the consistency check. Otherwise, the judgment matrix needs to be reconstructed.

1-9 point scale method is used to construct a judgment matrix for the first-level indexes and second-level indexes. Then the weights of the judgment matrix are obtained. And the consistency of the judgment matrix is checked. As is shown in Supplementary Schedule S3, the consistency check meets the corresponding requirements. The weights of the indexes are shown in Table 2.

2.2.4 Multi-index comprehensive unascertained measure

If μ_{ik} satisfies $0 \le \mu_{ik} \le 1, \mu_{ik} = \sum_{j=1}^{m} w_j \mu_{ijk} \, (k = 1, 2, \cdots, p)$, where w_j for the index weight, $(\mu_{ik})_{n \times p}$ represents the multi-index unascertained measure matrix.

$$(\mu_{ik})_{n \times p} = \begin{bmatrix} \mu_{11} & \mu_{12} & \cdots & \mu_{1p} \\ \mu_{21} & \mu_{22} & \cdots & \mu_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ \mu_{n1} & \mu_{n2} & \cdots & \mu_{np} \end{bmatrix} \tag{17}$$

2.2.5 Confirmation of sustainability assessment grade

The credible degree recognition criteria is introduced to obtain the sustainability assessment grade. Suppose that λ is the credible degree ($\lambda \ge 0.5$, usually, $\lambda = 0.6$ or 0.7), if $G_1 > G_2 > \cdots > G_p$,

$$p_0 = \min \left| p: \sum_{k=1}^{p} \mu_{ik} > \lambda, i = 1, 2, \cdots, n \right| \tag{18}$$

2.3 Implementation steps of RTTSAM

The study used AHP method to calculate the weights of sustainability assessment indexes. Then, a sustainability assessment model of rural toilet technology was established based on unascertained measure theory. The flowchart of the research method is shown in Figure 3.

TABLE 2 Weights of sustainability assessment indexes.

First-level index	Weight	Second-level index	Weight	General weight
Economy R_1	0.364	Construction cost R_{11}	0.278	0.101
		Equipment cost R_{12}	0.234	0.085
		Ancillary facility cost R_{13}	0.213	0.078
		Operation and maintenance cost R_{14}	0.121	0.044
		Policy support R_{15}	0.153	0.056
Services and management R_2	0.284	Treatment effect R_{21}	0.188	0.054
		Treatment capacity R_{22}	0.143	0.041
		Convenience R_{23}	0.182	0.052
		Safety R_{24}	0.158	0.045
		Durability R_{25}	0.155	0.044
		Operation and maintenance requirement R_{26}	0.175	0.050
Environment R_3	0.352	Waste reuse R_{31}	0.252	0.089
		Water conservation R_{32}	0.244	0.086
		Energy conservation R_{33}	0.200	0.070
		Noise control R_{34}	0.139	0.049
		Odor control R_{35}	0.165	0.058

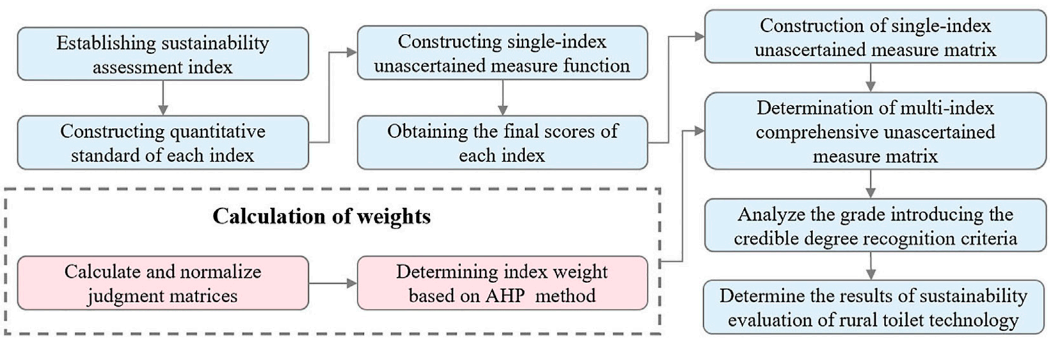

FIGURE 3
Flowchart of RTTSAM.

Step 1: Define the objects to be determined, and establish the sustainability assessment indexes and quantitative index grading standards.

Step 2: Construct the single-index unascertained measure function.

Step 3: Determine the single-index unascertained measure matrix.

Step 4: Calculate the weights of sustainability assessment indexes of rural toilets technology based on the AHP approach.

Step 5: Obtain the score of the sustainability assessment indexes of the assessment object.

Step 6: Determine multi-index comprehensive unascertained measure matrix.

Step 7: Introduce the credible degree recognition criteria to ensure the sustainability assessment grade of the assessment object.

2.4 Case study

The Honghai Village in Ordos, Inner Mongolia, China, was selected as a study area. The Honghai Village has a semi-arid continental climate. The minimum daily temperature in winter can be below −30°C in Honghai Village. The village has 1,384 inhabitants, mainly engaged in agriculture and animal

FIGURE 4
Village, building and toilets.

TABLE 3 Basic information.

No.	1	2	3	4	5
Occupation	Professor	Village chief	Professor	Local Officers	Inspector
Working year	16	30	17	9	9
Education Level	Doctor	High school	Doctor	Undergraduate	Undergraduate
No.	6	7	8	9	
Occupation	Local Officers	Local Officers	Professor	Inspector	
Working year	10	15	18	10	
Education Level	Undergraduate	Undergraduate	Doctor	Undergraduate	

husbandry. After implementing the "toilet revolution" policy, the toilets in the village have been upgraded. There are two types of toilets in Honghai Village: indoor toilets and outdoor toilets. The toilets use three-compartment septic tanks to treat human waste. Three-compartment septic tank toilet (TCSTT) is a type of toilet that can treat manure in combination with a sewage treatment system. In areas where sanitation systems are unavailable, these toilets can also effectively treat human waste independently through anaerobic reaction and sedimentation (Tan et al., 2021). The treatment time for human waste in the three tanks is 20 days (first tank), 10 days (second tank), and 30 days (third tank). The solid-based manure in the third tank was a kind of slow release fertilizer. The situation of the village and toilets is shown in Figure 4.

The study invited experts, officers, and users to assess the sustainability of the TCSTT technology used in Honghai Village. The basic information of them is shown in Table 3. By calculating the average of the remaining scores after removing the highest and lowest scores, the final score of each sustainability assessment index was obtained in Supplementary Schedule S4.

3 Result and discussion

(1) Calculating the first-level index comprehensive unascertained measure matrix.

Based on the second-level index unascertained measure matrix (see Supplementary Schedule S5) and the weight of the second-level indexes, the first-level index comprehensive unascertained measure matrix can be calculated as follows:

$$\mu = \begin{bmatrix} 0.163 & 0.814 & 0.023 & 0.000 & 0.000 \\ 0.152 & 0.296 & 0.458 & 0.094 & 0.000 \\ 0.604 & 0.360 & 0.037 & 0.000 & 0.000 \end{bmatrix} \tag{19}$$

(2) Calculating the total target comprehensive measure matrix.

Based on the first-level index unascertained measure matrix and the weight of the first-level indexes, the total target comprehensive measure matrix can be calculated as follows:

$$\mu_{total} = [0.315\ 0.507\ 0.151\ 0.027\ 0.000] \tag{20}$$

(3) Credible degree recognition.

According to the credible degree recognition criteria, take the confidence $\lambda = 0.6$. According to Eq. 18, when $P_0 = 2$, $0.315 + 0.507 = 0.822 > 0.6$, and $0.027 + 0.151 + 0.507 = 0.685 > 0.6$. That is, the sustainability assessment grade of this toilet technology can be judged as grade II. The error is acceptable, and the assessment results are reliable. Similarly, the sustainability assessment grade of the indexes are shown in Table 4.

The assessment results show that the sustainability grade of TCSTT technology is grade II. From the perspective of three dimensions, TCSTT technology has the highest sustainability assessment grade in environment dimension with grade I, followed by economy dimension with grade II and services and management

TABLE 4 Sustainability assessment grade of each index.

First-level index	Grade	Second-level index	Grade	First-level index	Grade	Second-level index	Grade
R_1	II	R_{11}	II	R_2	III	R_{24}	II
		R_{12}	II			R_{25}	I
		R_{13}	II			R_{26}	II
		R_{14}	II	R_3	I	R_{31}	I
		R_{15}	II			R_{32}	I
R_2	III	R_{21}	III			R_{33}	I
		R_{22}	III			R_{34}	I
		R_{23}	II			R_{35}	II

dimension with grade III. When the sustainability level of the index is Grade III or lower, it is necessary to take steps to improve or replace the toilet technology. For villages located in nature reserves, water sources, and other villages with special needs, measures must be taken to upgrade or replace toilet technology for index with sustainability levels of grade II or lower. For indexes with a sustainability level of grade I, there is no need to improve them. The Honghai Village is not in a nature reserve, water source, or special needs. The sustainability level of TCSTTs has been able to meet the needs of Honghai Village. The results reveal that sustainability of the TCSTTs in the economic and environmental dimensions is acceptable. While the sustainability grade of services and management dimension is grade III. This means that TCSTTs need to improve the sustainability of the service and management dimensions.

Among the economical dimension, TCSTT technology shows high sustainability performance in the construction index (Grade II), equipment cost index (Grade II), and ancillary facility costs index (Grade II). The construction of TCSTTs is not complicated. The TCSTTs require only the addition of a three-compartment septic tank made of brick and concrete, as compared to the original toilets used by the rural residents. Otherwise, rural residents can purchase a finished three-compartment septic tank (Tan et al., 2021). The simple construction process of TCSTT can effectively save construction cost. The waste treatment equipment of TCSTT is available as either a finished three-compartment septic tank or can be made from concrete. In addition to septic tanks, rural residents only need to purchase a small number of equipment, such as pipes. Rural residents can choose different equipment options according to their financial situation. The equipment costs of TCSTT can be effectively controlled. Currently, there is no sanitation system in Honghai Village. Local residents want to upgrade the toilets first and then raise funds to build a sanitation system. The TCSTTs can treat human waste independently with low demand for supporting facilities. TCSTTs can also be in connection with sanitation facilities. For Honghai villages that lack sanitation facilities, TCSTTs can not only reduce the cost of ancillary facilities at present, but also can be used as a pretreatment process when sanitation facilities are installed (Singh et al., 2019). Overall TCSTTs are easy to build and low investment, which provides a good basis for the local residents to accept this kind of toilets (Acey et al., 2019). For rural households, the maintenance of TCSTT is simple and infrequent. Therefore, the sustainability level of operation and maintenance costs index is grade II. Another index with a sustainability level of grade II is the policy support index. To promote the toilet revolution policy, the local government has reimbursed part of the toilet construction costs and organized bulk purchases of appliances for residents. The village government is able to assist rural residents in purchasing toilet maintenance services. With the support of the government, the cost of toilets is reduced. The support of policy reduces the economic pressure on rural residents while increasing their willingness to use and maintain toilets (Poortvliet et al., 2018). In this way, the policy support improves the sustainability of TCSTTs. Overall, the sustainability performance of TCSTT's economic indexes is good.

For the services and management dimension, the sustainability level of the treatment effect index and treatment capacity index is Grade III. This means that it can meet the local standards for human waste treatment, but still needs further improvement. TCSTTs treat human waste through natural anaerobic fermentation. In order to improve the effluent treatment effect, the manure emptying time interval can be appropriately extended when the temperature is low. TCSTTs take about 30 days to treat human waste, which is suitable for household human waste treatment. When the number of families is large, the size of the septic tank should be increased appropriately, or the number of finished three-compartment septic tanks should be increased to reduce the treatment pressure (MARA, 2020). The sustainability level of the operation and maintenance requirement index of TCSTT is Grade II, which means that the residents can reliably manage and maintain the toilets. After being treated, the liquid flows out, the residue accumulates needs to be cleaned. But only the third septic tank need to be cleaned each time. The rest of the septic tank is forbidden from being cleaned due to insufficient treatment time (Tan et al., 2021). In winter, the connection pipes of TCSTT are prone to clogging due to the low temperature. Therefore, the management and maintenance frequency need to be increased in winter. Local governments need to enhance residents' awareness of TCSTT management and maintenance methods in order to effectively improve the effectiveness of TCSTT treatment (Junghanns and Beery, 2020). Since TCSTT technology mainly adopts natural anaerobic fermentation, it produces combustible gas during the treatment process, but the yield is small, and the safety is high. TCSTT technology can be used for both outdoor and indoor toilets. The convenience (Grade II) and safety (Grade II) of TCSTTs are ensured. The structure of TCSTT is relatively simple. The central part is built with concrete, steel, and other materials with good durability. Therefore, the durability of TCSTT is very high (Grade

I). In general, the TCSTT can meet the needs of rural residents and is easy to use and maintain.

TCSTT technology has outstanding environmental performance (Grade I). The human waste from the anaerobic fermentation of the TCSTT can be used as fertilizer and can reduce the cost of fertilizer (Liu et al., 2018). The residents of Honghai Village are accustomed to using human waste to fertilize their crops. The waste from TCSTT can be effectively reused (Grade I). Since TCSTT treats waste through natural anaerobic fermentation. Therefore, the treatment process of human waste requires less water (Grade I), less energy (Grade I), and no noise (Grade I). While the concrete three-compartment septic tank may emit an odor (Grade II) in the treatment process. Residents who choose concrete three-compartment septic tanks often build outdoor toilets to reduce the impact of odors, which can also make it easier for residents to get fertilizer. For residents using indoor toilets, flushing equipment with a finished three-compartment septic tank can effectively reduce the impact of odors. TCSTTs have been able to effectively reduce the environmental impact of human waste while providing benefits to agricultural production. The residents of Honghai Village are able to accept and use TCSTTs.

Traditionally, water flushing toilets are always considered as one with sanitation facilities (Gao et al., 2017). However, in rural areas that lack sanitation systems and need to reuse waste, the choice of TCSTTs applied in decentralised is more sustainable. The TCSTT technology shows high sustainability in Honghai Village. The TCSTTs are simple in structure, flexible in design, and easy to use. The TCSTT technology used in Honghai Village is economically acceptable to rural residents, easy to maintain, and can effectively reduce the impact of human waste on the environment. Although the overall sustainability level of TCSTT technology is grade II, the sustainability performance of TCSTT can further improve by adding supporting facilities and adjusting the equipment option. The local government needs to strengthen the training of rural residents to build, use and maintain TCSTTs properly. In addition, TCSTTs is a good option for villages that are planning to build their own sanitation treatment systems. Rural residents can connect the TCSTTs to the sanitation facilities as a pretreatment process.

The field study of the toilet technology in this village revealed that the model results are valid. This implies that the model can obtain reliable assessment results in the sustainability assessment of rural toilets for which there are many uncertainties. Recent studies have been conducted to evaluate the performance of toilets and sanitation from environmental, economic, and technical dimensions. (Gao et al., 2017; Shi et al., 2018; Firmansyah et al., 2021). Although the present studies provide support for this study, the differences are significant. Firmansyah et al. (2021) discussed the performance of water flushing toilets used in small tropical islands in connection with sanitation. In contrast, the subject of this study is rural toilets in developing areas. In these underdeveloped rural areas, toilets require independent treatment of human waste due to the lack of a sanitation network. Therefore, the toilet technology used in rural areas differs significantly from other regions. In addition, the above studies emphasize the economic and environmental performance of the technology. However, the management and maintenance of toilets in underdeveloped rural areas rely more on the rural residents themselves (Wu et al., 2021). This means that the proper operation of toilets depends on the willingness of rural residents to accept the toilets, and their ability to manage and maintain the toilets (Poortvliet et al., 2018; Fu et al., 2022). For toilets used in rural areas, sustainability should include environmental improvement as well as the ability to use and maintain the toilets themselves. Therefore, this study evaluates the sustainability of rural toilets in three aspects: economic, services and management, and environmental. This study can help policymakers to select more feasible toilet technologies and promote sustainable development of toilets in developing rural areas.

4 Conclusion

For developing areas, upgrading toilets in rural areas is a meaningful way to stop the spread of fecal-borne disease, reduce poverty, and protect the environment. While some of the upgraded toilets are difficult to operate properly or even abandoned due to the difficulty of acceptance or maintenance by rural residents. Sustainable rural toilet technology mean that the toilets can reduce the environmental pollution caused by human waste while at the same time the toilets are accepted and used consistently by rural residents. The current researches have paid insufficient attention to the impact of rural residents on the sustainable performance of toilet technology. The study builds sustainability assessment indexes of rural toilet technology in three dimensions: economy, environment, and service and management. A sustainability assessment model based on UMT is developed to provide insights for upgrading toilets in rural areas. The RTTSAM is applied to the toilet technology used in Honghai village to illustrate the feasibility and validity.

The results show that the sustainability performance of TCSTT technology used in Honghai Village is high. While the service and management performance of TCSTT technology is general, which means the TCSTTs need to extend processing time and adjust equipment options in Honghai Village. The results of the study indicate that the impact of rural residents may play a crucial role in achieving sustainable rural toilets. And the sustainability performance of the same toilet technology will vary in different environments and changing needs of the rural residents.

Therefore, some practical implications are provided. The government should provide financial support to encourage rural residents to upgrade their toilets. The government should offer technical support for upgrading toilets and monitoring the quality of rural toilets. The government needs to strengthen the publicity of toilet upgrading and educate rural residents about the use and maintenance of toilets. This study contributes to support the upgrading of rural toilets, improve the health of rural residents, enhance the living environment of rural residents, and guide the local government to seek the sustainable development of rural areas.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization: SW, QC; Interpretation of the data: SW, QC, B-JH; Review and Editing: SW, QC, XL; Data curation and Formal

Analysis: SW, QC, B-JH, XL; Finally, all authors read the final version of the manuscript and approved accordingly.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1112689/full#supplementary-material

SUPPLEMENTARY SCHEDULE S1
1–9 point scale method.

SUPPLEMENTARY SCHEDULE S2
Random index (R.I.) values.

SUPPLEMENTARY SCHEDULE S3
Consistency check of judgment matrix.

SUPPLEMENTARY SCHEDULE S4
The final score of the sustainability assessment indexes.

SUPPLEMENTARY SCHEDULE S5
Single-index unascertained measure matrix.

References

Acey, C., Kisiangani, J., Ronoh, P., Delaire, C., Makena, E., Norman, G., et al. (2019). Cross-subsidies for improved sanitation in low income settlements: Assessing the willingness to pay of water utility customers in Kenyan cities. *World Dev.* 115, 160–177. doi:10.1016/j.worlddev.2018.11.006

Akaishi, T., Morino, K., Maruyama, Y., Ishibashi, S., Takayama, S., Abe, M., et al. (2021). Restoration of clean water supply and toilet hygiene reduces infectious diseases in post-disaster evacuation shelters: A multicenter observational study. *Heliyon* 7 (5), e07044. doi:10.1016/j.heliyon.2021.e07044

Anand, C., and Apul, D. S. (2011). Economic and environmental analysis of standard, high efficiency, rainwater flushed, and composting toilets. *J. Environ. Manag.* 92 (3), 419–428. doi:10.1016/j.jenvman.2010.08.005

Cheng, S., Li, Z., Uddin, S. M. N., Mang, H-P., Zhou, X., Zhang, J., et al. (2018). Toilet revolution in China. *J. Environ. Manag.* 216, 347–356. doi:10.1016/j.jenvman.2017.09.043

Dancer, S. J., Li, Y., Hart, A., Tang, J. W., and Jones, D. L. (2021). What is the risk of acquiring SARS-CoV-2 from the use of public toilets? *Sci. Total Environ.* 792, 148341. doi:10.1016/j.scitotenv.2021.148341

Devkota, J., Schlachter, H., and Apul, D. (2015). Life cycle based evaluation of harvested rainwater use in toilets and for irrigation. *J. Clean. Prod.* 95, 311–321. doi:10.1016/j.jclepro.2015.02.021

Firmansyah, I., Carsjens, G. J., De Ruijter, F. J., Zeeman, G., and Spiller, M. (2021). An integrated assessment of environmental, economic, social and technological parameters of source separated and conventional sanitation concepts: A contribution to sustainability analysis. *J. Environ. Manag.* 295, 113131. doi:10.1016/j.jenvman.2021.113131

Fu, H., Niu, J., Wu, Z., Cheng, B., Guo, X., and Zuo, J. (2022). Exploration of public stereotypes of supply-and-demand characteristics of recycled water infrastructure - evidence from an event-related potential experiment in Xi'an, China. *J. Environ. Manag.* 322, 116103. doi:10.1016/j.jenvman.2022.116103

Fu, H., Zhang, H., Zhang, M., and Hou, C (2023). Modeling and dynamic simulation of the public's intention to reuse recycled water based on eye movement data. *Water* 15 (1), 114. doi:10.3390/w15010114

Gao, H., Zhou, C., Li, F., Han, B., and Li, X. (2017). Economic and environmental analysis of five Chinese rural toilet technologies based on the economic input–output life cycle assessment. *J. Clean. Prod.* 163, S379–S391. doi:10.1016/j.jclepro.2015.12.089

Hill, G. B., Baldwin, S. A., and Vinneras, B. (2013). Evaluation of Solvita compost stability and maturity tests for assessment of quality of end-products from mixed latrine style compost toilets. *Waste Manag.* 33 (7), 1602–1606. doi:10.1016/j.wasman.2013.03.021

Ignacio, J., Alvin Malenab, R., Pausta, C., Beltran, A., Belo, L., Tanhueco, R., et al. (2018). Perceptions and attitudes toward eco-toilet systems in rural areas: A case study in the Philippines. *Sustainability* 10 (2), 521. doi:10.3390/su10020521

Junghanns, J., and Beery, T. (2020). Ecological sanitation and sustainable nutrient recovery education: Considering the three fixes for environmental problem-solving. *Sustainability* 12 (9), 3587. doi:10.3390/su12093587

Liu, D., Xie, B., Dong, C., Liu, G., Hu, D., Qin, Y., et al. (2018). Effect of fertilizer prepared from human feces and straw on germination, growth and development of wheat. *Acta Astronaut.* 145, 76–82. doi:10.1016/j.actaastro.2018.01.014

Liu, N., Xu, L., Han, L., Huang, G., and Ciric, L. (2021). Microbiological safety and antibiotic resistance risks at a sustainable farm under large-scale open-air composting and composting toilet systems. *J. Hazard. Mater.* 401, 123391. doi:10.1016/j.jhazmat.2020.123391

Liu, X., Dai, J., Ng, T-L., and Chen, G. (2019). Evaluation of potential environmental benefits from seawater toilet flushing. *Water Res.* 162, 505–515. doi:10.1016/j.watres.2019.07.016

MARA (2020). *GB/T 38836-2020: Technical specification for construction of rural household latrine with three-compartment septic tank*. Beijing: Standardization Administration of the People's Republic of China.

Poortvliet, P. M., Sanders, L., Weijma, J., and De Vries, J. R. (2018). Acceptance of new sanitation: The role of end-users' pro-environmental personal norms and risk and benefit perceptions. *Water Res.* 131, 90–99. doi:10.1016/j.watres.2017.12.032

Saaty, T. (1980). *The analytic hierarchy process: Planning, priority setting, resources allocation*. New York: McG raw-Hill Company.

Shi, Y., Zhou, L., Xu, Y., Zhou, H., and Shi, L. (2018). Life cycle cost and environmental assessment for resource-oriented toilet systems. *J. Clean. Prod.* 196, 1188–1197. doi:10.1016/j.jclepro.2018.06.129

Singh, R. P., Kun, W., and Fu, D. (2019). Designing process and operational effect of modified septic tank for the pre-treatment of rural domestic sewage. *J. Environ. Manag.* 251, 109552. doi:10.1016/j.jenvman.2019.109552

Tan, L., Zhang, C., Liu, F., Chen, P., Wei, X., Li, H., et al. (2021). Three-compartment septic tanks as sustainable on-site treatment facilities? Watch out for the potential dissemination of human-associated pathogens and antibiotic resistance. *J. Environ. Manag.* 300, 113709. doi:10.1016/j.jenvman.2021.113709

Tembhurkar, S., Ralegaonkar, R., Azevedo, A., and Madurwar, M. (2022). Low cost geopolymer modular toilet unit for ODF India – a case study. *Case Stud. Constr. Mater.* 16, e00937. doi:10.1016/j.cscm.2022.e00937

United Nations (2022). *Sustainable development goals reports 2022*. New York: United Nations.

Wang, G. Y. (1990). Unascertained information and its mathematical treatment. *J. Harbin Univ. Civ. Eng. Archit.* 23 (4), 1–8.

Wu, S., Zhang, Y., and He, B. J. (2021). Public willingness to pay for and participate in sanitation infrastructure improvement in western China's rural areas. *Front. Public Health* 9, 788922. doi:10.3389/fpubh.2021.788922

Xing, M., Liu, X., and Luo, F. (2022). How does the development of urban agglomeration affect the electricity efficiency of resource-based cities?—an empirical research based on the fsQCA method. *Socio-Economic Plan. Sci.* 2022, 101479. doi:10.1016/j.seps.2022.101479

Zakaria, F., Ćurko, J., Muratbegovic, A., Garcia, H. A., Hooijmans, C. M., and Brdjanovic, D. (2018). Evaluation of a smart toilet in an emergency camp. *Int. J. Disaster Risk Reduct.* 27, 512–523. doi:10.1016/j.ijdrr.2017.11.015

Zhou, W., Zhang, F., Cui, S., and Chang, K. C. (2022). Is there always a negative causality between human health and environmental degradation? Current evidence from rural China. *Int. J. Environ. Res. Public Health* 19 (17), 10561. doi:10.3390/ijerph191710561

Zhu, L., Zhao, Z., Wang, Y., Huang, Q., Sun, Y., and Bi, D. (2021). Weighting of toilet assessment scheme in China implementing analytic hierarchy process. *J. Environ. Manag.* 283, 111992. doi:10.1016/j.jenvman.2021.111992

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Faecal sludge emptying in Sub-Saharan Africa, South and Southeast Asia: A systematic review of emptying technology choices, challenges, and improvement initiatives

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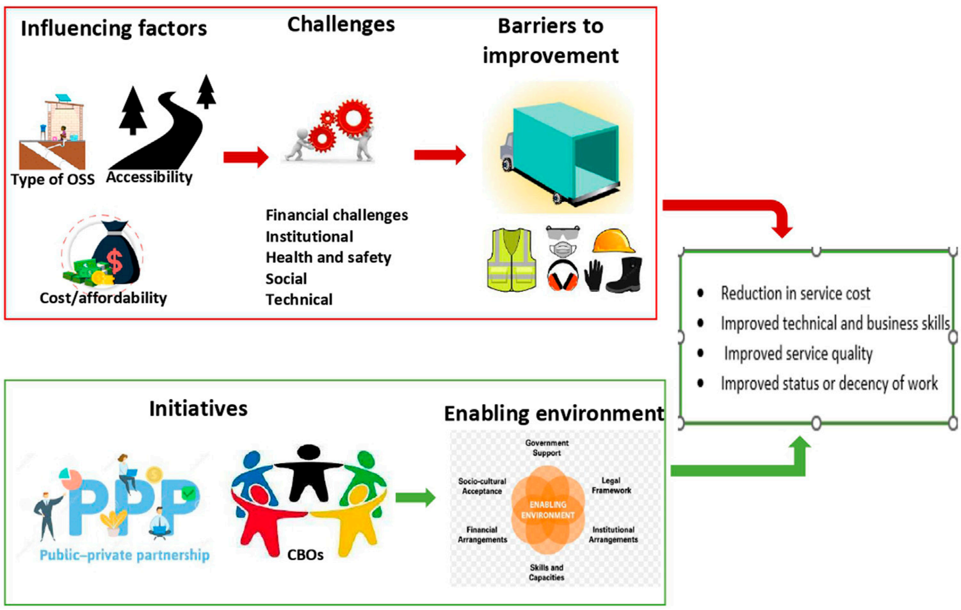
The emptying and transport of faecal sludge (FS) is a fundamental aspect of the sanitation service chain and is mostly carried out by private operators who usually face a lot of challenges. Our review assessed how influencing factors and challenges FS emptiers face are linked and in turn how they act as barriers to improvement initiatives. We conducted a systematic review of peer-reviewed journals on FS emptying in sub-Saharan Africa, South and Southeast Asia published between January 2002 and December 2021. Amongst the 37 journals reviewed, accessibility was mostly documented (n = 18) as a factor which affected choice of emptying method, followed by cost (n = 14), quality of service (n = 13) and then sludge thickness (n = 8). We grouped the types of challenges identified from the publications into five categories of financial, technical and institutional (n = 14, each), followed by health (n = 12) and then social challenges (n = 8). Discussions on initiatives (n = 13) used to improve the emptying business were limited to Cost/affordability of sanitation services and access to finance by FS emptiers, which were noted to be the major barriers to effective implementation of these strategies. This review identified the need for sensitizing the public on FS emptying, financial modelling of manual emptying business and a need to study the relationship between perceptions and emptying behavior of users.

KEYWORDS

onsite sanitation, pit emptiers, Sub-Saharan Africa, South and Southeast Asia, barriers, initiatives, desludging, faecal sludge management

1 Introduction

Globally, about 3.6 billion people lack access to safely managed sanitation services (UNICEF/WHO, 2020). For Low- and Middle-Income Countries (LMIC), the most common types of sanitation facilities used by people are On-Site Sanitation (OSS) systems, which include pit latrines, flush toilets, aqua privies, and septic tanks (Afolabi and Sohail, 2016; Akumuntu et al., 2017; Manga, et al., 2019; Manga et al., 2022b). The use of OSS leads to the accumulation of Faecal Sludge (FS), which needs to be desludged and transported to the designated disposal sites or the FS treatment facilities for treatment before disposal to ensure the wellbeing of the users as well as the protection of the surrounding environment (Junglen et al., 2020; Manga et al., 2021; Manga et al., 2022a; Tokwaro et al., 2023). The emptying and transport



GRAPHICAL ABSTRACT

of FS is carried out by a number of stakeholders which include the private sector, Non-Governmental Organizations (NGOs), local government and municipal authorities (Peal et al., 2014; Manga, 2017; Singh et al., 2021). For over two decades, the private sector has been more responsive than government to the gap in FS emptying and transportation (Bassan, 2014). Private operators usually consist of mechanized, semi-mechanized and manual emptiers or operators (Mbéguéré et al., 2010). These operators are important because having toilets without a hygienic service chain has dire consequences on the environment and society (Bongi and Morel, 2015; Prasad and Ray, 2019). Though these operators play a fundamental role in faecal sludge management (FSM) chain, they usually face a lot of challenges which limit their efficiency and affect the profitability of their business. These challenges are linked to factors which affect the choice of emptying methods and also serve as barriers to the effectiveness of improvement strategies (Lerebours et al., 2021). To better understand the FS emptying business, this study reviewed: 1) factors which determine the choice of an emptying method, 2) challenges faced by FS emptiers and 3) initiatives that have been implemented to improve FS emptying business in Africa, South and Southeast Asia. This review investigated how the factors which influence the choice of emptying methods are linked to the challenges faced by the emptiers. The review also discusses how the influencing factors and challenges act as barriers to successful implementation of improvement initiatives. The results from this review provide background data on the role of influencing factors and challenges on the improvement of FS emptying, which can be incorporated into policy framing, infrastructure development and targeted behavior change strategies.

2 Methodology

In this review, PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Moher et al., 2009; Sprouse et al., 2022) were followed to identify all the relevant publications pertaining to FS emptying in Sub-Saharan Africa (SSA), South Asia and Southeast Asia. These regions were chosen because of their wide coverage with OSS and in turn widely spread emptying businesses (Tremolet, 2012). Web of Science, Environmental Complete, Scopus, Global Health, and PubMed were systematically searched for peer-reviewed literature published in English language in the past 20 years (January 2002 to December 2021). Titles and abstracts of all the studies were initially screened, and then full texts of potentially relevant studies were further screened for data on FS emptying and transport using inclusion and exclusion criteria, and search terms which are presented in the Supplementary Material, Supplementary Tables S1, S2, respectively. The data extracted included author, study setting, date of publication, location where the study was carried out, factors which influence choice of emptying method, FS emptying and transport challenges, initiatives to improve FS emptying business.

3 Results and discussion

3.1 Selection of reviewed publications

A total of 974 articles were available from the database and when selection criteria were applied, 843 records were excluded of which 333 were duplicates. Of the remaining 131 full text articles assessed for eligibility, 94 articles were further excluded and 37 articles from 25 countries met the inclusion criteria (Figure 1).

3.2 Geographical location and settings of reviewed emptying and transport studies

A higher percentage ($n = 23$, 62%) of the 37 studies reviewed was located in SSA, 11 (30%) in South Asia and six (16%) in South East Asia, with the largest fraction from Bangladesh ($n = 8$, 22%) (Figures 2,

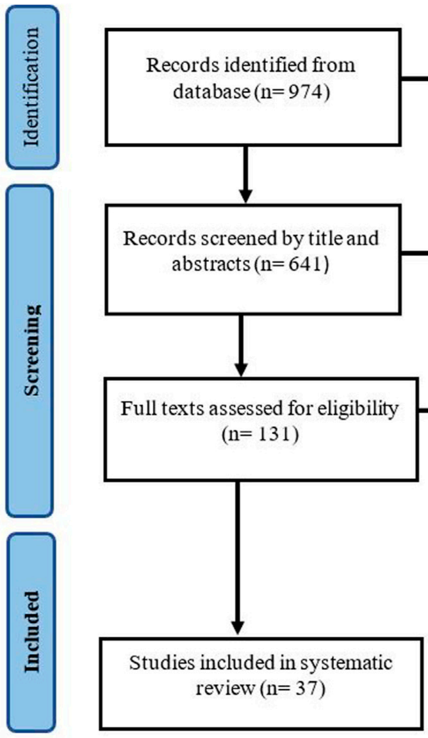


FIGURE 1
PRISMA flow diagram for studies in the systematic review of faecal sludge emptying in sub-Saharan Africa, South and Southeast Asia.

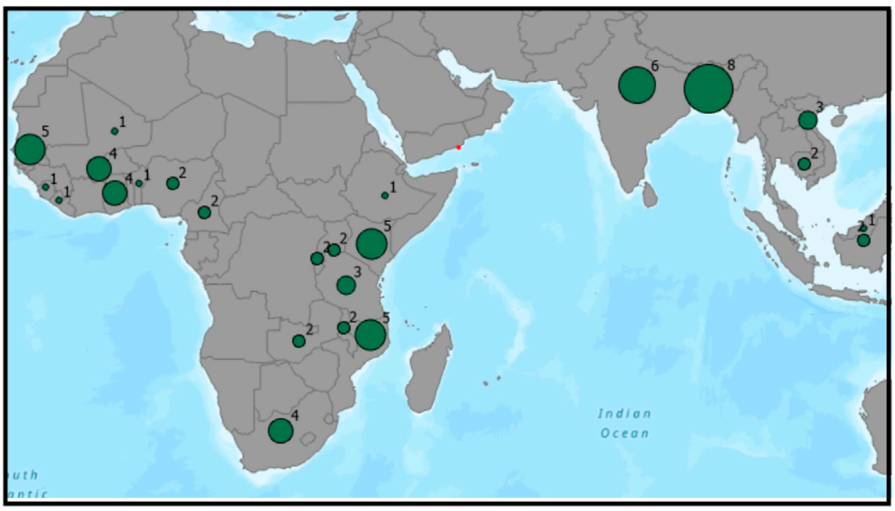


FIGURE 2
Number of studies in countries within Sub-Saharan Africa, South and Southeast Asia selected in the review.

3). Five of the included studies looked at FS emptying and transport in multiple countries; three of these studies considered countries in both Asia and SSA (Eawag and Sandec, 2006; Thye et al., 2009; Chowdry and Kone, 2012), while one looked at some countries in SSA (Lerebours et al., 2021) and the last one looked at some South Asian countries (Anh et al., 2018). Only one study examined FS emptying business in countries in SSA, South and Southeast Asia together with countries outside these regions (Hawkins et al., 2014).

Most of the studies were located in urban areas (n = 26, 70%), 10 (27%) in peri-urban areas and only one in a rural area (Figure 3). Only studies which were self-described as peri-urban were categorized as such while those which looked at cities were categorized as urban. The

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higher number of studies in the urban and peri-urban areas can be attributed to the growing interest of FS emptying in urban areas due to rapid urbanization and high population density, leading to generation of high FS volumes, hence, frequent filling of OSS facilities. The 37 studies included in this review comprised of 17 observational studies, 10 practitioner papers (journals and publications which aim at conveying research, models or even theory to practitioners and stakeholders in the FSM field, such as, FS emptiers, municipal authorities, households, non-governmental, community based organizations, 10 case studies and there were no experimental studies (Figure 3). It was also noted that there is increasing awareness on the importance of FS emptying, which has brought about increase in the number of studies published over time. For the 20 years considered, more than half of the studies were published in the last decade (n = 27; 73%).

3.3 Factors influencing choice of an emptying method

The prevalence of emptying methods shows that manual emptying was presented by majority of the studies (n = 32, 86%), followed by mechanical emptying (n = 26, 70%) and then emptying by other methods (gravitational or flooding out/pit diversion) (n = 4, 11%) (Figure 3). A total of 25 studies reported on emptying by both manual and mechanical methods, though four of these studies presented gravitational emptying or FS flooding out of the containment. Manual emptying involves the use of human power and hand tools such as spades, forks and containers/scopes (Mikhael et al., 2014) for the removal of FS while mechanical emptying involves the use of mechanized technologies like vacuum trucks (Thye et al., 2009; Chowdry and Kone, 2012). Gravitational emptying involves intentional release of FS to the environment by unplugging a drainpipe installed in an elevated or exposed portion of the pit, especially during heavy rains (Jenkins et al., 2015). The type of emptying method employed depends on cost/affordability of the service, accessibility, quality of the service, availability, and the thickness of the FS to be emptied (Figure 2). Figure 4 and Figure 5 show the frequency of discussing the aforementioned factors in relation to the emptying methods and region, respectively. From Figure 4, it can be observed that the number of papers which discussed each emptying factor in relation to mechanical emptying (Figure 4A) are the same with those that discussed each factor in relation to manual emptying (Figure 4B) except for cost/affordability of the service which was higher for manual emptying. The equal number of studies give an indication that the factors which negatively

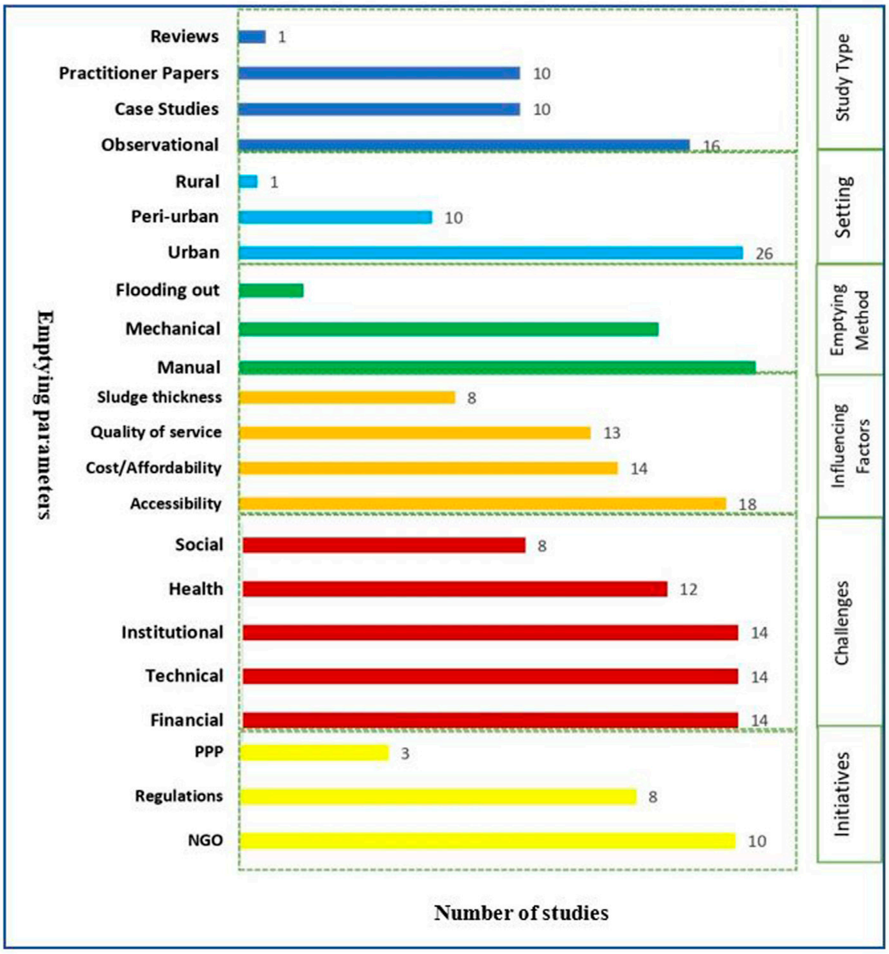

FIGURE 3
Characteristics of studies included in the review of feacal sludge emptying in Sub-Saharan Africa, South and Southeast Asia.

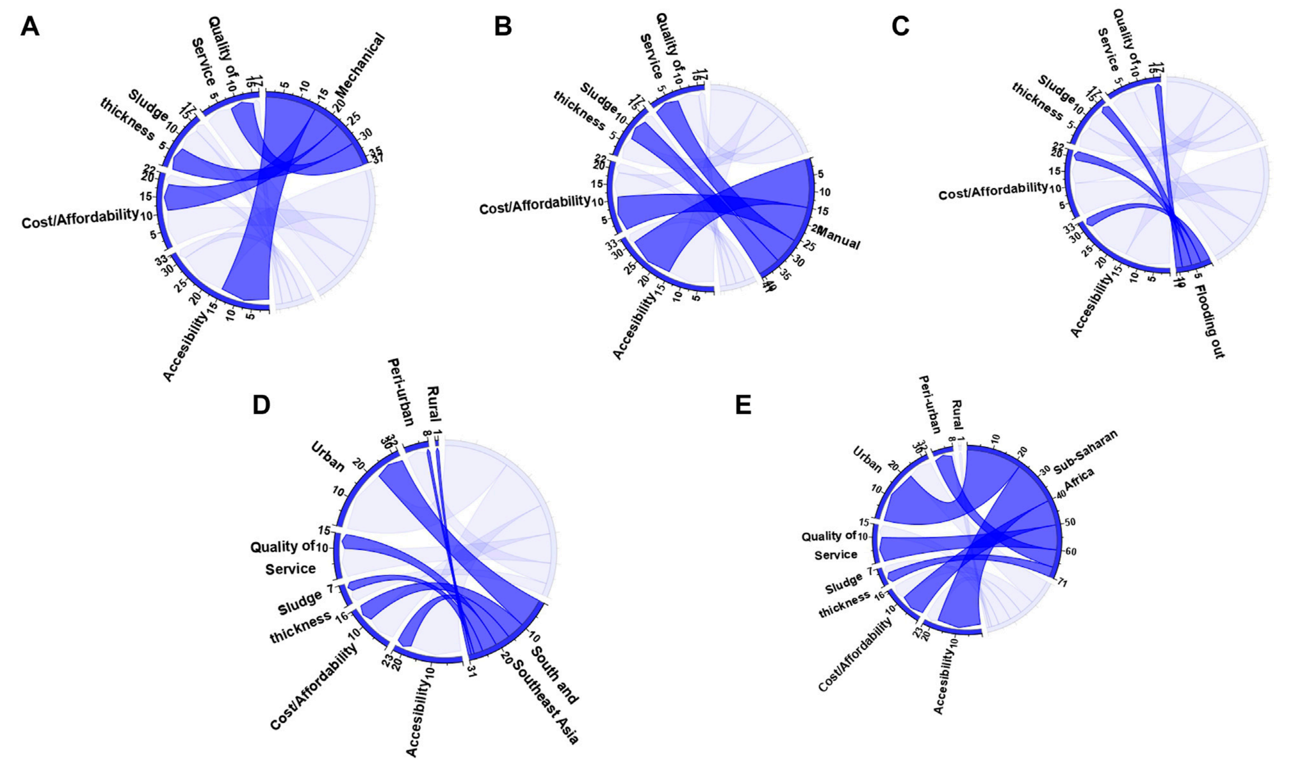

FIGURE 4
Factors influencing selection of emptying methods **(A)** Manual emptying method **(B)** Mechanical emptying method **(C)** Flooding out **(D)** Sub-Saharan Africa **(E)** South and Southeast Asia.

affect mechanical emptying could have positive impact on manual emptying and *vice versa*.

3.3.1 Accessibility to containment facilities and/or emptying means

Accessibility was discussed by 18 studies as a major factor influencing the choice of an emptying method. 12 of the 18 studies discussed accessibility in terms of access to sanitation facilities while 10 discussed access in terms of availability of service providers. It was observed that accessibility is a major factor which negatively affects mechanical emptying. This is mainly found in unplanned informal settlements with poor road conditions, making it difficult to traverse the narrow streets (Owusu, 2013; Kennedy-walker, 2015). This presents the need for long hose pipes thereby adding to the cost of emptying. Another problem is poor design and construction of containment facilities, which either have no or limited access for emptying as some dwellers construct other structures on top of them or too close (Holm et al., 2018). Such inaccessibility to sanitation facilities by mechanical emptiers necessitates the use of manual emptying, which is often discouraged. Chowdry and Kone (2012) reported manual emptying of public sanitation facilities in low-income areas of Kenya due to inaccessibility by trucks due to narrow paths. Jenkins et al. (2015) reported that in Tanzania, households with accessible plots and service availability were on average 23 times more likely to use a higher hygienic service than those without access.

Manual emptiers are known locally, easy to locate and can easily access the densely populated informal settlements, making them the most commonly used (Choudry and Kone, 2012; Hawkins and Muximpua, 2015). In Dhaka, the capital city of Bangladesh, it was observed that most people use manual emptying due to cost, flexibility of timing and the ease of availing the service. They find the process of accessing mechanical emptying services from the municipality to be lengthy and bureaucratic (Opel et al., 2011). This situation is not peculiar to Dhaka. A study by Singh et al. (2021) in Khulna Bangladesh, revealed that in many cases, households made use of manual emptiers as emptying service by the city corporation (Khulna city corporation, KCC) is not timely as households call for emptying only when the pit/tank is full and starts overflowing. This suggests that if municipal authorities make their procedures less bureaucratic and more friendly, accessibility will be increased, and this will in turn increase their profit.

3.3.2 Cost and/or affordability of the emptying service

Emptying cost was cited in 14 (38%) studies as the most influential factor affecting the choice of emptying method (Figure 2). Cost of mechanical emptying is reported to be higher than that of manual emptying in most of the studies. In the study by Balasubramanya et al. (2017) in Bhaluka Bangladesh, it was reported that mechanical emptying (13 USD) cost more than manual emptying (5 USD). The higher cost is attributed to high operation and maintenance costs as well as the cost of discharging FS at treatment plants or legal disposal sites (Mougoue et al., 2012; Hawkins and Muximpua, 2015; Prasad and Ray, 2019; Manga et al., 2020). Long distance to the disposal sites and the poor road conditions also contributes to the high operating costs (Mougoue et al., 2012; Oduro Kwarteng et al., 2019). Due to the

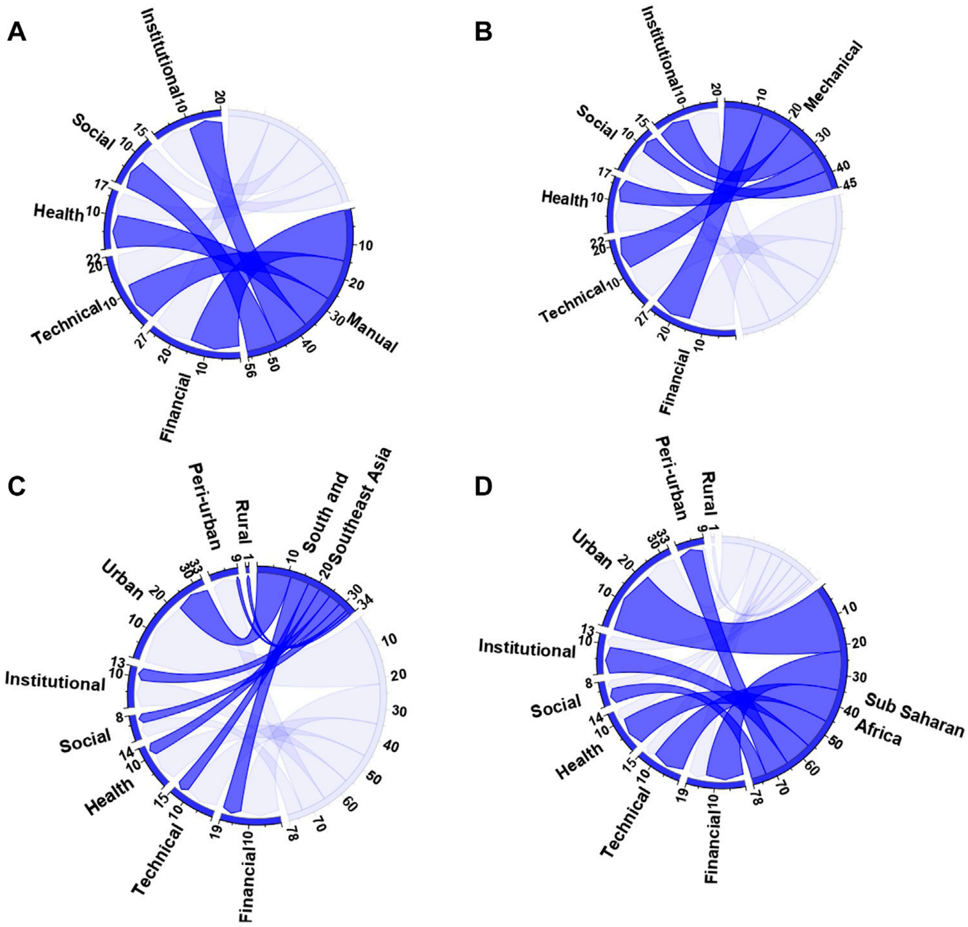

FIGURE 5
Challenges faced by feacal sludge emptiers **(A)** Manual emptying method **(B)** Mechanical emptying method **(C)**Sub-Saharan Africa **(D)** South and Southeast Asia.

absence of government support in most of these countries, it is the households to meet the higher cost of mechanical emptying, tempting them to employ manual emptying methods, despite having knowledge of risks involved. Hawkins and Muximpua (2015) reported the price of emptying services rendered as the most common disincentive to using hygienic mechanical emptying among pit latrine users in Maputo (Mozambique), and most people continue to use cheap and unhygienic manual emptying, where there is local burial and open dumping of FS. Even where road access is available, slum dwellers prefer manual emptiers as their charges are considerably lower than mechanical emptiers (Mallory et al., 2021). Some households which have little or no money to pay for emptying services have resorted to gravitational emptying which is the most dangerous method as large volumes of untreated FS are discharged into the environment (Jenkins et al., 2020; Rotowa and Ayadi, 2020). Though manual emptying is a cheaper method of emptying, the potential health effects to the users, emptiers and the environment in the long run makes it an inapt method.

Although most studies reported mechanical emptying to be more expensive than manual emptying, some studies reported otherwise. Parkinson and Quader (2008) in their study in Bangladesh noted that manual emptiers demand exorbitant prices from households especially in areas that are inaccessible by mechanical emptiers as they know that households have no alternative. Peletz et al. (2020) reported that in Kisumu Kenya, formal manual emptying was about four times more costly (6,169 KES or 62 USD) than mechanical emptying (by vacutugs) (1,630 KES or 16 USD).

3.3.3 Faecal sludge density or thickness

Eight studies reported on how variation in density or thickness of FS in OSS facilities affects the choice of emptying method (Figure 3). The thickness of FS depends on the quantity of solid wastes deposited in sanitation facilities, water addition, infiltration or exfiltration of water and the extent of compaction/solidification that has occurred (Manga et al., 2016; Simwambi et al., 2017; Semiyaga et al., 2022). FS from lined pit latrines and septic tanks is less thick compared to that from unlined pit latrines. This is because unlined pit latrines allow for the exfiltration of the liquid fraction of FS into the surrounding soils through the permeable sidewalls and open bottom (Tilley et al., 2008; Manga et al., 2022a).

The presence of very thick FS makes it difficult to empty the OSS facility as materials found in the pit are usually in a partially compacted or solidified form (Bakare, 2019). It has been noted that the mechanical emptiers are not usually effective in removing the heavier and compacted FS at the bottom of pits (Mougoue et al., 2012; Muxímpua and Hawkins, 2012). Sometimes, large quantities of water needs to be added to the pit to fluidize and mix its content before mechanical devices can be used (Bakare, 2019). This usually increases emptying costs as water is in short supply in such low income areas (Krueger et al., 2020). In addition, presence of thick FS usually affects the efficiency and reduces the useful life of the mechanical equipment due to blockage of suction pipes and valves, leading to damage of the equipment. In such cases the most viable emptying technique is to manually dig out the pit content (Bakare, 2019). However, it is imperative that when manual emptiers are called upon to empty the pits, they observe standard operating procedures by putting on personal protective equipment. This is needed to protect them from the hazardous nature of pit content.

3.3.4 Quality of FS emptying service

About one-third of the studies (n = 13, 35%) reported how the quality of service provided by the emptiers influenced the choice of emptying method (Figure 2). The quality of service is defined in terms of hygienic methods applied during emptying (n = 10, 77%), time spent emptying (n = 6, 46%), and complete emptying of FS contents (n = 5, 38%). Mechanical operators are found to provide more efficient, hygienic services, and easily accessing treatment plants compared to manual emptiers (Parkinson and Quader, 2008; Thye et al., 2009; Semiyaga et al., 2022). Mechanical operators are usually organized into registered companies, thereby providing safer working conditions than manual emptiers whose method of operation exposes the population to peril associated with poor FS handling (Mbéguéré et al., 2010; Zaquot et al., 2020). Manual emptiers commonly dump the FS into nearby drains, canals or water bodies, leading to severe public health and environmental risks (Boot and Scott, 2008; Jenkins et al., 2014). However, the quality of service was found to not only depend on hygiene, but also on the perceptions of people, income levels and the waiting times to assess the service. In Dar Es Salaam, Tanzania, it was observed that households preferred manual unhygienic methods because these methods removed all the FS from the pit and were more affordable than existing mechanical hygienic services (Jenkins et al., 2015).

3.4 Challenges faced by faecal sludge emptiers

The challenges faced by FS emptiers are categorized into social, health and safety, technical, financial, and institutional (Figure 3). At least a category of challenge faced by FS emptiers was discussed in each of the 37 studies. The frequency of reporting these challenges in relation to emptying methods and sub-region are illustrated in Figure 5. Figures 5A, B shows that in comparison to mechanical emptiers, manual emptiers face more challenges. This can mostly be attributed to the dangerous manner with which they carry out their work and their inability to be organized into groups which can voice out their opinions. From Figures 5C, D, it can be observed that the number of studies carried out in SSA are higher than those in South and South East Asia. The higher number of studies in SSA may be attributed to the fact that onsite sanitation systems are much more expensive in SSA than in South and South East Asia and this contributes to more challenges in SSA and in turn more studies in the region. Sanitation facilities in Africa are on average three times more expensive than in Asia due to factors such as high costs of materials (i.e., cement and bricks), lack of prefabricated or mass produced toilet components (which are common in Asia), and the informality of the construction sector which is dominated by micro-entrepreneurs (Ulrich et al., 2016).

3.4.1 Social challenges

The stigma associated with FS emptiers was discussed in eight studies, and this was mostly peculiar to manual emptiers. Manual emptying is carried out as an informal activity by poor people who need a form of living (Chowdry and Kone, 2012). Manual emptying is deemed illegal in a number of countries such as India, Kenya, Ghana and Bangladesh (Zaqout et al., 2020). In India, manual emptying is seen as a caste-based practice done by people who are members of the lowest social class (Prasad and Ray, 2019). Manual emptiers are usually socially excluded, very poor, and work under inhumane conditions (Prasad and Ray, 2019). In Kibera, a large slum in Nairobi, manual emptiers usually face violence and extortion in society (Eales, 2005; Parkinson and Quader, 2008; Mallory et al., 2021). Bassan et al. (2013) reported that the emptiers usually face harassment from the citizens in Maputo Mozambique. Manual emptiers are seen as carrying out undignified, demeaning work and most of the times are usually marginalized, hence, they usually carry out their tasks in the middle of the night in order not to be seen by the neighbours (Muxímpua and Hawkins, 2012). The problem faced by manual emptiers is further compounded by the fact that they are not formed into organizations, and therefore, do not have any association which could voice out their opinions when required. The sigma they face brings about psychological trauma and as a means of coping with this, the manual emptiers resort to taking intoxicants such as alcohol, opioids, tobacco and cocaine to numb their senses (Muxímpua and Hawkins, 2012; Gautam et al., 2021). However, the continuous use of alcohol and hard drugs has detrimental effects on the health of these workers.

3.4.2 Health and safety challenges

FS emptiers are usually exposed to a wide range of hazards while carrying out their work, and they do not usually have health insurance (Zaqout et al., 2020; Gautam et al., 2021). The 14 studies (38%) which documented the health and safety of the FS emptiers mainly discussed exposure to pathogens, musculoskeletal disorders, physical injuries and inhalation of harmful gases. FS is a very hazardous material that contains large amounts of pathogens (bacteria, protozoa, virus and worms) which pose serious health risks (Holm et al., 2015). The common routes through which the pathogens get into the emptiers' bodies are *via* hand-to-mouth contacts (accidental ingestion), inhalation and open cuts in the body (Fracchia et al., 2006). In the study carried out on pit emptiers in eThekwini region, Durban South Africa, pathogens were found in the gloves, bottom of the boots, hands and masks of the pit emptiers (Bonthuys, 2017). Some of these pathogens like *ascaris lumbricoides* (roundworm) eggs can remain viable for months because of their impermeable eggshells (Bonthuys, 2017; Capone et al., 2022; Manga et al., 2023). Infections by these organisms usually have appalling implications; for instance, helminths can cause neurological defects. FS emptiers are susceptible to sanitation related diseases such as dysentery, cholera, diarrhea, hepatitis A, typhoid and polio (Weststrate et al., 2019).

Manual emptiers are reported to develop musculoskeletal disorders due to the heavy work involving pulling, pushing and carrying heavy FS containers (Chumo et al., 2021). In addition, emptiers suffer from physical injuries which mainly occur in the process of accessing the containment system, whereby the workers get exposed to risk of bruises, wounds and injury mostly on the feet, knees and thighs as they move around bushes which have thorns without slippers; or in the processing of opening the containment systems covers/lids as these are usually heavy to be lifted with bare hands, and this can cause injuries to the workers' extremities (Gautam et al., 2021). It has been reported that a lot of sanitation workers die every year servicing pit latrines (Hawkins et al., 2014; Prasad and Ray, 2019). Furthermore, FS emptiers usually inhale harmful gases which could lead to asthmatic problems, respiratory issues, headaches, irritation and burning of the eyes, and sometimes death from suffocation (Patil and Kamble, 2017).

The health risks to the FS emptiers are a function of: 1) type and quantity of the viable pathogens in the emptied FS; 2) the design of the containment; and 3) operational practices and individual behavior, that is, the attitude to risk or compliance of both the workers and the household users. In a study by Bonthuys (2017), it was observed that while necessary protective gear and code of conduct were not often available, the emptiers did not always make use of the steps available to them for their protection. They posited that it was either because the emptiers did not have an in-depth understanding of the hazards associated with sludge emptying or they were not motivated to apply what they knew. In the study carried out in India by Prasad and Ray (2019), it was noted that the emptiers mentioned gloves and boots, which are available in the market were not suited to the type of job they do, and they did not want the public to perceive that the type of job they do is dangerous. In the study by Gautam et al. (2021), it was observed that some workers were of the belief that their longevity in the profession has helped them develop a certain degree of immunity, and they therefore, carry out pit emptying without using PPE. Households are partly responsible for health risks to workers due to their non-chalant attitude and practices ranging from non-compliance of septic tank construction to design standards, irregular cleaning and improper disposal of inappropriate items in toilets. The aforementioned show that solving the health and safety problems of FS workers goes beyond the use of PPE, it also involves steps such as behavioral change campaigns, improvements in decanting stations, and better access to appropriately designed tools.

3.4.3 Technical challenges

The technical challenges faced by FS emptiers were reported in 14 studies. The major technical challenge cited was poor construction of sanitation facilities. In Maputo Mozambique, sanitation facilities are built by the households who do not follow technical standards or guidelines, making them a source of threat to the emptiers (Muxímpua and Hawkins, 2012). In addition, poorly constructed pit latrines by untrained builders have been reported in Duala and Yaoundé in Cameroon (Mougoue et al., 2012). This has also been confirmed by Semiyaga et al. (2015) and Manga et al. (2022b). One factor that contributes to this is inadequate implementation of urban planning which brings about construction of residential dwellings with low quality sanitation facilities (Holm et al., 2015).

3.4.4 Financial challenges

The 14 studies discussed financial challenges it in terms of accessing capital to start the emptying business and the profitability of the business. Starting the FS emptying and transport business requires a great investment in purchasing a truck, acquiring administrative documents such as insurance, technical inspection, and operation or parking permit (Mougoue et al., 2012). Though financial assistance is usually obtained in the form of loans either from banks, thrift and loans from relations; accessing the money is usually difficult as banks, financial institutions and private entrepreneurs are not ready to invest in pit-emptying business (Opel et al., 2011). Most of the entrepreneurs are reported to only manage investing in second-hand mechanical trucks which have outlived most part of their useful lives and often breakdown, making it difficult for them to honour the deed of agreements when the credit was obtained (Mougoue et al., 2012).

Apart from the uncertainty and variability in the costs of leasing and buying equipment, the wages from FS emptying is low and irregular (Zaqout et al., 2020). The demand for the services of FS emptiers is subjected to seasonal variations as they can only depend on FS services during the rainy season (Nkasah et al., 2012; Zaqout et al., 2020). In the study by Chowdry and Kone (2012) on sanitation service providers in some countries in Africa and Southeast Asia, it was observed that the private service providers usually operate the FS business as an additional source of income rather than as their principal business. In this same study, it was noted that the manual emptiers are also engaged in other manual labor like construction, road sweeping, and cleaning public toilets (Chowdry and Kone, 2012). Muxímpua and Hawkins (2012) observed that though the manual emptiers in Maputo Mozambique usually take the business seriously, they usually carry out other side jobs as they stated that the FS services alone cannot sustain them. Also, the emptiers usually have considerable financial burdens from high healthcare expenditure especially as they have neither health insurance nor compensation for days lost due to illness (Zaqout et al., 2020).

3.4.5 Institutional challenges

The institutional challenges faced by FS emptiers were presented in 14 (38%) of the papers. The results show that there are either no institutional frameworks or the ones that exist are not properly enforced in a number of LMICs (Akumuntu et al., 2017). For these countries implementing the framework, there are usually challenges such as: lack of capacity (technical or financial) of the stakeholders involved to enforce the regulations (Holm et al., 2018; Kohlitz et al., 2018); inadequate sanitation-related regulations (Sinharoy et al., 2019; Weststrate et al., 2019); and inadequate data on the available sanitation facilities, service providers and their operations (Sinharoy et al., 2019). Prasad and Ray (2019) stated that in India, the emptying of pits and handling of wastes to a great extent, remains undiscussed in policy documents. The lack of credibility and consistency in the institutional framework leads to a situation whereby FS emptying and transport services are provided without adequate technology, regulations and safety precautions (Jayathilake et al., 2019).

The lack of regulation usually leads to imbalanced competition among the FS emptiers as those who operate as companies pay taxes while those who operate as individuals do not (Akumuntu et al., 2017). In Yaoundé Cameroon, it was observed that the public authorities impose tax at the disposal sites, but the money realized is not put back into sustenance of the system but rather used for the selfish gains of the authority. Moreover, there are no fixed prices as they depend on the bargaining power of the operator (Mougoue et al., 2012). In another study in Nkobikok, Yaoundé Cameroon, it was noted that the prices for emptying usually fluctuate due to undue obligatory or unofficial fees and bribes paid to officials by the emptiers (Noumba et al., 2017). In Vietnam and Thailand, the legislation for FS collection and transport is still neglected (Anh et al., 2018). Another example is in Accra Ghana where the responsibility of FSM falls under the Waste Management Department (WMD), but many private mechanical truck operators complain about their activities not being monitored regularly and effectively by WMD (Boot and Scott, 2008). In a study by Lerebours et al. (2021), where the opinions of different pit emptiers across sub -Saharan Africa were sought about the regulatory framework in place, the respondents said that rules and sanctions should be applicable to all operators including public operators to ensure fair competition. The emptiers who provide unsanitary services charge a lesser amount than the compliant service providers, thereby disturbing the market and reducing the financial viability of safe services.

For successful implementation of FSM, there is need for the development of institutional frameworks based on the specifics of the local situation (Kone, 2010; de La Brosse et al., 2016). The framework usually covers five aspects which include: 1) design and construction of onsite facilities; 2) demand of emptying and transport services; 3) operations through licenses and permits; 4) transport and disposal of faecal sludge; and 5) service tariffs (Trémolet, 2012; Cross and Coombes, 2014; Rao and Otoo, 2017). For successful implementation of institutional frameworks to occur, apart from laws and strategies being clearly defined, the roles and responsibilities of each stakeholder involved should be regulated and enforced, and the government should show strong dedication through consistent funding and training schemes. Included in these frameworks should be provisions for worker training and certificates through incentives by the sanitation authorities in order to improve the services rendered by these workers, allow for limited environmental impact and bring about safe work conduct. Also, monitoring, record keeping and performance evaluation should be incorporated into these frameworks as this will aid in informed decision-making in the long run.

3.5 Initiatives to improve faecal sludge emptying business

In order to reduce some of the challenges faced by pit emptiers and make the pit emptying business more sustainable and lucrative in LMICs, certain initiatives have been implemented. These initiatives which were presented in 13 (35%) of the papers reviewed include the use of private public partnership (PPP), Involvement of Non-Governmental Organizations (NGOs)/International Donor Agencies (IDAs)/Community Based Organizations (CBOs).

3.5.1 Private public partnership

Nijkamp et al. (2002) defines Private Public Partnership (PPP) as an institutionalized form of cooperation between public and private actors, who based on their specific objectives, work together towards a joint target. In the collection and transport of FS, the public sector is characterized by the local authorities which could be metropolitan, municipal or district while the private sector is a private company or private operator (Scott et al., 2013). Three of the studies in this review cited examples of where PPP have been implemented. In Marikina city in the Philippines, the water utilities, the city municipality and the private sector organizations worked together to implement a 5-year cycle sludge removal program. During the time for sludge removal, the city authorities provide support for the private sector organizations by sending trucks into the areas where the sludge removal will occur to advertise (through announcements by loudspeakers) the private companies in order to involve more households (Bassan, 2014). This initiative brought about 95% compliance with sludge removal in the areas involved through the generation of a working system that is supported by the public and private sectors and the household users (Bassan, 2014). Another area where this has been implemented is in Dakar Senegal, where the government regulated the activities of the private sector and helped to manage the FS treatment facilities. The private sector provided the emptying services to the population (its main customers) and the government contracted out part of the collective sewage network to the private sector and them with the task of pit emptying in religious cities on the eve of national ceremonies (Scott et al., 2013).

In Dhaka, the capital city of Bangladesh, a model with the brand name SWEEP was used for PPP whereby the local government or authority bought a vacuum tanker and leased it out to a private party. The local authority was also responsible for infrequent maintenance of the vehicle, marketing, regulation and FS disposal at a designated site. On its part, the private party paid a security deposit and a monthly lease fee to the government, carried out the emptying and transport services, and did regular operation and maintenance of the tanker. This initiative was reported to be profitable and successful (WSUP, 2016). In Kumasi Ghana, the Kumasi Metropolitan Assembly (KMA) mobilized revenue to finance FS collection, provided treatment plants, monitored the activities and operation of the private emptiers, and also helped to subsidize taxes on the importation of trucks' spare parts. The private sector helped in the collection of FS and contributed to the maintenance of the treatment plant (Owusu, 2013).

In sum, it can be seen that the use of PPP gives room for the local government to help the private sector through advertisements, subcontracting jobs, leasing equipment, provision of subsidies and also formulation and implementation of policies. This has helped to improve the profitability of FS emptying business and provide better working conditions for the emptiers.

3.5.2 Involvement of non-governmental organizations and international donor agencies in faecal sludge emptying business

Of the 37 studies reviewed, 10 (27%) documented the involvement of non-governmental organizations (NGOs), Community Based Organizations (CBOs) and International Donor Agencies (IDAs) in educating the emptiers and raising awareness on FSM. This helps to reduce the social stigma associated with FS emptying business. In Mukuru slum (Kenya), two NGOs (i.e. Sanergy and Umande Trust) helped in providing sanitation services to the residents. Sanergy is a private company which provides container-based sanitation services in Mukuru with regular emptying (Tilmans et al., 2015). Umande Trust worked closely with informal pit emptiers to provide 'bio-centres' which are public toilets based on anaerobic digestion technology, hence producing biogas that is used for cooking (Binale, 2011). The involvement of these organizations helped to reduce the violence sanitation workers face from hoodlums in order to carry out their work during the day rather than in the night.

In Maputo Mozambique, the Japanese Social Development Fund (JSDF), World Sanitation Program (WSP) of World Bank and World Sanitation for Urban Poor (WSUP) carried out a project–Maputo Sanitation Project - which involved equipping private service providers with technical, managerial and business skills, and equipment needed to provide FS emptying and transport services in a more hygienic manner (Hawkins and Muximpua, 2015). These operators were equipped with plastic water tanks mounted on handcarts and other equipment such as buckets, gulper (hand pump designed for desludging pit latrines), a diesel-powered trash pump for more liquid sludge and Personal Protective Equipment (PPE). The use of gulper equipment helped reduce the health and safety risks that the manual workers are usually exposed to.

Apart from the involvement of NGOs and IDAs, city corporations provide emptying services. For instance, the Kampala Capital City Authority (KCCA) in Kampala Uganda and Khulna City Corporation (KCC) in Bangladesh collaborate with local stakeholders to provide and improve FSM (Singh et al., 2021; Semiyaga et al., 2022; Singh et al., 2022). The city corporations help in subsidizing emptying price as well as encourage scheduled desludging. Scheduled desludging helps to reduce public health risks as residents do not have to wait till their tanks are full and overflowing (which can cause surface and ground water pollution).

From the aforementioned, it can be seen that the involvement of organizations in the emptying business has not only helped in improving the profitability but has also improving the quality of service provided by the emptiers. It has also brought about the subsidization of services thereby making it more affordable to the urban poor.

4 Links between challenges, influencing factors and barriers to improvement initiatives

Figure 6 is an illustration of the relationship between challenges faced by FS emptiers, factors which affect the choice of emptying methods and initiatives used in improving the emptying business. The characteristics of a particular location usually influences the type of setting (rural/urban) that would be found in the area, accessibility to the area, type of onsite sanitation facility found in the area and the quality of service affordable by residents of the area. The cost of emptying is a major factor which negatively affects mechanical emptiers as most people in poor communities cannot afford their services, which reduces the profitability of their business. Also, in order to save costs, most people do not carry out regular desludging but only request for the services of the emptiers when their onsite sanitation facilities are overflowing. This brings about health hazards to FS emptiers who have to come in direct contact with pathogenic FS littered all over the place. Lack of solid waste management systems in certain areas has propelled people to dump solid waste materials into sanitation facilities which causes physical injuries to manual emptiers. This also affects the useful life and efficiency of vacuum equipment due to blockage of suction pipes and valves. Accessibility as a factor negatively affects the profitability of mechanical trucks, which cannot operate in unplanned settlements with poor road conditions (Figure 6).

The use of PPPs and the involvement of NGOs, governmental organizations (GOs) or CBOs brings about the enabling environment required for the success of FS emptying business (Graphical Abstract). The six dimensions of the enabling environment for FSM include: government support, legal and regulatory framework, institutional arrangements, skills and capacities, financial arrangements, and sociocultural acceptance (Bassan, 2014). Governmental organizations through the introduction of subsidies can make improved sanitation services affordable to the poorest users. In addition, the government can provide regulations which will bring about standards for the construction of sanitation facilities, thereby eliminating the challenges faced by emptiers in

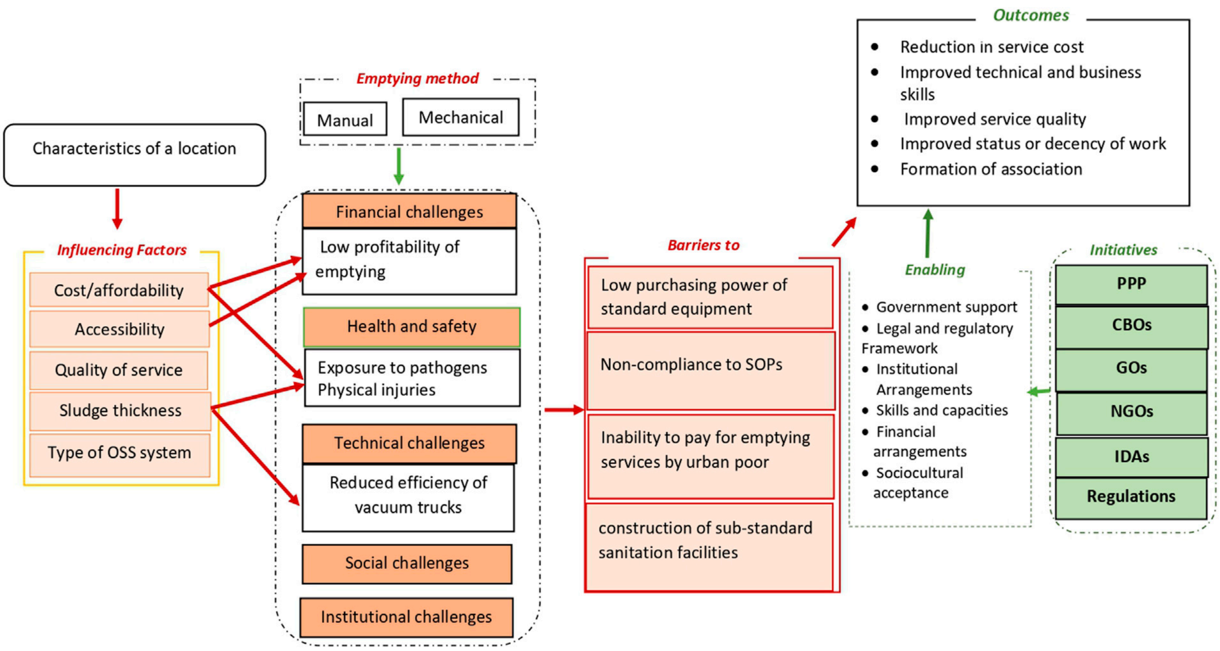

FIGURE 6
Relationship between factors influencing emptying methods, challenges faced by emptiers and improvement initiatives in FS emptying business.

accessing the facilities (Holm et al., 2015). Since the private sector plays a key role in FS emptying, the government should provide enabling environment for the private sector members through technical and business support (i.e, trainings on technical knowhow and financial management), financial assistance, provision and proper implementation of policies, strategies, institutional and regulatory frameworks. Also, governments through national health insurance schemes should provide access to healthcare services for the sanitation workers especially informal manual emptiers The introduction of PPP into FS emptying business is beneficial to both customers and FS emptiers. The customers get access to quality service while the emptiers have access to safe and clean collection machinery and PPE which improves the status and decency of the work (Hawkins and Muximpua, 2015; Holm et al., 2018). Also, PPP provides a platform through which emptiers (especially manual emptiers) can form associations which can give them an identity and propagate their voices when required. The involvement of NGOs and CBOs who usually hold regular workshops and trainings provides a platform for educating the emptiers on technical, business and behavioral skills which will help to improve the viability of their business (Kohlitz et al., 2018).

Though the aforementioned initiatives help to improve the working conditions of FS emptiers, certain influencing factors and challenges faced by the pit emptiers act as barriers to effective implementation of these initiatives. Challenges faced by FS emptiers especially limited access to finance affect their ability to comply with regulations and standard operating procedures. For instance, due to lack of financial resources, some emptiers especially manual operators cannot afford to buy standard equipment or PPE. Also, due to social challenges, some emptiers might not want to put on PPE as they do not want the public to perceive that the type of job they do is dangerous (Prasad and Ray, 2019). Furthermore, even if standards are put in place towards the construction of proper sanitation facilities, some poor households cannot afford to construct the facilities to design standards, they thereby make use of cheap and unethical methods. In addition, the provision of improved services by the emptiers has the implication that customers will be charged more for the services, which might not be viable as the urban poor might not be able to afford such services.

5 Implications of the review on faecal sludge emptying services

The results from this review show that cost is the most significant factor in influencing the choice of emptying method, hence, a major barrier to effective implementation of improvement strategies. Initiatives and regulations provided by the government and also trainings by NGOs, CBOs cannot be effective unless extra steps are taken to ensure that the emptiers have access to finance and services are subsidized for poor households. First, local authorities should help in bankrolling part of the services to enable FS emptying become a commercially viable business. If FS emptying services become viable, banks and financial institutions as well as private entrepreneurs may come forward to invest in it. In addition, bank loans should be made accessible to potential entrepreneurs in the sanitation sector. The loan conditions should be made more favorable with special consideration for small-scale enterprises and reduced interest charges over the short term. The health and safety budget for a municipality should include provision for health insurance for FS workers in order to make treatment affordable for these workers. In subsidizing sanitation services for households, government should identify sustainable resources for these subsidies which could be from government budgets, pro-poor sanitation surcharges imposed on utility bills, or higher fees charged to the wealthy (cross-subsidies). Though cost is the major factor which influences the choice of emptying method, use of cost reduction initiatives is not the sole solution to the challenges faced by FS emptiers. The combination of policies and regulations by the government, cost reduction initiatives, financial and technical trainings as well as awareness raising will help in overcoming the challenges faced by FS emptiers.

This review identified some gray areas which provide basis for future research work. Only one study was carried out in a rural area implying that studies in rural areas are limited. This is because emptying in rural areas are limited as most people rely on digging more latrines when the ones in use fill up due to availability of space in these areas. However, with increasing process of land use, there will be limited space for dig and cover method for full pits and there is potential of slipping back temporarily or even permanently to open defecation. Thus, there is need to sensitize the people in rural areas on the need for emptiable sanitation facilities.

Further, there is need to financially model FS emptying business in different communities especially for manual emptiers. The creation of viable business models for manual emptiers involving the use of suitable small-scale pit emptying technologies operated and supported through the provision of decentralized FS discharge points under a municipal framework will help in making their work more hygienic and also improve the profitability of their business.

Finally, there is need for studies on how user perception is related to emptying behavior. Understanding the link between peoples' perceptions towards risks/hazards and FSM in general, and their emptying behavior will enable the development of perception management strategies needed for successful implementation of effective behavioral change intervention programmes with focus on scheduled emptying. It is recommended that behavior change studies to gain insight on drivers and barriers to wearing PPE which will help in potential design options should be carried out. The mental health needs of FS emptiers should be investigated to provide better understanding of issues surrounding substance abuse and what steps can be taken to help improve their mental health.

6 Conclusion

Rapid urbanization in low- and middle-income countries amidst poverty shows that on-site sanitation systems are not likely to disappear anytime soon. Faecal sludge which accumulates in these facilities have to be emptied always; thus, emptying services would still be needed for a long time. The challenges faced by these emptiers mostly discussed in the reviewed papers were financial, technical and institutional challenges with social and health challenges being peculiar to manual emptiers. Though accessibility was the mostly discussed factor which influences the choice of emptying method, cost was observed to have the most influence as it overrides accessibility and service quality when it comes to the selection of an emptying method. Cost/affordability of the service and access to finance by FS emptiers were observed to be the major barriers to effective implementation of improvement initiatives. Very few studies discussed on initiatives which have been put in place to make emptying business more lucrative and sustainable. The limited number of studies imply that a lot still has to be done to improve FS emptying business. Research gaps identified in the study include the need for sensitization for those in rural areas on importance of FS emptying, financial modelling of manual emptying and studies on perceptions towards emptying for both users and FS emptiers. Addressing these research gaps will provide critical information needed by stakeholders in the sanitation sector to improve FS emptying business.

Author contributions

CM: Conceptualization; Methodology; Software; Formal Analysis; Investigation; Resources; Writing-original draft preparation; Visualization; SS: Formal Analysis; Investigation; Writing-Review and Editing; Visualization. MM: Conceptualization; Methodology; Software; Formal Analysis; Investigation; Resources; Writing-Review and Editing; Visualization; Supervision; Project Administration. All authors read and approved the final manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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References

Afolabi, O. O. D., and Sohail, M. (2016). Microwaving human faecal sludge as a viable sanitation technology option for treatment and value recovery – A critical review. *J. Environ. Manag.* 187, 401–415. doi:10.1016/j.jenvman.2016.10.067

Akumuntu, J. B., Wehn, U., Mulenga, M., and Brdjanovic, D. (2017). Enabling the sustainable faecal sludge management service delivery chain—a case study of dense settlements in kigali, Rwanda. *Int. J. Hyg. Environ. Health* 220 (6), 960–973. doi:10.1016/j.ijheh.2017.05.001

Anh, T. H., Koottatep, T., and Polprasert, C. (2018). Business model analysis for faecal sludge collection and transport services in Thailand and Vietnam. *J. Water Sanitation Hyg. Dev.* 8 (3), 556–567. doi:10.2166/washdev.2018.026

Bakare, B. F. (2019). Innovative approach for the management of faecal sludge accumulated in ventilated improved pit latrine: A case study of eThekwini municipality in durban South Africa. *J. Phys. Conf. Ser.* 1378 (4), 042006. doi:10.1088/1742-6596/1378/4/042006

Balasubramanya, S., Evans, B., Hardy, R., Ahmed, R., Habib, A., Asad, N. S. M., et al. (2017). Towards sustainable sanitation management: Establishing the costs and willingness to pay for emptying and transporting sludge in rural districts with high rates of access to latrines. *PLoS ONE* 12 (3), 1–14. doi:10.1371/journal.pone.0171735

Bassan, M. (2014). "Institutional frameworks for faecal sludge management," in *Feacal sludge management book*. Editors L. Strande, M. Ronteltap, and D. Brdjanovic (London, U.K.: IWA Publishing), 255–272.

Bassan, M., Mbéguéré, M., Tchonda, T., Zabsonre, F., and Strande, L. (2013). Integrated faecal sludge management scheme for the cities of Burkina Faso. *J. Water Sanitation Hyg. Dev.* 3 (2), 216–221. doi:10.2166/washdev.2013.156

Binale, A. (2011). "Umande trust bio-centre approach in slum upgrading," in *Les Cahiers D'Afrique de L'est*, 167–186. Available from: https://halshs.archives-ouvertes.fr/halshs-00755905/document.

Bongi, S., and Morel, A. (2015). *Understanding small scale providers of sanitation services: A case study of kibera*. Nairobi, Kenya: WSP field note.

Bonthuys, J. (2017). Radical shift" needed to reduce risks during pit emptying for workers, households. *Water Wheel.* 16 (6), 18–21. Available from: https://hdl.handle.net/10520/EJC-c162e23a9.

Boot, N. L. D., and Scott, R. E. (2008). "Faecal sludge management in Accra, Ghana: Strengthening links in the chain," in Access to Sanitation and Safe Water: Global Partnerships and Local Actions - Proceedings of the 33rd WEDC International Conference, Accra, Ghana, February 2008, 99–107.

Capone, D., Barker, T., Cumming, O., Flemister, A., Geason, R., Kim, E., et al. (2022). Persistent ascaris transmission is possible in urban areas even where sanitation coverage is high. *Environ. Sci. Technol.* 56 (22), 15969–15980. doi:10.1021/acs.est.2c04667

Chowdry, S., and Kone, D. D. (2012). *Business Analysis of fecal sludge management: Emptying and transportation services in Africa and Asia*. Final Draft Report. Seattle, WA: Bill and Melinda Gates Foundation Sponsored Project.

Chumo, I., Simiyu, S., Gitau, H., Kisiangani, I., Kabaria, C., Muindi, K., et al. (2021). Manual pit emptiers and their heath: Profiles, determinants and interventions. *Int. J. Med. Health Sci.* 15 (6), 207–213. Available from: https://www.researchgate.net/publication/353317434_Manual_Pit_Emp-tiers_and_Their_Heath_Profiles_Determinants_and_interventions (Accessed August 12, 2022).

Cross, P., and Coombes, Y. (2014). *Sanitation and hygiene in Africa: Where do we stand?* London, UK: IWA Publishing. Available from: http://library.oapen.org/handle/20.500.12657/33037.

de La Brosse, N., Stevens, L., and Casey, J. (2016). "Technology justice and faecal sludge management: Tackling the' second-generation' sanitation challenge in South Asia," in *6th technology justice policy briefing*.

Eales, K. (2005). in *Bringing pit emptying out of the darkness: A comparison of approaches in durban, South Africa, and kibera, Kenya. Sanitation partnerships series* (South Island: S.I.: Business Partners for Development Water and Sanitation Cluster).

Eawag and Sandec (2006). "Urban excreta management - situation, challenges, and promising solutions," in Presentation at the First International Faecal Sludge Management Policy Symposium and Workshop, Dakar, Senegal, 9-12 May 2006.

Fracchia, L., Pietronave, S., Rinaldi, M., and Giovanna, M. (2006). Site-related airborne biological hazard and seasonal variations in two wastewater treatment plants. *Water Res.* 40 (10), 1985–1994. doi:10.1016/j.watres.2006.03.016

Gautam, M., Wankhade, K., Sarangan, G., and Sudhakar, S. (2021). Framework for addressing occupational safety of de-sludging operators: A study in two Indian cities. *J. Environ. Manag.* 289 (2021), 112243. doi:10.1016/j.jenvman.2021.112243

Hawkins, P., Blackett, I., and Heymans, C. (2014). "The missing link in sanitation service delivery: A review of fecal sludge management in 12 cities," in *Water and Sanitation Program: Research Brief* (Washington, DC: World Bank), 1–8. Available from: http://documents.worldbank.org/curated/en/2014/04/19549016/targeting-urban-poor-improving-services-small-towns-missing-link-sanitation-service-delivery-review-fecal-sludge-management-12-cities (Accessed October 10, 2022).

Hawkins, P., and Muximpua, O. (2015). *Developing business Models for fecal sludge Management in Maputo*. Maputo, Mozambique: Water and Sanitation Program Report.

Holm, R. H., Kamangira, A., Tembo, M., Kasulo, V., Kandaya, H., Gijs Van Enk, P., et al. (2018). Sanitation service delivery in smaller urban areas (Mzuzu and Karonga, Malawi). *Environ. Urbanization* 30 (2), 597–612. doi:10.1177/0956247818766495

Holm, R., Tembo, J. M., and Thole, B. (2015). A comparative study of faecal sludge management in Malawi and Zambia: Status, challenges and opportunities in pit latrine emptying. *Afr. J. Environ. Sci. Technol.* 9 (11), 783–792. doi:10.5897/ajest2015.1971

Jayathilake, N., Drechsel, P., Keraita, B., Fernando, S., and Hanjra, M. A. (2019). Management from on-site sanitation facilities. *Resour. Recovery Reuse Ser.* 14. doi:10.5337/2019.211

Jenkins, M. W., Cumming, O., Scott, B., and Cairncross, S. (2014). Beyond 'improved' towards 'safe and sustainable' urban sanitation: Assessing the design, management and functionality of sanitation in poor communities of dar es Salaam, Tanzania. *J. Water, Sanitation Hyg. Dev.* 4 (1), 131–141. doi:10.2166/washdev.2013.180

Jenkins, M. W., Cumming, O., and Cairncross, S. (2015). Pit latrine emptying behavior and demand for sanitation services in dar Es Salaam, Tanzania. *Int. J. Environ. Res. Public Health* 12, 2588–2611. doi:10.3390/ijerph120302588

Junglen, K., Rhodes-Dicker, L., Ward, B. J., Gitau, E., Mwalugongo, W., Stradley, L., et al. (2020). Characterization and prediction of fecal sludge parameters and settling behavior in informal settlements in Nairobi, Kenya. *Sustain. Switz.* 12 (21), 1–13. doi:10.3390/su12219040

Kennedy-walker, B. R. (2015). *Planning for faecal sludge Management in informal urban settlements of low-income countries: A study of lusaka, Republic of Zambia*. PhD. Thesis. United Kingdom: School of Civil Engineering and Geosciences, NewCastle University. Available from: http://hdl.handle.net/10443/2856.

Kohlitz, J. P., Rostiani, R., Indarti, N., Murta, J., and Willetts, J. (2018). Sludge removal enterprises in Indonesia: Factors affecting entrepreneurial success. *J. Water, Sanitation Hyg. Dev.* 8 (2), 246–256. doi:10.2166/washdev.2018.085

Kone, D. (2010). Making urban excreta and wastewater management contribute to cities economic development: A paradigm shift. *Water Policy* 12 (4), 602–610. doi:10.2166/wp.2010.122

Krueger, B. C., Fowler, G. D., Templeton, M. R., and Moya, B. (2020). Resource recovery and biochar characteristics from full-scale faecal sludge treatment and co-treatment with agricultural waste. *Water Res.* 169, 115253. doi:10.1016/j.watres.2019.115253

Lerebours, A., Scott, R., and Sansom, K. (2021). Private emptiers' perspectives on the regulation of faecal sludge emptying services in Sub-Saharan Africa. *J. Water, Sanitation Hyg. Dev.* 11 (5), 785–793. doi:10.2166/washdev.2021.026

Mallory, A., Omoga, L., Kiogora, D., Riungu, J., Kagendi, D., and Parker, A. (2021). Understanding the role of informal pit emptiers in sanitation in nairobi through case studies in Mukuru and Kibera settlements. *J. Water Sanitation Hyg. Dev.* 11 (1), 51–59. doi:10.2166/washdev.2020.193

Manga, M., Evans, B. E., Camargo-Valero, M. A., and Horan, N. J. (2016). Effect of filter media thickness on the performance of sand drying beds used for faecal sludge management. *Water Sci. Technol.* 74 (12), 2795–2806. doi:10.2166/wst.2016.451

Manga, M., Evans, B., and Camargo-Valero, M. A. (2019). Inactivation of viable *Ascaris* eggs during fecal sludge Co-composting with chicken feathers and market waste. *Desalination Water Treat.* 163, 347–357. doi:10.5004/dwt.2019.24494

Manga, M., Bartram, J., and Evans, B. E. (2020). Economic cost analysis of low-cost sanitation technology options in informal settlement areas (case study: Soweto, Johannesburg). *Int. J. Hyg. Environ. Health* 233 (1), 289–298. doi:10.1016/j.ijheh.2019.06.012

Manga, M., Camargo-Valero, M. A., Anthonj, C., and Evans, B. E. (2021). Fate of faecal pathogen indicators during faecal sludge composting with different bulking agents in tropical climate. *Int. J. Hyg. Environ. Health* 232, 113670. doi:10.1016/j.ijheh.2020.113670

Manga, M., Evans, B. E., Ngasala, T. M., and Camargo-Valero, M. A. (2022a). Recycling of faecal sludge: Nitrogen, carbon and organic matter transformation during Co-composting of faecal sludge with different bulking agents. *Int. J. Environ. Res. public health* 19 (17), 10592. doi:10.3390/ijerph191710592

Manga, M., Kolsky, P., Rosenboom, J. W., Ramalingam, S., Sriramajayam, L., Bartram, J., et al. (2022b). Public health performance of sanitation technologies in Tamil Nadu, India: Initial perspectives based on *E. coli* release. *Int. J. Hyg. Environ. Health* 243, 113987. doi:10.1016/j.ijheh.2022.113987

Manga, M., Muoghalu, C., Camargo-Valero, M. A., and Evans, B. E. (2023). Effect of turning frequency on the survival of fecal indicator microorganisms during aerobic composting of fecal sludge with sawdust. *Int. J. Environ. Res. Public Health* 20 (3), 2668. doi:10.3390/ijerph20032668

Manga, M. (2017). *The feasibility of Co-composting as an upscale treatment method for faecal sludge in urban Africa*. Leeds, UK: Department of Civil Engineering, University of Leeds. Available online: https://etheses.whiterose.ac.uk/16997 (accessed on October 3, 2022).

Mbéguéré, M., Gning, J. B., Dodane, P. H., and Koné, D. (2010). Socio-economic profile and profitability of faecal sludge emptying companies. *Resour. Conservation Recycl.* 54 (12), 1288–1295. doi:10.1016/j.resconrec.2010.04.008

Mikhael, G., Robbins, D. M., and Ramsay, J. E. (2014). "Methods and means for collection and transport of faecal sludge," in *Feacal sludge management book*. Editors L. Strande, M. Ronteltap, and D. Brdjanovic (London, U.K.: IWA Publishing), 67–96.

Moher, D., Liberati, A., Tetzlaff, J., and Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *BMJ* 339, b2535. doi:10.1136/bmj.b2535

Mougoue, B., Ngnikam, E., Wanko, A., Feumba, R., and Noumba, I. (2012). Analysis of faecal sludge management in the cities of douala and yaounde in Cameroon. *Sustain. Sanit. Pract.* 10 (13), 11–21. Available from: http://www.ecosan.at/ssp/issue-12-faecal-sludge-management/SSP-13_Oct2012_11-21.pdf (Accessed August 30, 2022).

Muxímpua, O., and Hawkins, P. (2012). "Building blocks for effective faecal sludge management in per-urban areas: The role of small-scale service providers in Maputo," in *2nd international conference in feacal sludge management* (Durban, South Africa: WHO and UNICEF JMP), pp. 29–31. Available from: http://www.wssinfo.org/data-estimates/table/.

Nijkamp, P., Burch, M. V. D., Vindigni, G., and Nijkamp, P. (2002). A comparative institutional evaluation of public-private partnerships in Dutch urban land-use and revitalisation projects. *Urban Stud.* 39 (10), 1865–1880. doi:10.1080/0042098022000002993

Nkasah, A., Fisher, J., and Sohail, M. (2012). Manual pit emptying as a sustainable livelihood in Ghana. *Eng. Sustain.* 165, 215–221. doi:10.1680/ensu.10.00056

Noumba, I., Ngnikam, E., Mougoue, B., Wanko, A., and Berteigne, B. (2017). Weak links in the chain: Diagnosis of the faecal sludge management chain in Nkobikok, Yaoundé, Cameroon. *Net J. Soc. Sci.* 5 (4), 55–67. Available from: https://netjournals.org/pdf/NJSS/2017/4/17-020.pdf (Accessed August 25, 2022).

Oduro-Kwarteng, S., Awuah, E., and Nyarko, K. B. (2019). "Shifting from public shared toilets to home toilets in urban settlements: Implications of household demand in Kumasi, Ghana. Water, sanitation and hygiene: Sustainable development and multisectoral approaches," in *Proceedings of the 34thWEDC international conference* (Addis Ababa, Ethiopia, 1–8. Available from: https://www.scopus.com/inward/record.url?eid=2-s2.0-84891404866&partnerID=40&md5=4ee614ac613141a1b7823436d99c5657.

Opel, A., Bashar, M. K., and Ahmed, M. F. (2011). *Landscape Analysis and business model assessment in faecal sludge management: Extraction and transportation models in Bangladesh*. Bangladesh: Draft Report, Bill and Melinda Gates Foundation Project.

Owusu, C. (2013). *Public - private partnership in faecal sludg collection and treatment in ashanti region of Ghana*. Unpublished MSc. Thesis. Ghana: Department of Civil Engineering, Kwame Nkrumah University of Science and Technology.

Parkinson, J., and Quader, M. (2008). The challenge of servicing on-site sanitation in dense urban areas: Experiences from a pilot project in Dhaka. *JSTOR* 27 (2), 149–163. doi:10.3362/1756-3488.2008.017

Patil, P. V., and Kamble, R. K. (2017). Occupational health hazards in sanitary workers of chandrapur city, central India. *Int. J. Environ.* 6 (3), 15–24. doi:10.3126/ije.v6i3.18095

Peal, A., Evans, B., Blackett, I., Hawkins, P., and Heymans, C. (2014). Fecal sludge management (FSM): Analytical tools for assessing FSM in cities. *J. Water, Sanitation Hyg. Dev.* 4 (3), 371–383. doi:10.2166/washdev.2014.139

Peletz, R., Feng, A., Macleod, C., Vernon, D., Wang, T., Kones, J., et al. (2020). Expanding safe fecal sludge management in kisumu, Kenya: An experimental comparison of latrine pit-emptying services. *J. Water Sanitation Hyg. Dev.* 10 (4), 744–755. doi:10.2166/washdev.2020.060

Prasad, C. S., and Ray, I. (2019). When the pits fill up: (in)visible flows of waste in urban India. *J. Water Sanitation Hyg. Dev.* 9 (2), 338–347. doi:10.2166/washdev.2019.153

Rao, K. C., and Otoo, M. (2017). Resource recovery and reuse as an incentive for a more viable sanitation service chain. *Water Altern.* 10 (2), 493–512. Available from: https://www.water-alternatives.org/index.php/alldoc/articles/vol10/v10issue2/367-a10-2-17/file (Accessed September 23, 2022).

Rotowa, O. O., and Ayadi, P. A. (2020). Faecal sludge management in the residential cores of akure, Nigeria faecal sludge management in the residential cores of akure, Nigeria. *J. Environ. Prot. Ecol.* 10 (2), 15–22. Available from: https://www.researchgate.net/profile/Olukayode-Rotowa/publication/342750679_Faecal_Sludge_Management_in_the_Residential_Cores_of_Akure_Nigeria/links/5f04b10592851c52d61e3400/Faecal-Sludge-Management-in-the-Residential-Cores-of-Akure-Nigeria.pdf (Accessed September 24, 2022).

Scott, P., Cotton, A., and Khan, M. S. (2013). Tenure security and household investment decisions for urban sanitation: The case of Dakar, Senegal. *Habitat Int.* 40, 58–64. doi:10.1016/j.habitatint.2013.02.004

Semiyaga, S., Okure, M. A. E., Niwagaba, C. B., Katukiza, A. Y., and Kansiime, F. (2015). Decentralized options for faecal sludge management in urban slum areas of sub-saharan Africa: A review of technologies, practices and end-uses. *Resour. Conservation Recycl.* 104, 109–119. doi:10.1016/j.resconrec.2015.09.001

Semiyaga, S., Bamuhimbise, G., Apio, S. C., Kinobe, J. R., Nkurunziza, A., Lukooya, N. B., et al. (2022). Adequacy of vacuum and non-vacuum technologies for emptying faecal sludge from informal settlements of Kampala City. *Habitat Int.* 125, 102596. doi:10.1016/j.habitatint.2022.102596

Simwambi, A., Hibler, S., Pietruschka, B., and Hawkins, P. (2017). "Approaches to faecal sludge management in peri-urban areas: A case study in the city of lusaka," in *FSM innovation - case studies on the business, policy and technology of faecal sludge management*, 145–156.

Singh, S., Gupta, A., Alamgir, M., and Brdjanovic, D. (2021). Exploring private sector engagement for faecal sludge emptying and transport business in khulna, Bangladesh. *Int. J. Environ. Res. Public Health* 18 (5), 1–14. doi:10.3390/ijerph18052755

Singh, S., Laker, F., Bateganya, N. L., Nkurunziza, A. G., Semiyaga, S., and Brdjanovic, D. (2022). Evaluation of business models for fecal sludge emptying and transport in informal settlements of Kampala, Uganda. *WaterSwitzerl.* 14 (18), 2914–2915. doi:10.3390/w14182914

Sinharoy, S. S., Pittluck, R., and Clasen, T. (2019). Review of drivers and barriers of water and sanitation policies for urban informal settlements in low-income and middle-income countries. *Util. Policy* 60, 100957. doi:10.1016/j.jup.2019.100957

Sprouse, L., Liles, A., Cronk, R., Bauza, V., Tidwell, J. B., and Manga, M. (2022). Interventions to address unsafe child feces disposal practices in the Asia-Pacific region: A systematic review. *H2Open Journal* 5 (4), 583–602. doi:10.2166/h2oj.2022.137

Thye, Y. P., Templeton, M. R., and Ali, M. (2009). "Pit latrine emptying: Technologies, challenges and solutions," in Conference Proceeding: EWB-UK Research Conference, February 20, 2009.

Tilley, E., Lüthi, C., Morel, A., Zurbrügg, C., and Schertenleib, R. (2008). *Compendium of sanitation systems and technologies*. Belley, France: Imprimerie Nouvelle Gonnet.

Tilmans, S., Russel, K., Sklar, R., Page, L. N., Kramer, S., and Davis, J. (2015). Container-based sanitation: Assessing costs and effectiveness of excreta management in cap haitien, Haiti. *Environ. Urbanization* 27 (1), 89–104. doi:10.1177/0956247815572746

Tokwaro, R., Semiyaga, S., Niwagaba, C. B., Nakagiri, A., Sempewo, J. I., Moughalu, C. C., et al. (2023). Application of black soldier fly larvae in decentralized treatment of faecal sludge from pit latrines in informal settlements in Kampala City. *Front. Environ. Sci.* 11, 138. doi:10.3389/fenvs.2023.1118635

Trémolet, S. (2012). Sanitation economics: Understanding why sanitation markets fail and how they can improve. *JSTOR* 32 (4), 273–285. doi:10.3362/1756-3488.2013.029

Ulrich, L., Salian, P., Saul, C., Jüstrich, S., and Lüthi, C. (2016). *Assessing the costs of on-site sanitation facilities, study report by eawag-sandec*. (March).

UNICEF/WHO (2020). *UNICEF and WHO joint monitoring Program for water, sanitation and hygiene (JMP) annual report 2020*. Retrieved from: https://washdata.org/report/jmp-2020-annual-report (Assessed August 5, 2022).

Water and Sanitation for the Urban Poor (WSUP) (2016). Urban sanitation research initiative 2017-2022: Driving sector change in urban sanitation. *Sustain. Switz.* 8 (12), 3–28. Available from: https://core.ac.uk/download/pdf/141922769.pdf (Accessed September 16, 2022).

Weststrate, J., Gianoli, A., Eshuis, J., Dijkstra, G., Cossa, I. J., and Rusca, M. (2019). The regulation of onsite sanitation in Maputo, Mozambique. *Util. Policy* 61, 100968. doi:10.1016/j.jup.2019.100968

Zaqout, M., Cawood, S., Evans, B. E., and Barrington, D. J. (2020). Sustainable sanitation jobs: Prospects for enhancing the livelihoods of pit-emptiers in Bangladesh. *Third World Q.* 42 (2), 329–347. doi:10.1080/01436597.2020.1810560

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Biochar as a novel technology for treatment of onsite domestic wastewater: A critical review

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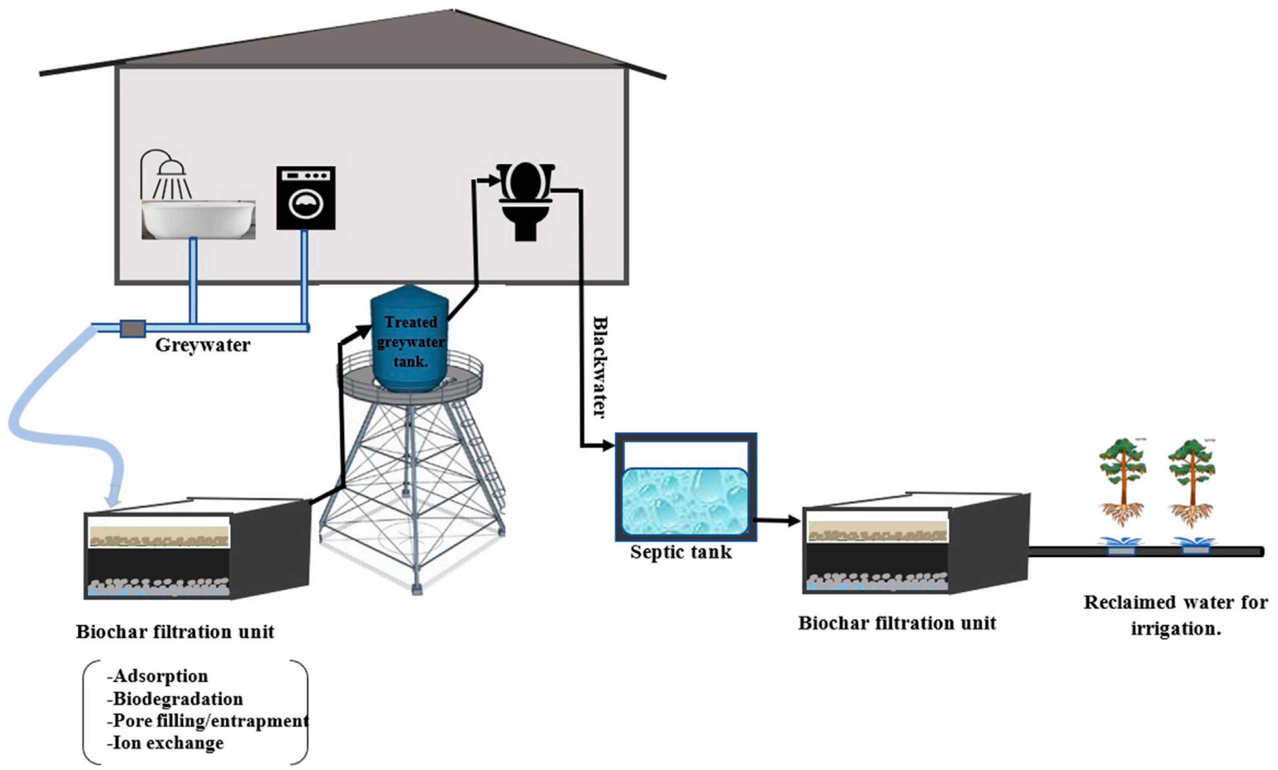
Globally, about 2.7 billion people depend on onsite sanitation systems (OSS) (e.g., septic tanks) for their sanitation needs. Although onsite sanitation systems help in providing primary treatment for domestic wastewater, they don't effectively remove nutrients, pathogens, and other inorganic contaminants. Previous studies have posited that the use of post treatment systems which incorporate biochar leads to improved contaminant removal efficiency. However, the mechanism through which contaminants are removed and factors potentially affecting the removal are still understudied. To fill this knowledge gaps, this review discusses factors which affect efficiency of biochar in removing contaminants found in onsite domestic wastewater, modifications applied to improve the efficiency of biochar in removing contaminants, mechanisms through which different contaminants are removed and constraints in the use of biochar for onsite wastewater treatment. It was noted that the removal of contaminants involves a combination of mechanisms which include adsorption, filtration, biodegradation, ion exchange, pore entrapment. The combination of these mechanisms is brought about by the synergy between the properties of biochar and microbes trapped in the biofilm on the surface of the biochar. Future areas of research such as the modification of biochar, use of biochar in the removal of antibiotic resistant genes (ARGs), application of wet carbonization methods and resistance of biochar to physical disintegration are also discussed. This study provides useful information that can be applied in the use of biochar for the treatment of wastewater and guide future design of treatment systems for optimized treatment performance.

KEYWORDS

biochar, biomass, greywater, organic waste, wastewater treatment, pyrolysis, biofiltration, wastewater reuse



GRAPHICAL ABSTRACT

1 Introduction

In many low- and middle-income countries, the sanitation needs of most people are met by on-site sanitation systems (OSS) due to their low capital and maintenance costs (Strande et al., 2014; Manga et al., 2019; Krueger et al., 2020; Manga et al., 2020). Although these systems are cost-effective, they are unsustainable due to their inability to properly treat human excreta. Furthermore, the liquid released from these systems into the surrounding soils is a source of environmental pollution and a threat to public health and environmental quality (Manga et al., 2022a; Capone et al., 2022). One such system is the septic tank discharging to a soak away pit, that is currently in use by about 1.7 billion people worldwide and is considered a minimum standard for use in public/congregated places in some developing nations (WHO and UNICEF, 2021). Limitations of these systems have brought about the need to explore subsequent post-treatment or polishing technologies required to achieve the desired effluent disposal or reuse standards. Various ecologically safe and cost-effective technologies such as constructed wetlands (CW) or subsurface wastewater infiltration systems (SWIS), have shown to be promising systems (Mburu et al., 2013). However, these systems are not effective in removing phosphorus from wastewater due to the fact that they make use of sand bed media and do not have sufficient capacity to bind phosphorus for a prolonged period (Brix and Arias, 2005). Different kinds of media such as oyster shell, limestone, calcite, zeolite, and biochar have been applied to improve the contaminant removal efficiency of these soil-based biofiltration systems (Gungor and Unlu, 2005; Gill et al., 2009; Wang et al., 2013; Zhang et al., 2015). Amongst the aforementioned amendment materials, biochar holds great potential to improve the removal of contaminants due to its ability to adsorb various organic and inorganic compounds, good cation exchange capacity and ability to serve as growth media for biofilm. Though a lot of investigations have been carried out on the use of biochar for centralized wastewater treatment, the use of biochar for the treatment of effluent from onsite containment units is still nascent and there are still some knowledge gaps. Mechanisms through which different contaminants can be removed and factors which affect the ability of biochar to adsorb contaminants found in onsite domestic wastewater are not well documented. The aim of this paper is to critically evaluate the applicability of biochar for the treatment of effluent from onsite containment units especially septic tanks. The review specifically discusses: 1) Factors which affect efficiency of biochar in removing contaminants in onsite domestic wastewater; 2) biochar modifications to improve contaminant removal efficiency; 3) mechanisms of different contaminants removal; and 4) constraints, gaps and areas of future research in the use of biochar for onsite wastewater treatment.

2 Composition of domestic onsite wastewater

Domestic on-site wastewater emanates from onsite wastewater treatment systems (OWTS) which are used for the treatment and disposal of household wastewater in places where centralized sewerage systems are not available (Babcock et al., 2014). Some of the most commonly used OWTS are septic systems, cesspools, aerobic treatment units (ATUs), above-ground mounded soil systems, subsurface drip irrigation systems, land application systems such as spray irrigation, and aquatic systems such as wetlands and lagoons. OWTS are multistage

TABLE 1 Physicochemical properties of domestic wastewater.

pH	Turbidity (mg/L)	TS (mg/L)	TDS (mg/L)	TSS (mg/L)	DO (mg/L)	COD (mg/L)	BOD_5 (mg/L)	TN (mg/L)	NH_4^+-N (mg/L)	NO_3 -N (mg/L)	PO_4^{3-}P (mg/L)	TP (mg/L)	Reference
6.7	210.0	328.0	96.0	232.0	1.02	305.6	176.0	17.3	12.5	1.8			Oladoja and Ademoroti (2006)
				1,653 ± 1,174			1,160 ± 350	100 ± 56	99 ± 19		39 ± 28		Pishgar et al. (2021)
7.6 ± 0.1					1.3 ± 0.8	690 ± 150	330 ± 103	120 ± 31	110 ± 20	8 ± 5.3		13 ± 6.5	Lusk et al. (2017)
6.4–10.1		252–3,320		22–1,690		139—4,584	112–1,101	16–189	1.6–94	0.2–8.5		0.2–32	Lowe et al. (2009)
	17–394				0.19–21.9	17–394			0.06–112	0.24–26.5	0.02–5.12		Agoro et al. (2018)
		800		240		325	225	35	20			10	Alley (2007)
				653		1,202	505		59			13	Awuah et al. (2014)

TS, total solids; TSS, total suspended solids; TDS, total dissolved solids; DO, dissolved oxygen; BOD, biological oxygen demand; COD, chemical oxygen demand; TN, total nitrogen; TP, total phosphorus; NH_4^+-N, ammonium nitrogen; NO_3 -N, nitrate nitrogen; PO_4^{3-}P, orthophosphate.

systems which make use of a combination of technology and natural processes to collect and treat wastewater. The treated effluent is released into the environment through a dispersal unit which makes use of a network of soil infiltration trenches (leach field) where the effluent is further treated as it percolates through the vadose zone prior to discharge to local groundwater (Lamichhane, 2007; Manga et al., 2022a).

Domestic on-site wastewater is made up of human faeces, urine, cleansing material, flush water and at times grey water and contains various pollutants which include organic matter (biochemical oxygen demand (BOD) and chemical oxygen demand (COD)), nutrients (i.e., nitrogen and phosphorous) (Table 1), pathogens, heavy metals, pharmaceutical, and personal care products (PPCPs) (Manga et al., 2016; Martikainen et al., 2018; Guruge et al., 2019; Farkas et al., 2020; Semiyaga et al., 2022; Tokwaro et al., 2023). Pathogens found in onsite domestic wastewater include bacterial pathogens (i.e., *Escherichia coli, Legionella pneumophila, Leptospira* spp, *Salmonella* spp, *Shigella* spp, *Vibro cholera*, and *Yersinia enterocoliticia*), viral pathogens (e.g., adenovirus, enterovirus, hepatitis A, norovirus, reovirus, rotavirus, and echovirus) and helminths (ascaris, hookworm, whipworm) (Table 2) (Lusk et al., 2017; Manga, 2017; Manga et al., 2023). Heavy metals in domestic wastewater emanate from detergents and body care products (Akpor et al., 2014). The most common heavy metals in domestic wastewater are lead (Pb), mercury (Hg), cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), silver (Ag), zinc (Zn), manganese (Mn), and iron (Fe) (Table 3) (Chino et al., 1991; Manga et al., 2022b). Different kinds of PPCPs have been found in domestic onsite wastewater and they include ibuprofen, caffeine, erythromycin, ciprofloxacin, sulfamethoxazole, ketoprofen, carbamazepine (Table 3) (Miège et al., 2009).

The quantities of each of the aforementioned contaminants in domestic wastewater stream usually varies with factors such as weather conditions, number of users, water use patterns (Oteng-Peprah et al., 2018). Majority of these pollutants are persistent in nature (especially PPCPs) and cannot be easily removed using conventional onsite treatment techniques, such as sand filter and soil infiltration treatment systems. These systems have been proven to be only partially effective in removing different kinds of organic micropollutants found in domestic wastewater including PPCPS. For instance, Gros et al. (2016) noted low to intermediate removal of PPCPs in soil beds that are used for onsite filtration (e.g., 46% removal for ibuprofen, 86% for diclofenac, 44% for metoprolol, and 73% for caffeine), while Blum et al. (2017) reported insignificant (>10%) removal of acetaminophen in soil beds A summary of the concentration and ranges of these pollutants in domestic wastewater, quality of effluent from onsite systems as well as removal efficiencies are presented in Tables 1–3.

Currently, the methods used for removing PPCPs from wastewater include electrochemical method (Barrios et al., 2016), microbial method (Ferreira et al., 2016), membrane process, chemical oxidation process and adsorption method (Acero et al., 2015). Amongst the aforementioned methods, adsorption is widely accepted because of its cost effectiveness, high efficiency, and wide processing range. The most commonly used adsorbents are activated carbon, silica gel, alumina, polyacrylamide, adsorbent resin, and zeolite (Esmaeeli et al., 2017; Qu et al., 2018; Peng et al., 2019; Jiang et al., 2020). Though activated carbon has very large specific surface area and in turn a large adsorption capacity, it is expensive while other adsorbents like silica gel, alumina, adsorbent resin have narrow adsorption surface and polyacrylamide is difficult to produce (Cheng et al., 2021). This necessitates the need for other treatment techniques which are efficient, economical, and environmentally friendly such as the use of biochar. When compared with other adsorbents, biochar presents a potential low-cost and effective adsorbent; the properties of biochar such as its large surface area, porous structure, enriched surface functional groups and mineral components make it possible for it to be used as proper adsorbent for contaminants in domestic wastewater. The specific properties of biochar including large specific surface area, porous structure, enriched surface functional groups and mineral components make it possible to be used as proper adsorbent to remove pollutants from aqueous solutions (Tan et al., 2015).

TABLE 2 Microbial composition of domestic wastewater.

Pathogenic micro-organism	Concentration in domestic wastewater	Concentration in effluents from onsite wastewater systems	Removal efficiencies (%)	Reference
Bacterial pathogen				
Total coliform	4.4–8.6 log_{10} CFU/100 mL	1.15–7.78 log_{10} CFU/100 mL	84.15–99.99	Quiñónez-Díaz et al. (2001); Winward et al. (2008); Horn et al. (2014)
Fecal coliform	4.1–7.9 log_{10} CFU/100 mL	0.6–9.91 log_{10} CFU/100 mL	96.02–99.99	Karim et al. (2004); Garcia et al. (2008); Akunna et al. (2017)
Fecal streptococci	3.1–6.1 log_{10} CFU/100 mL	—	99.29–99.93	Reinoso et al. (2008); Abdel-Shafy and El-Khateeb, (2013)
Escherichia coli	5.8–7.8 log_{10} CFU/100 mL	0.17–6.7 log_{10} CFU/100 mL	73.91–99.99	Boutilier et al. (2010); Akunna et al. (2017); Manga et al. (2022a)
Salmonella	4.7 log_{10} CFU/100 mL	—	68.38–99.99	Eregno and Heistad, (2019); Amin et al. (2020)
Shigella	1.0–3.8 log_{10} CFU/100 mL	—	96.33–99.72	Zhou et al. (2015); Amin et al. (2020)
Clostridium perfringens	0–6.0 log_{10} CFU/100 mL	—	93.69–99.96	García et al. (2013); Morató et al. (2014)
Pseudomonas aeruginosa	3.8–5.0 log_{10} CFU/100 mL	—	96.92–99.21	Winward et al. (2008); Morató et al. (2014)
Enterococci	3.3–6.6 log_{10} CFU/100 mL	0.3–16.5 log_{10} PFU/100 mL	80.05–99.99	Akunna et al. (2017); Humphries et al. (2020)
Viral pathogen				
F-specific bacteriophage	2.8–6.3 log_{10} PFU/100 mL	—	36.90–99.99	Karim et al. (2004); Torrens et al. (2009); Perez-Mercado et al., 2019
Rotavirus	2.9–8.1 log_{10} copies/mL	—	97.28–99.99	Zhou et al. (2015); Zhang et al., 2016; Humphries et al. (2020)
Norovirus GI and GII	3.1–8.9 log_{10} copies/mL	—	73.80–99.99	Kauppinen et al. (2014); Amin et al. (2020); Humphries et al. (2020)
Adenovirus	5.0–7.3 log_{10} copies/mL	—	77.83–99.99	Kauppinen et al. (2014); Kaliakatsos et al. (2019)
Enterovirus	7.6–7.8 log_{10} copies/mL		98.73–99.99	Kaliakatsos et al. (2019); Humphries et al. (2020)
Protozoa				
Giardia	0.6–4.9 log_{10} cysts/L		99.91	Karim et al. (2004); Amin et al. (2020)
Cryptosporidium	0–140 oocysts/L		99.87	Falabi et al. (2002); Reinoso et al. (2008)
Helminths	9.6–244 eggs/L	0.5–16.5 eggs/L	53.70–99.98	Stott et al. (2003); Reinoso et al. (2008); García et al. (2013); Manga et al., 2016; Capone et al., 2022; Manga, 2017

CFU, colony forming unit; PFU, plaque forming unit.

3 Biochar and factors influencing contaminant removal by biochar

3.1 Production of biochar

Biochar is a solid residue produced either by pyrolysis or gasification of biomass with former being the widely used technique. Pyrolysis refers to the thermal decomposition of organic materials in an inert atmosphere (oxygen-limited environment). The pyrolysis process can be represented by a generic chemical reaction (Eq. 1).

$$C_aH_bO_c\,(biomass) \xrightarrow{heat} \sum\nolimits_{liquid} C_rH_sO_t + \sum\nolimits_{gas} C_xH_yO_z + H_2O + C\,(char) \quad (1)$$

Depending on the operating conditions such as as temperature, heating rate, residence time, and pressure, pyrolysis process can be divided into three classes: Slow pyrolysis (carbonization), fast pyrolysis, and flash pyrolysis (Demibraş, 2001). Flash pyrolysis is distinguished from fast pyrolysis by relatively higher heating rates, and very low

TABLE 3 Pharmaceutical and personal care products detected in domestic wastewater, concentrations in effluent of onsite systems, and removal efficiencies by onsite systems.

Contaminant	Concentration (ng/L)	Concentration in effluent (ng/L)	Median removal efficiency (%)	Reference
Erythromycin	53–340	—	—	Miège et al. (2009), Sim et al. (2011), Terzić et al. (2008), Yang et al. (2011)
Ciprofloxacin	413–620	—	—	Terzić et al. (2008); Miège et al. (2009); Sim et al. (2011); Yang et al. (2011)
Sulfamethoxazole	29–1,180	4–2,900	40	Terzić et al. (2008); Kasprzyk-Hordern et al. (2009); Miège et al. (2009); Behera et al. (2011); Sim et al. (2011); Schaider et al. (2017)
Trimetoprim	205–2,192	30–1,500	60	Terzić et al. (2008); Kasprzyk-Hordern et al. (2009); Miège et al. (2009); Behera et al. (2011); Sim et al. (2011); Yang et al. (2011); Schaider et al. (2017)
Diclofenac	131–1,340	10–1,400	82	Terzić et al. (2008); Kasprzyk-Hordern et al. (2009); Miège et al. (2009); Behera et al. (2011); Sim et al. (2011); Yang et al. (2011); Schaider et al. (2017)
Ibuprofen	2,265–69,700	2,900–13,500	53	Miège et al. (2009); Santos et al. (2009); Behera et al. (2011); Schaider et al. (2017)
Ketoprofen	123–1,580	50–1,500	—	Terzić et al. (2008); Kasprzyk-Hordern et al. (2009); Miège et al. (2009); Santos et al. (2009); Behera et al. (2011); Schaider et al. (2017)
Caffeine	2,349–80,000	4,800–93,800	34	Santos et al. (2009); Behera et al. (2011); Yang et al. (2011); Schaider et al. (2017)
Naproxen	335–6,000	30–161	54	Terzić et al. (2008); Kasprzyk-Hordern et al. (2009); Miège et al. (2009); Santos et al. (2009); Behera et al. (2011); Sim et al. (2011); Schaider et al. (2017)
Carbamazepine	64–1,694	5–13,800	6–10	Terzić et al. (2008); Kasprzyk-Hordern et al. (2009); Miège et al. (2009); Behera et al. (2011); Sim et al. (2011); Yang et al. (2011); Schaider et al. (2017)
Atenolol	30–12,913	—	—	Terzić et al. (2008); Kasprzyk-Hordern et al. (2009); Miège et al. (2009); Behera et al. (2011)

residence time (0.5–2 s). The choice of pyrolysis process used depends on the most preferred product. If the aim is the production of liquid and/or gaseous products, then fast pyrolysis is recommended but if the aim is more formation of biochar, then slow pyrolysis is to be used. The use of pyrolysis for biochar production from biomass is considered to be an affordable and environmentally friendly process (Ahmad et al., 2012). Biochar production is considered environmentally friendly since it stores carbon in a stable form thereby offsetting the release of greenhouse gases into the atmosphere (Xiang et al., 2020). In producing biochar from pyrolysis, process parameters such as temperature, residence time, heating rate are responsible for determining the yield of the biochar.

3.2 Factors for contaminant removal using biochar

3.2.1 Internal factors

The ability of biochar to remove contaminants present in wastewater is governed by some of its intrinsic properties (physicochemical and spectral properties of biochar) such as the feedstock type, specific surface area and porosity. The factors which influence the ability of biochar to remove contaminants can be external (related to pyrolysis conditions, feedstock type and properties of the solution to be treated). The later depends on the preparation process and pyrolysis conditions used the following sections will elaborate more about these factors:

3.2.1.1 Specific surface area and porosity

The specific surface area (SSA) and porosity of biochar are major parameters that influence its ability to adsorb contaminants (Liu et al., 2015). When biomass is being pyrolyzed, some of the volatile components are lost and this leads to the formation of micropores on the surface of the biochar (Bagreev et al., 2001). The pore size is very important for adsorption as biochar with small pore size cannot trap large sorbate, regardless of their charges or polarity (Ahmedna et al., 2004). When biochar is highly porous, it has high potential for filtration and this presents two major advantages when it is used as a biofilter for water/wastewater treatment: 1) Good water-holding capacity in the pores and 2) ability to harbor biofilm in pores without clogging (Li et al., 2016).

Biochar porosity and SSA vary considerably with pyrolysis temperature with high temperature ranges leading to larger pore size and larger surface area which in turn leads to increased

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TABLE 4 Characteristics of biochar from various feedstock.

Biochar	Ultimate analysis (%)					T (°C)	EC (mS/cm)	Porosity (%)	Ash content (%)	pH	Particle size (mm)	Surface area (m^2/g)	Reference
	C	H	N	S	O								
Sewage sludge and cotton stalks	40.86	1.52	2.65						48.45	9.08		21.56 ± 1.56	Wang et al. (2021)
Sewage sludge	24.27 ± 0.03	0.87 ± 0.01	2.97 ± 0.03	0.44 ± 0.01	5.13 ± 0.07				65.61 ± 0.02				Ali et al. (2022a)
Sewage sludge	16	0.87	2.10	0.60		550			76.6	7.98	13.4	12.0	Zhao et al. (2020)
Sewage sludge	39.57	1.17	5.67	0.38		550	745			9.77	3.95	3.98	Stylianou et al. (2020)
Faecal sludge	21.1	1.55	1.32	0.03	13.69	750	2.70			11.81		3.52	Nicholas et al. (2022)
Faecal sludge	38.8	4.1	1.9	1.2	9.13	250			42.9			4.4	Fakkaew et al. (2018)
Poultry litter	28.46	0.88	1.58	0.48		550	4123			10.43	3.94	14.03	Stylianou et al. (2020)
Poultry litter	7.49	0.43	0.76	0.43		550			87.2	9.95	16	7.09	Zhao et al. (2020)
Poultry litter	44.77	0.91	1.94	0.41	5.8	700	0.981		49.9	9.9		66.7	Cantrell et al. (2012)
Spent coffee grounds (SCG)	87.38	2.36	4.28	0.25		550	2723			9.42	60.39	1.53	Stylianou et al. (2020)
Orange Peels	67	1.47	2.05			700			14.9		1.6	501	Chen et al. (2011)
Fir TW	74.6	1.9	0.1		21	600			2.4		14.5	695.1	Rahman et al. (2021)
Olive stones	51.5	6.3	0.3	0.1	41.9	800			0.61	7.8		278	Petrov et al. (2008)
Olive pulp	56.7	5.5	0.3	0.3	37.4	800			1.34	7.7		295	Petrov et al. (2008)
Rubberwood sawdust	86.7 ± 0.10	3.32 ± 0.40	0.49	0.04	7.89 ± 0.05				5.79 ± 0.02				Ali et al. (2022b)
Willow Pine-spruce								60-74				170-200	Perez-Mercado et al. (2018)
Corn Cobs	46.92 ± 0.30	6.08 ± 0.05	0.61 ± 0.02		44.8 ± 0.29				1.54 ± 0.01	7.86			Intani et al. (2018)
Husks	44.96 ± 0.32	6.02 ± 0.07	0.49 ± 0.02		45.57 ± 0.29				2.97 ± 0.02	9.09			
Straw	47.42 ± 0.20	5.98 ± 0.02	0.26 ± 0.02		41.75 ± 0.16				4.60 ± 0.06	9.31			
Corn cobs	82.8	2.08	1.39	0.19	9.28		2.39 ± 0.01		5.65 ± 0.35	8.74 ± 0.07		10.38	Pipiška et al. (2022)
Wood chips	79.9	1.59	0.45	0.18	11.72		0.36 ± 0.01		6.61 ± 0.46	8.58 ± 0.01		53.68	Pipiška et al. (2022)
Oak Bark	71.25	2.63	0.46	0.02	12.99	450			11.1			1.9	Mohan et al. (2011)

(Continued on following page)

TABLE 4 (*Continued*) Characteristics of biochar from various feedstock.

Biochar	Ultimate analysis (%)					T (°C)	EC (mS/cm)	Porosity (%)	Ash content (%)	pH	Particle size (mm)	Surface area (m²/g)	Reference
	C	H	N	S	O								
Soybean stover	81.98	1.27	1.3		15.45	700			17.18	11.3		420.3	Ahmad et al. (2012)
Peanut shells	83.76	1.75	1.14	0.00	13.34	700			8.91	10.57		448.2	Ahmad et al. (2012)
Rice husk	42.1	2.2	0.5		12.1	500			42.2			34.4	Liu et al. (2012)
Rice straw	45.7	2.13	1.17	0.29		550			42.9	10.3	7.85	4.15	Zhao et al. (2020)
Swine solid	52.9	0.74	2.61	0.85	4.03	700	0.194		52.9	9.5		4.1	Cantrell et al. (2012)

adsorption efficiency. The aforementioned trend has been noted in quite a number of studies. Chen et al. (2014) noted that when pyrolysis temperature increased from 500°C to 900°C, the pore volume of biochar increased from 0.056 to 0.099 cm^3/g while the surface area increased from 25.4 to 67.6 m^2/g. However, in some cases, biochar produced at high temperature has lower surface area and porosity. Chun et al. (2004) observed that the surface area of wheat straw biochar reduced when the pyrolysis temperature decreased from 700°C to 600°C. The reduced surface area is due to the fact that at high temperature, the porous structure of biochar may be reduced by graphitization bringing about reduced surface area. Thus, it is necessary to optimize pyrolysis temperature to obtain biochar with the required adsorptive characteristics.

3.2.1.2 Feedstock type

Different kinds of organic materials can be used as feedstock to produce biochar; these organic materials can be plant-based, manure-based, or agricultural/food processing residual–based biomass (Table 4). The composition of the parent material influences the yield, elemental content, and the microstructure of the biochar. Generally, plant-based biochar has high lignin content, which results in high biochar yield. Animal manure and sludge have high inorganic content implying that large quantities of ash will be generated from the feedstock when it is pyrolyzed leading to significant reduction in the surface structure and reaction properties of the biochar (Zielinska et al., 2015).

Feedstock type and pyrolysis temperature influence the quantity of ash in biochar and in turn the use to which the biochar can be put (Ali et al., 2022a). Generally, biochar from sewage sludge and faecal sludge have higher ash contents than biochar from wood and agricultural/food processing residue. The high ash content of biochar from sewage sludge is principally due to the high mineral/inorganic matter content of sludge which is turned into ash after pyrolysis (Zielinska et al., 2015). The high ash content of biochar from sludge implies that it can be applied as soil amendment while biochar from wood and agricultural/food are better suited for the removal of contaminants in wastewater (Perez-Mercado et al., 2018). This implies that if biochar from faecal sludge and sewage sludge are to be utilized for wastewater filtration, they will need to be co-pyrolyzed with other biomass with lower ash content.

Pyrolysis process leads to a change in elemental composition of the raw material, which is usually reflected by an increase in carbon (C) content and a decrease in hydrogen (H), and oxygen (O) contents. This results in an increase in the aromatic properties and a decrease in the polarity of the biochar. Generally, livestock manure and sewage sludge biochar have relatively higher nitrogen (N) and sulfur (S) contents than plant-based biochar which has higher C contents. The higher carbon content of plant-based biochar is due to the fact that they are lignocellulosic materials which have high lignin content that promote carbonization and increase the biochar carbon content (Tomczyk et al., 2020). Also, due to the fact that wood-based biochar maintains its plant cell structure and contains interconnected pores (5–10 μm diameter), it allows for better retention and entrapment of bacteria (Abit et al., 2012). This fact was corroborated by Lau et al. (2017) who noted that biochar produced from forestry wood waste removed 92%–99% *E. coli* from synthetic storm water.

3.2.2 External conditions

Pyrolysis process parameters such as temperature, heating rate, residence time as well as absorbent dose and solution pH influence the intrinsic properties of biochar and in turn its ability to adsorb contaminants (Gopinath et al., 2021).

3.2.2.1 Temperature

The temperature at which pyrolysis is carried out influences the ability of biochar to remove contaminants as it affects the yield, specific surface area, types, and abundance of the surface functional groups on biochar (Zhou et al., 2019). Various researchers have conducted experiments to determine the effect of temperature on adsorption properties of biochar. Hossain et al. (2011) carried out the pyrolysis of dried sewage sludge under different temperatures, which ranges from 300°C to 700°C at heating rate of 10°C/min under nitrogen gas atmosphere in a horizontal tubular reactor. It was observed that biochar yield decreased from 72.3% to 63.7%, 57.9%, and 52.4% when temperature was increased from 300 to 400, 500 and then 700°C, respectively. This is because, when temperature increases, the decomposition of the organic material occurs at a faster rate and certain parts of the raw biomass are lost (Qurat-ul-Ain et al., 2021). In addition, Konczak et al. (2019) reported that the specific surface area increased from 69.7 to 75.5 and 89.2 m^2/g, when the pyrolysis temperature increased from 500 to 600°C and 700°C, respectively. This is due to removal of volatile matter leading to the opening of pores and in turn providing additional surface area. Also, pyrolysis temperature influences the percentage of carbon (C), oxygen (O), and hydrogen (H) contents in biochar as increase in temperature leads to an increase in the percentage of carbon but decreases the oxygen and hydrogen content in the mixture (Weber and Quicker, 2018). The considerable changes in H and O contents have been attributed to the cleavage of heterocyclic compounds and nitrile group at elevated temperature (Konczak et al., 2019).

3.2.2.2 Adsorbent dose

The amount of biochar applied has significant influence on the adsorption efficiency and in turn application of the optimum dose for contaminants removal, which is vital for cost-effective application. Increase in adsorption dosage enhances the adsorption efficiency of both organic and inorganic pollutants due to the availability of numerous bonding or sorption sites. Chen et al. (2011) investigated the removal of toxic metals (Cd, Cu, Pb, and Zn) from wastewater using biochar made from hardwood and corn straw. They observed that the adsorption efficiency of toxic metals by biochar improved when biochar concentration increased from 0.5 to 5 g/L. The increase in adsorption efficiency was attributed to increase in the number of active sites and surface area brought about by increase in amount of biochar. This observation is similar to results obtained by Lalhruaitluanga et al. (2010); Tsai and Chen (2013); Lu et al. (2017); Wang et al. (2018) observed similar results when they noted that increasing the biochar amount increased adsorption of organic pollutants. This shows that high concentration of biochar has a positive impact on the adsorption of pollutants and it would be therefore useful to find the optimum dose, which is a key factor to minimize the biochar production costs in view of its industrial application, (Ambaye et al., 2021). However, the adsorption efficiency can be negatively correlated with adsorbent dose when its optimized dose is exceeded (Saltalı et al., 2007). This can be attributed to the unsaturation of sorption sites and also overcrowding of adsorbent molecules, which may lead to overlapping (Merrikhpour and Jalali, 2012).

3.2.2.3 Residence time

Residence time which is the amount of time the water molecules spend within the adsorbent is another important factor to consider during adsorption process. In general, the adsorption process has two-stages; a first stage which is rapid and quantitatively significant and a second stage which is slower. In the first stage, a larger surface of adsorbent is easily available but the pores of the biochar get clogged with time, leading to reduced adsorption and higher residence time in the second stage. Kizito et al. (2015) investigated the effect of contact time on the adsorption of ammonium ion (NH_4^+) and observed that NH_4^+ adsorption increased rapidly with time in the first 6–8 h and became significantly slower until equilibrium was reached. A similar observation was also made by Saltalı et al. (2007).

3.2.2.4 Solution pH

The solution pH is an essential parameter in the adsorption process and its influence depends on the biochar type and target contaminants. The pH influences both the surface charge and the degree of ionization and speciation of the biochar (Kołodyńska et al., 2012; Regmi et al., 2012). Changes in solution pH bring about changes on the surface functional groups found on biochar; when the solution is acidic, most of the functional groups on biochar are protonated and are present in positively charged form favoring adsorption of anions (Oh et al., 2012; Abdel-Fattah et al., 2014). With an alkaline solution, the surface of biochar is negatively charged, and the cations can easily be captured by biochar surface. The aforementioned trends have been noted in studies of different heavy metals adsorption on various kinds of biochar. Tong et al. (2011) investigated Cu (II) ion adsorption on three different types of biochar and observed that the adsorption of Cu (II) ion was increased when the solution pH was increased from 3.5 to 6.0. In another study by Chen et al. (2011) where biochar made from hardwood and corn straw were used to adsorb metals like copper, zinc, and lead, it was noted that when the pH increased from 2.0 to 5.0, the adsorption capacity of the metallic cations also increased. But at pH above 5.0, there was a decrease in the adsorption capacity due to hydroxide complex formation (Ambaye et al., 2021) Similar results were reported by Lu et al. (2012) who noted enhanced Pb adsorption on sludge derived biochar at increased pH.

3.2.2.5 Heating rate

The heating rate during pyrolysis usually affects the structural and physicochemical properties of the resulting biochar most especially the pore structure (Yaman, 2004). When the heating rate is low and residence time is long and the pyrolysis process will occur slowly leading to full carbonization of the organic matter content. This brings about perforation in the pore wall structure of the biochar and subsequent decrease in the number of micropores in the biochar. When heating rate is high, large amount of volatile matter will escape from the feedstock within a short time leading to formation of a loose, and well-developed pore structure (Pan et al., 2021).

4 Modification of biochar for enhanced contaminant removal

When biochar is produced without any modification, it has poor surface functional groups (only $C-O, C=O$, and OH groups are present) and possesses small surface area and micro-pores (Xiang et al., 2020). These poor properties hinder wide application of biochar necessitating the need for modification of its properties to improve its function. The functionality of biochar can be improved by physical and chemical methods and through impregnation with nanomaterials. Table 5 shows the characteristics of activated biochar from different sources.

4.1 Physical activation

Water vapour and carbon dioxide (CO_2) are the most commonly used oxidizing agents for physical activation of biochar (Sajjadi et al., 2018). Biochar is subjected to extremely high temperatures (800°C–1,100°C) and active atmosphere pressure with vapour, CO_2 or a mixture. The process increases the porosity and specific surface area of the biochar. The chemical reactions governing physical modification by steam using CO_2 and H_2O as reagents, are expressed in Equations (2)–(4) (Bansal et al., 1988).

$$C + H_2O \rightarrow CO + H_2,\ \Delta H = 117\,\mathrm{kJ/mol} \quad (2)$$

$$C + CO_2 \rightarrow 2CO,\ \Delta H = 159\,\mathrm{kJ/mol} \quad (3)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2,\ \Delta H = 41\,\mathrm{kJ/mol} \quad (4)$$

In the study by Kołtowski et al. (2017), significant changes in physical properties such as specific surface area, micro-pores, and surface chemical characteristics (such as functional groups, polarity, and hydrophobicity) were observed after physical activation. The activation of cotton shell biochar using steam and CO_2 independently and then in combination was investigated by Yang et al. (2010), where results showed that the specific surface area of the activated carbon increased by over 2000 m^2/g irrespective of the activation agent used.

4.2 Chemical activation of biochar

In chemical activation, biochar is impregnated with either acids (sulfuric acid, H_2SO_4; hydrochloric acid, HCl; phosphoric acid, H_3PO_4; nitric acid HNO_3; and carbon dioxide, CO_2), alkalis (potassium hydroxide, KOH; sodium hydroxide, NaOH and potassium carbonate K_2CO_3) or oxidizing agents (hydrogen peroxide, H_2O_2, and potassium permanganate $KMnO_4$). Acidic activation is purposely done to introduce acidic surface functional groups to biochar. Depending on the type and concentration of the acidic agent, SSA and pore structure of biochar can be altered. Peng et al. (2016) reported that 1 M of HCl enhanced the surface area of biochar by more than 50%. Another study by Vithanage et al. (2015) reported a significant increase of more than 2,400% (i.e., 2.3 to 571 m^2/g) when biochar was activated by 30% H_2SO_4 and oxalic acids. Feedstock type and method of preparation have a strong effect on the properties of biochar modified by alkali. Similarly, it is reported that the type and proportion of alkali activator have profound effect on the characteristics of biochar (Shen and Zhang, 2019). The activation of biochar by oxidizing agents such as H_2O_2 and $KMnO_4$ is reported to enhance oxygen-containing surface function groups. In a study by Wang et al. (2015) where hickory-wood biochar was activated by impregnating it with $KMnO_4$, it was observed that there was an increase in the surface area from 101 to 205 m^2/g. Also, the adsorption capacity towards Pb (II), Cu (II), and Cd(II) was enhanced after the modification. In another study by Xue et al. (2012) where biochar from agricultural residue was modified with H_2O_2, it was noted that when compared to the control group without modification, the modified one had higher oxygen functional groups particularly the carboxyl group and this lead to enhanced lead adsorption capacity (22.82 mg/g for the modified biochar and 0.88 mg/g for unmodified biochar).

4.3 Impregnation methods

In impregnation, metal salts or oxides, hydroxides and nanoparticles are being applied for biochar surface modification to enhance contaminant removal capacity due to their high abundance, cost-effectiveness, environmental friendliness, and chemical stability (Li et al., 2017). Biochar impregnation can be conducted by 1) soaking or suspending the biomass followed by pyrolysis and 2) pyrolysis of the biochar followed by impregnation (Ahmed et al., 2016). In a study by Chen et al. (2011), biochar was produced at different temperatures and impregnated with magnetite (Fe_2O_3) for the removal of phosphorus. It was observed that the modified biochar showed higher phosphorus adsorption (~99% removal) than unmodified biochar. In another study by Li et al. (2017), it was noted that adding ferric chloride ($FeCl_3$) to biochar increased the phosphorus adsorption rate from 1 to 16.58 mg/g of biochar. Zhou et al. (2014) observed that when biochar surface was loaded with zerovalent iron (ZVI)–silver (Ag) nanoparticles (NPs) complex, the growth of *E. coli* was completely hindered. Silver nanoparticles (Ag-NPs) serve as antimicrobial particles due to a range of mechanisms such as disruption of cell wall and cytoplasmic membrane, denaturation of ribosomes, interruption of ATP production, and interference of DNA replication (Yin et al., 2020). Biochar composites impregnated with nanomaterials have also been found to improve the removal of PPCPs. For instance, the adsorption capacities of a group of PPCPs [salicylic acid (683 mg g−1), naproxen (533 mg g−1), and ketoprofen (444 mg g−1)] were 11–45 times higher in iron oxide (Fe2O3)-impregnated biochar when compared with those of unmodified biochar (Baccar et al., 2012; Karunanayake et al., 2017; Ahmed & Hameed, 2018; Anfar et al., 2020). Higher adsorption capacities of caffeine, ibuprofen, and acetylsalicylic acid were observed in biochar impregnated with iron oxide nanoparticle (Liyanage et al., 2020).

TABLE 5 General characteristics of activated biochar from different sources.

Activation method	Feedstock	Temp (°C)	Hold time (min)	Yield (%)	S_{BET} (m^2/g)	V_{tot} (cm^3/g)	V_{micro} (cm^3/g)	D_{ave} (nm)	Reference
PA (steam: N_2), CH	WT	800	78		840		0.22	2.74	Kołtowski et al. (2017)
PA (CO_2), CH	WT	800	78		512		0.17	2.16	Kołtowski et al. (2017)
PA (steam), MWH	CS	900	75	42.2	2,079	1.21	0.97		Yang et al. (2010)
PA (CO_2), MWH	CS	600	210	37.5	2,288	1.30	1.01		Yang et al. (2010)
PA (CO_2+steam)	CS	900	75	39.2	2,194	1.30	1.01		Yang et al. (2010)
PA (Steam: N_2+H_2O), CH	CS	800	120	76.3		0.39	0.35	0.68	Cagnon et al. (2009)
PA (35% steam, 65% N_2), CH	CS	800	120		524.5	0.23	0.21	1–6	Achaw & Afrane (2008)
PA (inter atm), CH	CS	600	60	21.29	378	0.26	0.12		Singh et al. (2008)
PA (steam), CH	CS	1,000	120	45	1,926	1.26	0.93	2.62	Li et al. (2008)
PA (CO_2), CH	CS	900	480		1,964	0.98		1.3–2.1	Wei et al. (2007)
PA (N_2+H_2O), CH	DS	700	180	22.31	421		0.484		Bouchelta et al. (2008)
PA (Steam), CH	OP	800	120	12.20	1,090	0.860	0.430		Petrov et al. (2008)
	SEOP	800	120	17.80	998	0.820	0.400		
PA (CO_2)	OS	850	120	65.3	778	0.342	0.406		Román et al. (2008)
PA (Steam)			60	82.5	1,074	0.377	0.525		
PA (CO_2/Steam)			60	76.5	1,187	0.384	0.553		
PA (CO_2)	MCA	800	60		383	0.2028	0.1884	21.21	Aworn et al. (2008)
	CCA				770	0.4026	0.3637	20.33	
	BBA				467	0.2785	0.2189	23.84	
	SFA				518	0.3246	0.2365	25.05	
PA (Steam)	MCC	800	60		718	0.4283	0.3338	23.88	Aworn et al. (2008)
	CCC				651	0.3447	0.3139	21.18	
	BBA				491	0.3253	0.2231	26.51	
	SFA				464	0.4211	0.4256	20.18	
CA (NaOH)	PC	800	120		13,060.3		0.307		Jung et al. (2013)
CA (PTFE)	PM	700	120		218.1	0.315		57.8	Zhang et al. (2013)
CA ($ZnCl_2$), CH	SBB	700	90		1826	0.966	0.711	2.22	Demiral and Gündüzog (2010)
PA&CA (KOH followed by CO_2), CH	CS	850	120		1,026	0.58		2.25	Din et al. (2009)
CA (H_2SO_4), CH	CS	600	60	99.35	380	0.36	0.12		Singh et al. (2008)
CA (NH_3.H_20), CH	CS	850	210		2061	1.01			Wei et al. (2007)
CA ($ZnCl_2$), CH	CS	500	180		1,266	0.73	0.68		Azevedo et al. (2007)
CA ($ZnCl_2$) followed by PA (steam), CH	CS	900	30		2,114	1.31	1.14		Azevedo et al. (2007)
CA (K_2CO_3), CH	OP	500–1,100	60	15.20	1,610	0.843	0.437		Petrov et al. (2008)
	SEOP	500–1,100	60	16.2	1850	0.819	0.461		
CA (H_2O_2)	CW	900	120	22.7	1705	1.041	0.764		

(Continued on following page)

TABLE 5 (*Continued*) General characteristics of activated biochar from different sources.

Activation method	Feedstock	Temp (°C)	Hold time (min)	Yield (%)	S_{BET} (m^2/g)	V_{tot} (cm^3/g)	V_{micro} (cm^3/g)	D_{ave} (nm)	Reference
									López de Letona Sánchez et al. (2006)
CA (CO_2)	ATP	800	60		840	0.55	0.39		Gañán et al. (2006)
CA (H_3PO_4)	Eucalyptus	500	60	26	1,239	1.109	0.9815	8.49	Patnukao and Pavasant (2008)

PA, Physical activation; CA, Chemical activation; MWH, Microwave heating; CH, Conventional heating; CS, Coconut shells; WT, willow tree; V_{tot}, total pore volume; V_{micro}, micropore area; D_{ave}, average pore diameter; BET, Brunauer-Emmett-Teller; DS, Date stones; OP, Olive pulp; SEOP, Solvent extracted olive pomace; MCA, Macadamia nutshell char; CCA, Corn cob char; BBA, Bagasse bottom ash; SFA, Sawdust fly ash; PTFE, polytetrafluoroethylene (Teflon); PM, Pig manure.

5 Mechanisms of contaminants removal from domestic wastewater using biochar

When biochar is applied as a support media for the treatment of domestic wastewater, several physical, chemical, and biological mechanisms are responsible for pollutant removal. However, the dominant removal mechanism depends on several factors which include the biochar's physicochemical properties, system configuration and operational condition (Quipse et al., 2022). These mechanisms include adsorption, biodegradation, ion exchange, and pore filling/entrapment.

5.1 Adsorption

The mechanism used by biochar for adsorption is dependent on the heterogeneity of the adsorbent surface and the nature of the pollutant (adsorbate). Adsorption to the biochar surface occurs through van der Waals forces and hydrogen bonds with functional groups, filtration, electrostatic interaction, ion exchange, and surface complexation (Li et al., 2019; Cheng et al., 2021). When organic contaminants are to be removed, electrostatic attraction, hydrophobic sorption, hydrogen bond, π-π electron-donor acceptor interactions and pores fillings facilitate the adsorption process. For the removal of inorganic pollutants (heavy metals), the adsorption process occurs through electrostatic attraction, ion exchange, complexation, and co-precipitation. In complexation and co-precipitation, the metals present in the domestic wastewater form complexes with oxide minerals or free carboxyl and hydroxyl functional groups available on the biochar surface after which they settle (physical sorption) or form layers (precipitation) on the biochar surface (Li et al., 2014). Pharmaceutical and personal care products which are emerging contaminants are usually adsorbed by biochar mainly by mechanisms of electrostatic attraction, hydrophobic effects, aromatic p-donor and cationic p-acceptor conjugation, hydrogen bonding and pore filling (Zhang et al., 2019; Xiang et al., 2020).

Pore filling is another mechanism through which contaminants are removed from onsite wastewater by adsorption. The pore network of biochar is usually made of micropores <2 nm, mesopores ~2–50 nm, and macropores >50 nm; the micropores and small mesopores (2–20 nm) contribute majorly to the surface area of the biochar and mostly influence its uptake for organic compounds (Pignatello et al., 2006). Pore filling is usually applied for the removal of organic contaminants in domestic wastewater and this is a function of the total micropore and mesopore volume on biochar pore surface (Nguyen et al., 2007; Hao et al., 2013). The pore fling mechanism depends upon nature, type of the biochar, as well as the polarity of the organic contaminant. Kasozi et al. (2010) studied the removal of organic contaminants from wastewater using biochar made from oak, gamma-grass and loblolly pine; it was noted that the biochars' strong affinity for catechol (PPCP) was mainly due to micropore filling.

5.2 Biodegradation

The synergy between the properties of biochar and the metabolism of microbial organisms attached to the surface of biochar play a significant role in its removal of contaminants (Faulwetter et al., 2009). Biochar's distinct physicochemical characteristics such as large surface area and excellent pore structure make it support several microbial communities (Wang et al., 2020; Deng et al., 2021). The pH of biochar and the nature of dissolved oxygen carbon (DOC) are also important parameters for microbial growth on biochar. There is limited evidence in literature documenting the effects of biochar on the composition, activities and diversities of microorganisms during the treatment of household wastewater. Dalahmeh et al. (2014) evaluated the effect of bark, charcoal and sand filters on microbial diversity and potential respiration during the treatment of greywater. It was observed in the study that charcoal filters enhanced the development of diverse microbial communities. For the bacterial community composition, 33%, 25%, 13%, and 11% were reported for classes g-proteobacteria, a-proteobacteria, b-proteobacteria and Clostridia, respectively. There was a negative correlation between potential respiration and depth in both charcoal and bark filters due to fast mineralization of easily biodegradable matter in the topmost layer and subsequent oxygen depletion in the layers underneath. This is an indication that charcoal filters should be prepared to be more shallow in comparison with sand filters in greywater treatment systems; Deng et al. (2021) revealed that the use of biochar as a substrate in constructed wetlands was found to support many functional microbes such as nitrifying and denitrifying bacteria.

This is because biochar has large SSA and several pores making it easier to trap huge amounts of organic matter which supports reproduction and metabolism in microorganisms (Gul et al., 2015; Ji et al., 2020; Jia et al., 2020; Yuan et al., 2020). Other researchers also observed an enhancement of functional microorganisms in relation with organic matter degradation and nitrogen removal due to biochar amendments in constructed wetlands (Guo et al., 2020; Ji et al., 2020; Liang et al., 2020; Deng et al., 2021). The addition of biochar has the potential to increase the proportion of microorganism groups. With this, microbial activity is enhanced and the stress in removing toxic substances is eliminated (Wang et al., 2020). The overall effect of biochar incorporation is that there is regulation of microbial activities which enhances the removal of pollutants.

5.3 Ion exchange

Ion exchange is a reversible reaction which occurs between ions in the liquid phase and ions in the solid phase. During ion exchange, when ions in the liquid phase get adsorbed by the ion exchange solid, the ion exchange solid releases equivalent ions back into the solution to maintain the electrical neutrality of the aqueous solution. (Cheng et al., 2021). Ion exchange is the main mechanism for removing heavy metals from wastewater by biochar and the ion exchange capacity is usually influenced by pyrolysis temperature as temperatures greater than 350°C decreases the ion exchange capacity of biochar. Several studies have noted that higher ion exchange capacity leads to higher adsorption efficiency for metals (El-Shafey, 2010; Trakal et al., 2016). Though ion exchange is the main mechanism for removing metals from onsite domestic wastewater, PPCPs cannot be easily removed by ion exchange. This is due to the fact that they cannot be easily converted into ionic forms. (Cheng et al., 2021).

5.4 Synergetic removal of contaminants from onsite domestic wastewater

Synergetic removal of PPCPs, organic matter and nutrients from wastewater using biochar filters involves the combination of adsorption and biodegradation processes. When adsorption and biodegradation processes are used together, biochar filters can be made self-sustaining through bio-regeneration; microbes (naturally present in water or externally introduced to suit target contaminants) can be immobilized on the surface of porous carbon forming biofilms which then metabolize and degrade the adsorbed contaminants in a bio-regeneration process. This bio regeneration process frees up clogged pores of the biochar, rejuvenating its adsorptive capacity thereby increasing its lifespan (Simpson, 2008; Jin et al., 2013). Also, nutrients such as nitrogen which are retained on the surface of biochar filters can help to enhance the biodegradation process. A study conducted by Jefferson et al. (2001) showed increased biological treatment (increased COD removal and oxygen uptake) after micronutrients (Zn) and macronutrients (N, P) were added.

Figure 1 shows the various mechanisms through which contaminants are removed from domestic onsite wastewater by biochar.

6 Previous studies on the use of biochar for the treatment of onsite domestic wastewater

Previous studies have successfully incorporated biochar into on-site sanitation facilities for the treatment of domestic wastewater. Mwenge and Seodigeng (2019) carried out experiments in laboratory plastic columns where activated biochar from agricultural wastes sandwhiched between two gravel layers was used as filter for the removal of TSS, NH_3-N, NO_3-N, and COD in kitchen, floor cleaning, showering and laundry greywater. Two different loadings of biochar—200 and 400 g—were used and it was observed that as the amount of biochar used increased, removal efficiency of contaminants across the wastewater types increased. Also, the initial concentration of pollutants used in the biochar had effect on the removal efficiency as it was noted that kitchen wastewater which had the highest pollutant concentration had the highest removal rate for most of the contaminants. The results of the study showed that the biochar column had efficiency with TSS (95% on kitchen greywater), NH_4-N (85% on bathroom greywater), NO_3-N (76% on kitchen greywater) and COD (63% on kitchen greywater).

Sidibe (2014) determined the effectiveness of salix leaves biochar filter for the removal of COD, *Salmonella* spp. And male-specific phages from artificial greywater in a laboratory filtering columns. The hydraulic loading rate was 0.032 m^3 m^{-2} day^{-1} and the organic loading rate was 76 mg BOD_5 m^{-2} day^{-1} (240 g COD m^{-2} day^{-1}). It was noted that the reduction of COD in 60 cm high biochar filter was 90%, 3 log_{10} reduction for *Salmonella* spp. But there was very low reduction for the virus (2 log_{10}reduction for male-specific phages). Very low reduction in MS2 virus concentration has also been noted by Dalahmeh et al. (2016) who carried out an experiment using laboratory scale columns loaded with biochar. Perez-mercado et al. (2019) studied the suitability of hardwood biochar filter for the removal of pathogens (*S. cerevisiae,* E. *coli, Enterococcus* spp and bacteriophage (MS2)) in domestic wastewater prior to use for irrigation. It was observed that biochar filter effectively removed *S. cerevisiae* from greywater. However, its effect on virus removal was found to be insignificant. These poor reductions in virus concentration in the laboratory scale biochar filters suggest that biochar has low capacity for the removal of virus. Lalander et al. (2013) reported that the virus removal by greywater filtration systems depends on the pH of the filter medium as the charge of the viruses changes with pH. The isoelectric point (pH at which a molecule is electrically neutral) of most viruses is in the acidic pH range (Dowd et al., 1998). Hence, for the removal of virus, further measures that can be used to make the pH of biochar acidic should be explored. Also, the use of finer particle biochar media to ensure better straining can be investigated. From a review of the studies, it can be seen that most of the studies were carried out with the use of column filters. More studies need to be carried out using other kinds of filters like the horizontal flow filters instead of the column filters.

Dalahmeh et al. (2016) used pilot scale sand bed biochar filter for the treatment of household grey water and reported the removal efficiency of biochar filter for BOD_5, TSS, and *E. coli* to be 93%, 85% and 1log_{10} reduction, respectively. Niwagaba et al. (2014) constructed a 60 cm high gravel biochar filter for greywater treatment and reported high removal efficiency of BOD_5, TSS and faecal coliforms (FC) which are 96%, 85.2%, and 95%, respectively after

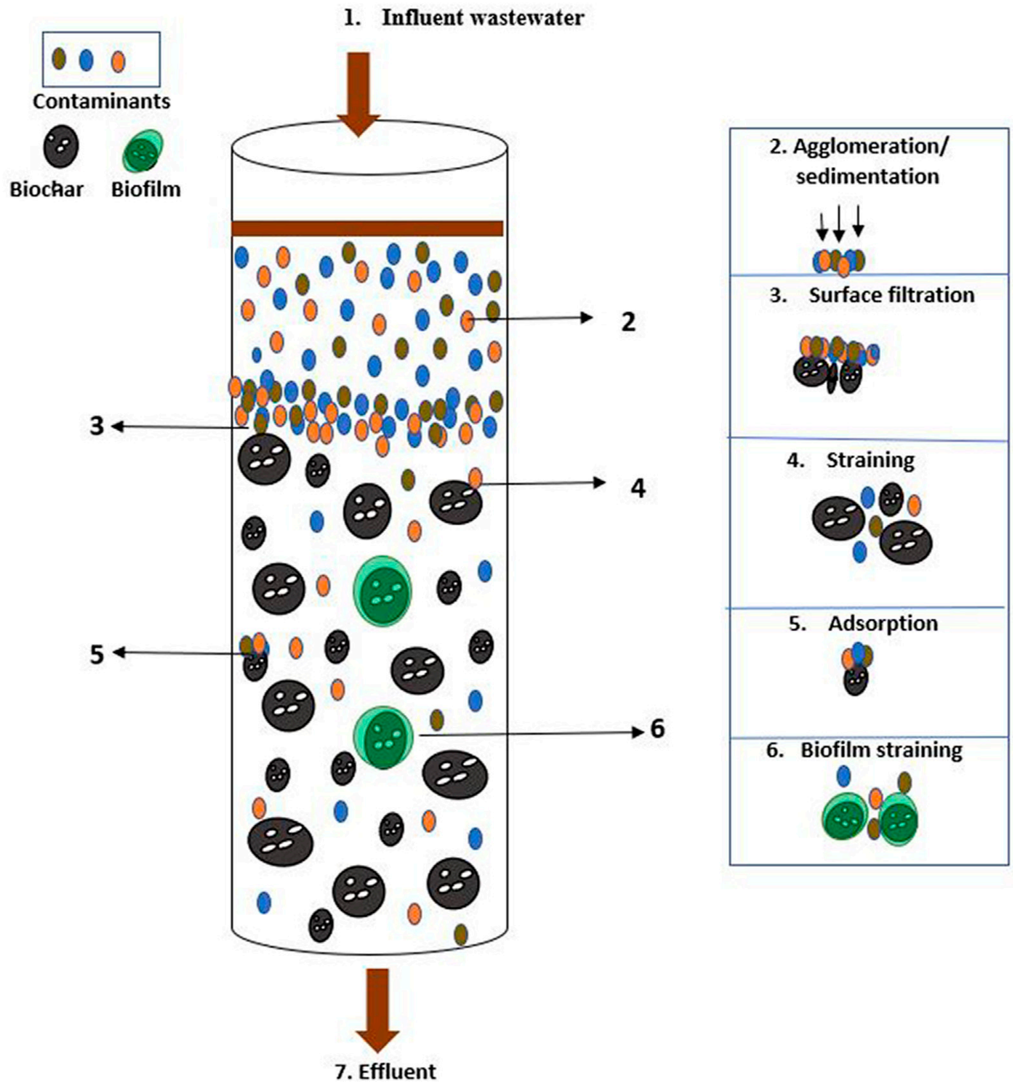

FIGURE 1
The various mechanisms through which contaminants are removed from onsite domestic wastewater by biochar (Modified from Quipse et al., 2022).

36 h of operation. In contrast to the study of Dalahmeh et al. (2016), it can be seen that the study by Niwagaba et al. (2014) achieved high removal of faecal coliform. These differences can be a direct influence of the properties of the bacteria, the features of the biofilm-supporting materials (sand versus gravel), environmental factors as pH and temperature, the presence of other bacteria, the nutrients (quality and quantity) in the media which together play a role in the removal of faecal coliform (Van Houdt & Michiels, 2010).

Perez-mercado et al. (2018) studied the effect of different biochar filters (pine-spruce, willow and activated biochar) on the removal of COD, total phosphorus and nitrate phosphorus from onsite wastewater before irrigation. All types of biochar and all particle sizes of pine-spruce biochar achieved a high degree of removal of organic material (COD >90%). Willow biochar and activated biochar showed higher removal of total and phosphate phosphorus (>70%) than in pine-spruce biochar. It was noted that the particle size influenced the COD removal efficiency as the larger particle size (2.8 mm) had significantly lower removal efficiency (94%) than the smaller particle sizes (0.7 and 1.4 mm with greater than 99% removal efficiency). The lower removal efficiency of the larger particle size may be attributed to the fact that the larger particle size allows for larger macropores between the particles and it is likely that there is rapid passage through the filter which gives less contact time between the filter and the contaminants in the wastewater and thus less treatment efficiency.

In a study by Kholoma et al. (2016), biochar (about 0.2 m) was placed on top of a sand layer (0.8 m) in a filtration unit which was used for reclaiming domestic wastewater containing 1.9 mg P/L. It was observed that the phosphorus removal efficiency improved by 25.6% in the biochar-amended sand column when compared to the column with only sand. Gupta et al. (2016) mixed oak tree biochar with horizontal flow constructed wetland filter media used for treating synthetic wastewater. The application of biochar brought about increased contaminant removal with removal rates of 91.3% for COD, 58.3% for TN, 58.3% for NH_3, 92% for NO_3-N, 79.5% for TP, and 67.7% for PO_4. . In a pilot-scale study by

Bolton et al. (2019), the addition of 100% chipped hemp fibre biochar filter after a horizontal flow gravel wetland for the treatment of domestic wastewater brought about better phosphorus (P) removal in the long term (5 months); 97% P removal was noted compared with 87% in the control (Bolton et al., 2019). The aforementioned studies show that using biochar as a filter media can improve the removal efficiency of phosphorus by constructed wetlands (constructed wetlands typically do not have high removal efficiency for phosphorus).

Forbis-Strokes et al. (2018) applied wastewater containing high concentrations of nitrogen to both unsaturated biochar trickling filters and saturated filters for 1 year and observed that the ammonium ion (NH_4^+) removal rate was higher in unsaturated biochar nitrifying column (0.075–0.100 kg N/m^3. day) than that of the control gravity column (0.041–0.094 kg N/m^3. day). In another trickling filter study, when biochar was added to the sand column, the total nitrogen removal efficiency of the system increased from 8% to 42% (Tait et al., 2015). From all the aforementioned studies, it is seen that the addition of biochar to the treatment units improves the quality of the effluent from these systems making it a suitable alternative for the treatment of onsite domestic wastewater. Biochar-amended onsite sanitation systems have also been applied for enhanced PPCP adsorption (Cheng et al., 2021). Williams et al. (2015) noted that when eucalyptus wood and wheat residue biochar were applied to the soil matrix (0.5 t/ha), the removal of selected active pharmaceutical ingredients (propranonol and carbamazepine) increased by threefold. In another case study, various filtration matrices - (a) 100% silica sand, (b) 100% ZVI, (c) biochar-amended sand (50% v/v), and (d) 10% ZVI +40% biochar +50% sand (v/v)- were compared for their PPCP removal performance. It was observed that the column with a combination of ZVI, biochar, and sand showed the highest PPCP removal efficiency (>97% removal of all PPCPs at 10 μg/L of each chemical) within the top 10 cm of the column while the 100% sand control column did not show effective removal for the tested PPCPs (0.3 μg/L in the effluent) (Liu et al., 2019). Table 6 is a summary of studies which have investigated the suitability of biochar for greywater treatment.

7 Management of spent biochar, constraints, gaps and areas of future research in the use of biochar for wastewater treatment

7.1 Management of spent biochar

Since biochar is usually applied for the removal of toxic pollutants, its disposal needs to be carefully considered. The management option depends on the contaminant removed by the biochar and some of the management options include: Use as a soil conditioner, re-use in wastewater treatment, energy source and landfilling. The following sections discusses these mentioned management options:

7.1.1 Spent biochar as a soil conditioner

If biochar is loaded with nutrients such as ammonium, nitrate, and phosphate, without other toxic pollutants, it can be used as slow-release organic fertilizer into surrounding fields and degraded lands to improve soil fertility and consequently improve crop yield and quality (Yao et al., 2011; Zhang et al., 2013). This is a practical solution which can be used to promote organic farming, and even alleviate agricultural non-point pollution runoff leading to multiple agronomic and environmental benefits (Werner et al., 2018; Kizito et al., 2019; Zheng et al., 2019). However, if biochar is used to adsorb toxic pollutants such as heavy metals and organic pollutants, it cannot be applied to the soil and there will be need to investigate its desorption/regeneration.

7.1.2 Re-use of spent biochar in wastewater treatment

The desorption/regeneration properties of biochar have been investigated by several studies in order to determine the economic feasibility of reusing it as an adsorbent. Zhang et al. (2013) reported that the adsorbed uranyl ion U(VI) could be effectively desorbed from the spent biochar using 0.05 mol/L HCL in four times of adsorption–desorption cycles. In another study, food waste biochar which was loaded with dye was desorbed using ethanol. The results showed that the biochar could be used repeatedly without much loss in the total adsorption capacity of the dyes (Parshetti et al., 2014). Despite the feasibility of reuse, the wide source of waste biomass for producing biochar may make the recovery process economically unnecessary. Therefore, the assessment of the economic feasibility of desorption/regeneration process is needed in the future adsorption process.

7.1.3 Spent biochar as energy source

Apart from regeneration, spent biochar can be used for energy conversion, storage devices, capacitors, and catalyst/catalyst support. Studies have shown that metal impregnated biochar can replace carbon nanotubes and might also be used for tar removal or as supercapacitors (Qian and Chen, 2013). Also, spent biochar can be used for energy production by combustion (Kaetzl et al., 2019).

7.1.4 Landfilling of spent biochar

After re-use, spent biochar can be safely disposed into landfills and can be incinerated. However, knowledge on the disposal of spent biochar using these methods is limited. The stability, potential pollution, effect on the carbon sequestration, and economical feasibility of using these methods to deal with the spent biochar remain unclear necessitating the need for further research in this area.

7.2 Constraints, gaps and areas of future research in the use of biochar for onsite wastewater treatment

Although biochar presents a cost effective and innovative technique for the treatment of onsite domestic wastewater, it still has some constraints which affect its applicability. Biochar is known to physically disintegrate in aqueous solution (Bangham and Razouk, 1938); the physical breakdown occurs through several mechanisms. High oxygen to carbon (O:C) ratio biochar. Can dissolve readily when it is exposed to rewetting or saturation cycles (Parr et al., 1931). Water and water vapor absorption may put stress on the physical structure of biochar due to exothermic graphite sheet swelling. The aforementioned mechanisms lead to the swelling and expansion of biochar's physical structure which paves way for further fragmentation (Théry-parisot et al., 2010). Moreover, the mechanical strength of biochar reduces with age (Spokas et al., 2014). Consequently, the prolonged exposure of biochar to stress may lead to the formation of fragments during

TABLE 6 Summary of the effect of biochar on household wastewater treatment.

Reference	Country	Type of wastewater	Scale	Main findings	Practical implications
Boano et al. (2021)	Italy	Artificial greywater	Lab-scale	20% biochar additive resulted in the highest removal of 50.7% COD.	The study demonstrated the potential benefits of incorporating biochar into GW treatment in green walls
				In terms of BOD_5, and MBAS, the removal efficiency was 96%, and 71.4%, respectively. 3.1$\log_{10}$ reduction was recorded for *E. coli*	
Moges et al. (2015)	Norway	Student dormitory-bathrooms, laundries, hand washing basins, dish washing machines, and kitchens	On-site	The removal of OM, TN, turbidity and odor by biochar was significant	The research demonstrated a unique opportunity to enhance the performance of decentralized greywater treatment system by using appropriate materials to improve effluent quality
Perez-mercado et al. (2019)	Sweden		On-farm	Biochar filters for on-farm treatment system did not result significant removal of bacterial and viruses. However, the removal of *S. cerevisiae* from greywater was significant (>1.0 $\log_{10}$ CFU)	The findings, as well as certain technical and management factors can help build a systematic strategy for designing biochar filters for on-farm treatment of GW for irrigation
Dalahmeh et al. (2016)	Jordan	Household greywater	Small-scale: household of 7 members	Biochar filter effectively eliminated 93 percent of BOD_5 and 85 percent of TSS, but the removal of *E. coli* by biochar filter medium was not significant	This study demonstrated the suitability of biochar for onsite greywater treatment system for garden irrigation
Berger (2012)	Sweden	Artificial greywater	Lab-scale	Biochar filter had a COD removal efficiency of 99%	The performance of biochar filters in removing TP from greywater is an indication that biochar can be used for the removal of OM and phosphorus in GW treatment plants
				Biochar filters remarkably removed 89% and 86% of TP and PO_4-P, respectively. The study did not report on pathogens	
Mwenge & Seodigeng (2019)	South Africa	Kitchen, floor cleaning, shower and laundry	Lab-scale	Results from the study found 95%, 76% and 63% removal of TSS, NO_3-N and COD, respectively, on kitchen GW and NH_4-N had a removal efficiency of 85% on GW from bathroom, as the highest removal efficiency of the studied contaminants	The results indicated the suitability of biochar to treat greywater for onsite non-potable reuse purposes such as irrigation, flushing of toilets, *etc.*
Hussain et al. (2021)	Belgium	Bathroom, kitchen	Pilot scale, full-scale	Findings from the study indicate that the removal rates of total coliforms and ammonium were 99% and 97%, respectively. Also, turbidity (86%), TSS (67%), and BOD_5 (83%) were significantly removed	This study established that Total Value Wall (TVW) is a sustainable treatment technique for the treatment of greywater and reuse purposes such as toilet flushing
Sidibe (2014)	Sweden	Artificial greywater	Lab scale	Biochar medium filters was found to be effective in the reduction of *Salmonella* spp. On the average, *Salmonella* spp. And bacteriophages $\log_{10}$ reduction were determined to be 2.72 and 1.47, respectively. COD removal was observed to be 90%, on average	Observations made in the work confirms possibility of the use of biochar to enhance the greywater quality for reuse
Ndung'u (2020)	Kenya	Male and female students' hostel	Lab scale	Results obtained from this study indicated that biochar produced at a temperature of 500°C had a percentage removal of 60.60% for COD, 89.36% for K^+ and 65.43% for Na^+	The study established that biochar derived from banana stalks can be used for GW treatment, which can be reuse for agricultural purposes
Dalahmeh et al. (2014)	Sweden	Artificial GW	Lab scale	Charcoal filters efficiently removed 97% BOD_5 and 98%, 95% and 84% reductions of N, COD and TSS, respectively, were observed	Suitable performance by charcoal indicates that, it can be used for GW treatment to reach irrigation quality

wastewater treatment necessitating the need to develop biochar which can withstand physical breakdown in order to maximize the long-term biochar potential for wastewater treatment.

Biochar is a promising material for on-site sanitation treatment due to its excellent properties. Nevertheless, research on this technology is still in its infancy. Further research is required to optimize the usage of biochar to minimise the release of harmful substances into the atmosphere. It is also important to identify the optimum biochar dose and the number of times each dose can be used for faecal sludge management to enhance adsorption of pollutants. Even though there are similarities between biochar and modified carbon, the physicochemical properties of biochar are known to be highly heterogeneous, depending on the type of feedstock and pyrolysis operating conditions. Thus, validated standardized protocols for biochar technology and its subsequent adoption in on-site sanitation treatment systems is still lacking (Gwenzi et al., 2017). Advanced pyrolysis techniques with precise reaction condition control, high energy efficiency, and low environmental impact at a reduced cost are required for increased biochar usage.

In addition, biochar production through pyrolysis technology is inefficient and energy intensive making it less attractive option now. Homagain et al. (2016) carried out life cycle and cost assessment (LCCA) for the production of biochar from wood and posited that biochar production by pyrolysis is a costly investment. This is especially true in a situation where biochar has to be activated/modified to improve its functionality; if pyrolysis is to be used for the production of biochar, then the substrate has to be pyrolyzed first before it is activated and this methodology usually requires multiple treatment steps, high electricity and energy inputs, and corrosive chemicals, which makes it a tedious, expensive, and complex method (Zhou et al., 2019). Thus, efforts should be geared towards more techniques which can improve the functionality of biochar such as simultaneous pyrolysis and activation. One notable option is through the use of wet carbonization methods such as the use of hydrothermal carbonization (HTC) which is used for producing hydrochar. HTC has an added advantage of eliminating pre-drying, which is highly energy intensive and a huge financial load in biomass pre-treatment when performed under pyrolysis. Additionally, a higher conversion efficiency (40%–70%), and lower operating temperatures make HTC a more suitable technology than pyrolysis (Kambo & Dutta, 2015) on sustainable point of view. Also, the use of hydrothermal carbonization enables the addition of active reagents to the liquid media during carbonization and activation, to form functional biochars in a one-step reaction (Fu et al., 2018).

In developing economies, environmental groups may consider biochar technology to be futuristic and overly ambitious since there is lack of pilot-scale and industrial level adoption. Presently, studies on biochar for onsite sanitation including treatment of faecal sludge and greywater have been investigated using only laboratory-scale. The effects of biochar for onsite sanitation on the environment is not properly understood. The conditions of real environment are more complicated than the conditions created in the laboratory, resulting in high uncertainties in biochar application on the environment. Thus, more *in situ* experiments are required to ascertain the real effect of biochar on the environment before full-scale applications.

Physical and chemical modification which are predominantly used for biochar activation are energy intensive, expensive and are associated with environmental concerns. Thus, the design of low-cost, highly effective biochar-based adsorbent for on-site sanitation and faecal sludge treatment using biological modification needs to be explored. Due to its high surface area and porous structure, biochar can be employed as a scaffolding material for colonizing and growing biofilms. The microorganisms may adhere to the surface of biochar and develop an extracellular biofilm. In this modification system, while biochar adsorbs other contaminants such as heavy metals due to its porous structure, high surface area and different functional groups, the microorganisms will enhance the degradation of organic contaminants. This synergistic removal effect makes biologically modified biochar effective for on-site sanitation treatment systems. Simultaneously, both organic and inorganic pollutants can be removed *via* biodegradation and sorption processes, respectively.

Finally, the use of biochar for wastewater treatment is widely reported in the literature but its effect in mitigating antimicrobial resistance in household wastewater is largely unknown; the effect of biochar in mitigating the migration of antibiotic resistant genes (ARGs) is still unexplored. Emerging microbial pathogens with ARGs have become a major public health problem. These genes are dangerous because they can easily proliferate through horizontal gene transfer (unresistant bacteria obtain the necessary gene element from the mobile genetic element and become resistant) and when released into waterbodies/environment, they can alter the microbial community structure and in turn affect the quality of water (Feng et al., 2020). Thus, there is urgent need for detailed investigations to ascertain the potential of biochar in mitigating ARGs present in onsite wastewater. There is need to explore how intrinsic properties of biochar can influence its ability to remove ARGs in onsite wastewater. Also, modifications such as the use of transition metals to increase the amount of persistent free radicals (PFRs) present on biochar surface should be investigated.

8 Conclusion

A critical review of biochar production technologies, properties and its application for the treatment of onsite domestic wastewater is presented in this paper. It is observed that the application of biochar to onsite wastewater treatment systems brings about improvement in the treatment efficiency of these systems. The removal of different contaminants by biochar is achieved through the combination of mechanisms which include adsorption, ion exchange, filtration, electrostatic attraction, biodegradation and pore-filling. The synergistic removal of contaminants is brought about by the properties of biochar together with the microbes found in biofilm trapped on biochar surface. There are still other areas where further research is required in the application of biochar for the treatment of onsite domestic wastewater. There is need to research on the validation of standardized protocols for biochar production and scaling up of biochar production from laboratory scale to full-scale. Further research is also needed to enhance biochar properties and its subsequent potential for the removal of AMR/drug resistance and emerging pollutants in domestic wastewater.

Author contributions

CM: Conceptualization; methodology; software; formal analysis; investigation; writing-original draft preparation; visualization. PO: Conceptualization; methodology; software; formal analysis; investigation; writing-original draft preparation; visualization. AN: Writing-review and editing. SL: Formal analysis; investigation; writing-review and editing. SS: Formal analysis; investigation; writing-review and editing; visualization. OI: Conceptualization; formal analysis; investigation; writing-review and editing; visualization; supervision. MM: Conceptualization; methodology; software; formal analysis; investigation; resources; writing-original draft preparation; writing-review and editing; visualization; supervision; project administration. All authors read and approved the final manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Abdel-Fattah, T. M., Mahmoud, M. E., Ahmed, S. B., Huff, M. D., Lee, J. W., and Kumar, S. (2014). Biochar from woody biomass for removing metal contaminants and carbon sequestration. *J. Ind. Eng. Chem.* 22, 103–109. doi:10.1016/j.jiec.2014.06.030

Abdel-Shafy, H. I., and El-Khateeb, M. A. (2013). Integration of septic tank and constructed wetland for the treatment of wastewater in Egypt. *Desalin. Water Treat.* 51, 3539–3546. doi:10.1080/19443994.2012.749585

Abit, S. M., Bolster, C. H., Cai, P., and Walker, S. L. (2012). Influence of feedstock and pyrolysis temperature of biochar amendments on transport of *Escherichia coli* in saturated and unsaturated soil. *Environ. Sci. Technol.* 46 (15), 8097–8105. doi:10.1021/es300797z

Acero, J. L., Benitez, F. J., Real, F. J., and Rodriguez, E. (2015). Elimination of selected emerging contaminants by the combination of membrane filtration and chemical oxidation processes. *Water Air Soil Pollut.* 226, 139. doi:10.1007/s11270-015-2404-8

Achaw, O., and Afrane, G. (2008). The evolution of the pore structure of coconut shells during the preparation of coconut shell-based activated carbons. *Microporous Mesoporous Mater.* 112, 284–290. doi:10.1016/j.micromeso.2007.10.001

Agoro, M. A., Okoh, O. O., Adefisoye, M. A., and Okoh, A. I. (2018). Physicochemical properties of wastewater in three typical South African sewage works. *Pol. J. Environ. Stud.* 27 (2), 491–499. doi:10.15244/pjoes/74156

Ahmad, M., Soo, S., Dou, X., Mohan, D., Sung, J., Yang, J. E., et al. (2012). Effects of pyrolysis temperature on soybean stover- and peanut shell-derived biochar properties and TCE adsorption in water. *Bioresour. Technol.* 118, 536–544. doi:10.1016/j.biortech.2012.05.042

Ahmed, M. B., Zhou, J. L., Ngo, H. H., Guo, W., and Chen, M. (2016). Progress in the preparation and application of modified biochar for improved contaminant removal from water and wastewater. *Bioresour. Technol.* 214, 836–851. doi:10.1016/j.biortech.2016.05.057

Ahmed, M. J., and Hameed, B. H. (2018). Adsorption behavior of salicylic acid on biochar as derived from the thermal pyrolysis of barley straws. *J. Clean. Prod.* 195, 1162–1169. doi:10.1016/j.jclepro.2018.05.257

Ahmedna, M., Marshall, W. E., Husseiny, A. A., Rao, R. M., and Goktepe, I. (2004). The use of nutshell carbons in drinking water filters for removal of trace metals. *Water Res.* 38, 1062–1068. doi:10.1016/j.watres.2003.10.047

Akpor, O. B., Ohiobor, G. O., and Olaolu, T. D. (2014). Heavy metal pollutants in wastewater effluents: Sources, effects and remediation. *Adv. Biosci. Bioeng.* 2, 37–43. doi:10.11648/j.abb.20140204.11

Akunna, J. C., O'Keeffe, J. M., and Allan, R. (2017). Reviewing factors affecting the effectiveness of decentralised domestic wastewater treatment systems for phosphorus and pathogen removal. *Desalin.* Water Treat. 91, 40–47. doi:10.5004/dwt.2017.20750

Ali, L., Palamanit, A., Techato, K., Baloch, K. A., and Jutidamrongphan, W. (2022b). Valorization of rubberwood sawdust and sewage sludge by pyrolysis and co-pyrolysis using agitated bed reactor for producing biofuel or value-added products. *Environ. Sci. Pollut. Res.* 29 (1), 1338–1363. doi:10.1007/s11356-021-15283-6

Ali, L., Palamanit, A., Techato, K., Ullah, A., Chowdhury, M. S., and Phoungthong, K. (2022a). Characteristics of biochars derived from the pyrolysis and Co-pyrolysis of rubberwood sawdust and sewage sludge for further applications. *Sustainability* 14 (7), 3829. doi:10.3390/su14073829

Alley, E. R. (2007). *Water quality control handbook*. New York, USA: McGraw-Hill Handbooks.

Ambaye, T. G., Vaccari, M., van Hullebusch, E. D., Amrane, A., and Rtimi, S. (2021). Mechanisms and adsorption capacities of biochar for the removal of organic and inorganic pollutants from industrial wastewater. *Int. j. sci. environ. technol.* 18 (10), 3273–3294.

Amin, N., Liu, P., Foster, T., Rahman, M., Miah, M. R., Ahmed, G. B., et al. (2020). Pathogen flows from on-site sanitation systems in low-income urban neighborhoods, dhaka: A quantitative environmental assessment. *Int. J. Hyg. Environ. Health* 230, 113619. doi:10.1016/j.ijheh.2020.113619

Anfar, Z., Zbair, M., Ait Ahsiane, H., Jada, A., and El Alem, N. (2020). Microwave assisted green synthesis of Fe2O3/biochar for ultrasonic removal of nonsteroidal anti-inflammatory pharmaceuticals. *RSC Adv.* 10 (19), 11371–11380. doi:10.1039/d0ra00617c

Aworn, A., Thiravetyan, P., and Nakbanpote, W. (2008). Preparation and characteristics of agricultural waste activated carbon by physical activation having micro- and mesopores. *J. Anal. Appl. Pyrolysis* 82 (2), 279–285. doi:10.1016/j.jaap.2008.04.007

Awuah, E., Amankwah-Kuffuor, R., Gyasi, S. F., Lubberding, H. J., and Gijzen, H. J. (2014). Characterization and management of domestic wastewater in two suburbs of kumasi, Ghana. *Res. J. Environ. Sci.* 8 (6), 318–330. doi:10.3923/rjes.2014.318.330

Azevedo, D. C. S., Araujo, J. C. S., Bastos-Neto, M., Torres, A. E. B., Jaguaribe, E. F., and Cavacante, C. L. (2007). Microporous activated carbon prepared from coconut shells using chemical activation with zinc chloride. *Microporous Mesoporous Mater.* 100, 361–364. doi:10.1016/j.micromeso.2006.11.024

Babcock, R. W., Jr, Lamichhane, K. M., Cummings, M. J., and Cheong, G. H. (2014). Condition assessment survey of onsite sewage disposal systems (OSDSs) in Hawaii. *Water Sci. Technol.* 70 (6), 1083–1089. doi:10.2166/wst.2014.336

Baccar, R., Sarrà, M., Bouzid, J., Feki, M., and Blánquez, P. (2012). Removal of pharmaceutical compounds by activated carbon prepared from agricultural by-product. *Chem. Eng. J.* 211, 310–317. doi:10.1016/j.cej.2012.09.099

Bagreev, A., Bandosz, T., and Locke, D. (2001). Pore structure and surface chemistry of adsorbents obtained by pyrolysis of sewage sludge-derived fertilizer. *Carbon* 39 (13), 1971–1979. doi:10.1016/s0008-6223(01)00026-4

Bangham, D. H., and Razouk, R. I. (1938). The swelling of charcoal Part V. The saturation and immersion expansions and the heat of wetting. *Proc. R. Soc. Lond.* 166 (927), 572–586. doi:10.1098/rspa.1938.0112

Bansal, R. C., Donnet, J. B., and Stoeckli, F. (1988). *Active carbon*. New York: Marcel Dekker). doi:10.1080/01932699008943255

Barrios, J. A., Cano, A., Becerril, J. E., and Jimenez, B. (2016). Influence of solids on the removal of emerging pollutants in electrooxidation of municipal sludge with boron-doped diamond electrodes. *J. Electroanal. Chem.* 776, 148–151. doi:10.1016/j.jelechem.2016.07.018

Behera, S. K., Kim, H. W., Oh, J. E., and Park, H. S. (2011). Occurrence and removal of antibiotics, hormones and several other pharmaceuticals in wastewater treatment plants of the largest industrial city of Korea. *Sci. Total Environ.* 409, 4351–4360. doi:10.1016/j.scitotenv.2011.07.015

Berger, C. (2012). *Biochar and activated carbon filters for greywater treatment – comparison of organic matter and nutrients removal*. Uppsala, Sweden: Swedish University of Agricultural Sciences.

Blum, K. M., Andersson, P. L., Renman, G., Ahrens, L., Gros, M., Wiberg, K., et al. (2017). Non-target screening and prioritization of potentially persistent, bioaccumulating and toxic domestic wastewater contaminants and their removal in on-site and large-scale sewage treatment plants. *Sci. Total Environ.* 575, 265–275. doi:10.1016/j.scitotenv.2016.09.135

Boano, F., Costamagna, E., Caruso, A., Fiore, S., Chiappero, M., Galvão, A., et al. (2021). Evaluation of the influence of filter medium composition on treatment performances in an open-air green wall fed with greywater. *J. Environ. Manag.* 300, 113646. doi:10.1016/j.jenvman.2021.113646

Bolton, L., Joseph, S., Greenway, M., Donne, S., Munroe, P., and Marjo, C. E. (2019). Phosphorus adsorption onto an enriched biochar substrate in constructed wetlands treating wastewater. *Ecol. Eng.* 142, 100005. doi:10.1016/j.ecoena.2019.100005

Bouchelta, C., Medjram, M. S., Bertrand, O., and Bellat, J. P. (2008). Preparation and characterization of activated carbon from date stones by physical activation with steam. *J. Anal. Appl. Pyrolysis* 82 (1), 70–77. doi:10.1016/j.jaap.2007.12.009

Boutilier, L., Jamieson, R., Gordon, R., Lake, C., and Hart, W. (2010). Performance of surface-flow domestic wastewater treatment wetlands. *Wetlands* 30, 795–804. doi:10.1007/s13157-010-0067-1

Brix, H., and Arias, C. A. (2005). The use of vertical flow constructed wetlands for on-site treatment of domestic wastewater: New Danish guidelines. *Ecol. Eng.* 25 (5), 491–500. doi:10.1016/j.ecoleng.2005.07.009

Cagnon, B., Py, X., Guillot, A., Stoeckli, F., and Chambat, G. (2009). Contributions of hemicellulose, cellulose and lignin to the mass and the porous properties of chars and steam activated carbons from various lignocellulosic precursors. *Bioresour. Technol.* 100, 292–298. doi:10.1016/j.biortech.2008.06.009

Cantrell, K. B., Hunt, P. G., Uchimiya, M., Novak, J. M., and Ro, K. S. (2012). Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. *Bioresour. Technol.* 107, 419–428. doi:10.1016/j.biortech.2011.11.084

Capone, D., Barker, T., Cumming, O., Flemister, A., Geason, R., Kim, E., et al. (2022). Persistent Ascaris transmission is possible in urban areas even where sanitation coverage is high. *Environ. Sci. Technol.* 56 (22), 15969–15980. doi:10.1021/acs.est.2c04667

Chen, T., Zhang, Y. X., Wang, H. T., Lu, W. J., Zhou, Z. Y., Zhang, Y. C., et al. (2014). Influence of pyrolysis temperature on characteristics and heavy metal adsorptive performance of biochar derived from municipal sewage sludge. *Bioresour. Technol.* 164, 47–54. doi:10.1016/j.biortech.2014.04.048

Chen, X., Chen, G., Chen, L., Chen, Y., Lehmann, J., McBride, M. B., et al. (2011). Adsorption of copper and zinc by biochars produced from pyrolysis of hardwood and corn straw in aqueous solution. *Bioresour. Technol.* 102 (19), 8877–8884. doi:10.1016/j.biortech.2011.06.078

Cheng, N., Wang, B., Wu, P., Lee, X., Xing, Y., Chen, M., et al. (2021). Adsorption of emerging contaminants from water and wastewater by modified biochar: A review. *Environ. Pollut.* 273, 116448. doi:10.1016/j.envpol.2021.116448

Chino, M., Moriyama, K., Saito, H., and Morn, T. (1991). The amount of heavy metals derived from domestic sources in Japan. *Water, air, soil Pollut.* 57 (1), 829–837. doi:10.1007/bf00282946

Chun, Y., Sheng, G., Chiou, C. T., and Xing, B. (2004). Compositions and sorptive properties of crop residue-derived chars. *Environ. Sci. Technol.* 38, 4649–4655. doi:10.1021/es035034w

Dalahmeh, S. S., Jönsson, H., Hylander, L. D., Hui, N., Yu, D., and Pell, M. (2014). Dynamics and functions of bacterial communities in bark, charcoal and sand filters treating greywater. *Water Res.* 54, 21–32. doi:10.1016/j.watres.2014.01.019

Dalahmeh, S. S., Lalander, C., Pell, M., Vinnerås, B., and Jönsson, H. (2016). Quality of greywater treated in biochar filter and risk assessment of gastroenteritis due to household exposure during maintenance and irrigation. *J. Appl. Microbiol.* 121 (5), 1427–1443. doi:10.1111/jam.13273

de Letona Sánchez, M. L., Macias-Garcia, A., Díaz-Díez, M. A., Cuerda-Correa, E. M., Ganan-Gomez, J., and Nadal-Gisbert, A. (2006). Preparation of activated carbons previously treated with hydrogen peroxide: Study of their porous texture. *Appl. Surf. Sci.* 252 (17), 5984–5987. doi:10.1016/j.apsusc.2005.11.022

Demiral, H., and Gündüzog, G. (2010). Removal of nitrate from aqueous solutions by activated carbon prepared from sugar beet bagasse. *Bioresour. Technol.* 101, 1675–1680. doi:10.1016/j.biortech.2009.09.087

Demirbaş, A. (2001). Biomass resource facilities and biomass conversion processing for fuels and chemicals. *Energy Convers. Manag.* 42 (11), 1357–1378. doi:10.1016/s0196-8904(00)00137-0

Deng, S., Chen, J., and Chang, J. (2021). Application of biochar as an innovative substrate in constructed wetlands/biofilters for wastewater treatment: Performance and ecological benefits. *J. Clean. Prod.* 293, 126156. doi:10.1016/j.jclepro.2021.126156

Din, A. T. M., Hameed, B. H., and Ahmad, A. L. (2009). Batch adsorption of phenol onto physiochemical-activated coconut shell. *J. Haz* 161, 1522–1529. doi:10.1016/j.jhazmat.2008.05.009

Dowd, S. E., Pillai, S. D., Wang, S., and Corapcioglu, M. Y. (1998). Delineating the specific influence of virus isoelectric point and size on virus adsorption and transport through sandy soils. *Appl. Environ. Microbiol.* 64 (2), 405–410. doi:10.1128/aem.64.2.405-410.1998

El-Khateeb, A. Y., Elsherbiny, E. A., Tadros, L. K., Ali, S. M., and Hamed, H. B. (2013). Phytochemical analysis and antifungal activity of fruit leaves extracts on the mycelial growth of fungal plant pathogens. *J. Plant Pathology Microbiol.* 4 (9), 1–6. doi:10.4172/2157-7471.1000199

El-Shafey, E. I. (2010). Removal of Zn(II) and Hg(II) from aqueous solution on a carbonaceous sorbent chemically prepared from rice husk. *J. Hazard Mater* 175, 319–327. doi:10.1016/j.jhazmat.2009.10.006

Eregno, F. E., and Heistad, A. (2019). On-site treated wastewater disposal systems—the role of stratified filter medias for reducing the risk of pollution. *Environ. Int.* 124, 302–311. doi:10.1016/j.envint.2019.01.008

Esmaeeli, F., Gorbanian, S., and Moazezi, N. (2017). Removal of estradiol valerate and progesterone using powdered and granular activated carbon from aqueous solutions. *Int. J. Environ. Res.* 11, 695–705. doi:10.1007/s41742-017-0060-0

Fakkaew, K., Koottatep, T., and Polprasert, C. (2018). Faecal sludge treatment and utilization by hydrothermal carbonization. *J. Environ. Manag.* 216, 421–426. doi:10.1016/j.jenvman.2017.09.031

Falabi, J. A., Gerba, C. P., and Karpiscak, M. M. (2002). Giardia and Cryptosporidium removal from wastewater by a duckweed (Lemna gibba L.) covered pond. *Lett. Appl. Microbiol.* 34, 384–387. doi:10.1046/j.1472-765x.2002.01104.x

Farkas, K., Walker, D. I., Adriaenssens, E. M., McDonald, J. E., Hillary, L. S., Malham, S. K., et al. (2020). Viral indicators for tracking domestic wastewater contamination in the aquatic environment. *Water Res.* 181, 115926. doi:10.1016/j.watres.2020.115926

Faulwetter, J. L., Gagnon, V., Sundberg, C., Chazarenc, F., Burr, M. D., Brisson, J., et al. (2009). Microbial processes influencing performance of treatment wetlands: A review. *Ecol. Eng.* 35, 987–1004. doi:10.1016/j.ecoleng.2008.12.030

Feng, D., Guo, D., Zhang, Y., Sun, S., Zhao, Y., Shang, Q., et al. (2020). Functionalized construction of biochar with hierarchical pore structures and surface O-/N-containing groups for phenol adsorption. *Chem. Eng. J.* 410, 127707. doi:10.1016/j.cej.2020.127707

Ferreira, L., Rosales, E., Danko, A. S., Sanroman, M. A., and Pazos, M. M. (2016). Bacillus thuringiensis a promising bacterium for degrading emerging pollutants. *Process Saf. Environ. Prot.* 101, 19–26. doi:10.1016/j.psep.2015.05.003

Forbis-Stokes, A. A., Rocha-Melogno, L., and Deshusses, M. A. (2018). Nitrifying trickling filters and denitrifying bioreactors for nitrogen management of high-strength anaerobic digestion effluent. *Chemosphere* 204, 119–129. doi:10.1016/j.chemosphere.2018.03.137

Fu, M., Mo, C., Li, H., Zhang, Y., Huang, W., and Wong, M. H. (2018). Comparison of physicochemical properties of biochars and hydrochars produced from food wastes. *J. Clean. Prod.* 236, 117637. doi:10.1016/j.jclepro.2019.117637

Gañán, J., González, J. F., González-García, C. M., Ramiro, A., Sabio, E., and Román, S. (2006). Carbon dioxide-activated carbons from almond tree pruning: Preparation and characterization. *Appl. Surf. Sci.* 252 (17), 5993–5998. doi:10.1016/j.apsusc.2005.11.025

García, J. A., Paredes, D., and Cubillos, J. A. (2013). Effect of plants and the combination of wetland treatment type systems on pathogen removal in tropical climate conditions. *Ecol. Eng.* 58, 57–62. doi:10.1016/j.ecoleng.2013.06.010

Garcia, M. L., Lapa, K. R., Foresti, E., and Zaiat, M. (2008). Effects of bed materials on the performance of an anaerobic sequencing batch biofilm reactor treating domestic sewage. *J. Environ. Manage.* 88 (4), 1471–1477. doi:10.1016/j.jenvman.2007.07.015

Gill, L. W., O'Luanaigh, N., Johnston, P. M., Misstear, B. D. R., and O'Suilleabhain, C. (2009). Nutrient loading on subsoils from on-site wastewater effluent, comparing septic tank and secondary treatment systems. *Water Res.* 43 (10), 2739–2749. doi:10.1016/j.watres.2009.03.024

Gopinath, A., Divyapriya, G., Srivastava, V., Laiju, A. R., Nidheesh, P. V., and Kumar, M. S. (2021). Conversion of sewage sludge into biochar: A potential resource in water and wastewater treatment. *Environ. Res.* 194, 110656. doi:10.1016/j.envres.2020.110656

Gros, M., Blum, K. M., Jernstedt, H., Renman, G., Rodriguez-Mozaz, S., Haglund, P., et al. (2016). Screening and prioritization of micropollutants in wastewaters from on-site sewage treatment facilities. *J. Hazard. Mater.* 328, 37–45. doi:10.1016/j.jhazmat.2016.12.055

Gul, S., Whalen, J. K., Thomas, B. W., Sachdeva, V., and Deng, H. (2015). Physico-chemical properties and microbial responses in biochar-amended soils: Mechanisms and future directions. *Agric. Ecosyst. Environ.* 206, 46–59. doi:10.1016/j.agee.2015.03.015

Gungor, K., and Unlu, K. (2005). Nitrite and nitrate removal efficiencies of soil aquifer treatment columns. *Turkish J. Eng. Environ. Sci.* 29, 159–170.

Guo, F., Zhang, J., Yang, X., He, Q., Ao, L., and Chen, Y. (2020). Impact of biochar on greenhouse gas emissions from constructed wetlands under various influent chemical oxygen demand to nitrogen ratios. *Bioresour. Technol.* 303, 122908. doi:10.1016/j.biortech.2020.122908

Gupta, P., Tae-woong, A., and Lee, S.-M. (2016). Use of biochar to enhance constructed wetland performance in wastewater reclamation. *Environ. Eng. Res.* 21 (1), 36–44. doi:10.4491/eer.2015.067

Guruge, K. S., Goswami, P., Tanoue, R., Nomiyama, K., Wijesekara, R. G. S., and Dharmaratne, T. S. (2019). First nationwide investigation and environmental risk assessment of 72 pharmaceuticals and personal care products from Sri Lankan surface waterways. *Sci. Total Environ.* 690, 683–695. doi:10.1016/j.scitotenv.2019.07.042

Gwenzi, W., Chaukura, N., Noubactep, C., and Mukome, F. N. D. (2017). Biochar-based water treatment systems as a potential low-cost and sustainable technology for clean water provision. *J. Environ. Manag.* 197, 732–749. doi:10.1016/j.jenvman.2017.03.087

Hao, F., Zhao, X., Ouyang, W., Lin, C., Chen, S., Shan, Y., et al. (2013). Molecular structure of corncob-derived biochars and the mechanism of atrazine sorption. *Agron. J.* 105 (3), 773–782. doi:10.2134/agronj2012.0311

Homagain, K., Shahi, C., Luckai, N., and Sharma, M. (2016). Life cycle cost and economic assessment of biochar-based bioenergy production and biochar land application in Northwestern Ontario, Canada. *For. Ecosyst.* 1, 21–10. doi:10.1186/s40663-016-0081-8

Horn, T. B., Zerwes, F. V., Kist, L. T., and Machado, Ê. L. (2014). Constructed wetland and photocatalytic ozonation for University sewage treatment. *Ecol. Eng.* 63, 134–141. doi:10.1016/j.ecoleng.2013.12.012

Hossain, M. K., Strezov Vladimir, V., Chan, K. Y., Ziolkowski, A., and Nelson, P. F. (2011). Influence of pyrolysis temperature on production and nutrient properties of wastewater sludge biochar. *J. Environ. Manag.* 92, 223–228. doi:10.1016/j.jenvman.2010.09.008

Humphries, B., Weaver, L., Burbery, L., Webber, J., Morgan, L., and Gregor, J. (2020). Microbial pathogen removal from domestic effluent using coral sand in Kiribati. *J. Appl. Microbiol.* 128, 1208–1220. doi:10.1111/jam.14555

Hussain, A., Janson, A., Matar, J. M., and Adham, S. (2021). Membrane distillation: Recent technological developments and advancements in membrane materials. *Emergent Mater.* 5, 347–367. doi:10.1007/s42247-020-00152-8

Intani, K., Latif, S., Cao, Z., and Müller, J. (2018). Characterisation of biochar from maize residues produced in a self-purging pyrolysis reactor. *Bioresour. Technol.* 265, 224–235. doi:10.1016/j.biortech.2018.05.103

Jefferson, B., Burgess, J. E., Pichon, A., Harkness, J., and Judd, S. J. (2001). Nutrient addition to enhance biological treatment of greywater. *Water Res.* 35 (11), 2702–2710. doi:10.1016/S0043-1354(00)00553-4

Ji, B., Chen, J., Mei, J., Chang, J., Li, X., Jia, W., et al. (2020). Roles of biochar media and oxygen supply strategies in treatment performance, greenhouse gas emissions, and bacterial community features of subsurface-flow constructed wetlands. *Bioresour. Technol.* 302, 122890. doi:10.1016/j.biortech.2020.122890

Jia, L., Liu, H., Kong, Q., Li, M., Wu, S., and Wu, H. (2020). Interactions of high-rate nitrate reduction and heavy metal mitigation in iron-carbon-based constructed wetlands for purifying contaminated groundwater. *Water Res.* 169, 115285. doi:10.1016/j.watres.2019.115285

Jiang, N., Shang, R., Heijman, S. G. J., and Rietveld, L. C. (2020). Adsorption of triclosan, trichlorophenol and phenol by high-silica zeolites: Adsorption efficiencies and mechanisms. *Separ. Purif. Technol.* 235, 116152. doi:10.1016/j.seppur.2019.116152

Jin, P., Jin, X., Wang, X., Feng, Y., and C, X. (2013). "Biological activated carbon treatment process for advanced water and wastewater treatment," in *Biomass now: Cultivation and utilization*, 153–192. doi:10.5772/52021

Jung, C., Park, J., Lim, K. H., Park, S., Heo, J., Her, N., et al. (2013). Adsorption of selected endocrine disrupting compounds and pharmaceuticals on activated biochars. *J. Hazard. Mater.* 263, 702–710. doi:10.1016/j.jhazmat.2013.10.033

Kaetzl, K., Lübken, M., Uzun, G., Gehring, T., Nettmann, E., Stenchly, K., et al. (2019). On-farm wastewater treatment using biochar from local agro-residues reduces pathogens from irrigation water for safer food production in developing countries. *Sci. Total Environ.* 682, 601–610. doi:10.1016/j.scitotenv.2019.05.142

Kaliakatsos, A., Kalogerakis, N., Manios, T., and Venieri, D. (2019). Efficiency of two constructed wetland systems for wastewater treatment: Removal of bacterial indicators and enteric viruses. J. Chem. Technol. Biotechnol. 94, 6001–2130. doi:10.1002/jctb.6001

Kambo, H. S., and Dutta, A. (2015). A comparative review of biochar and hydrochar in terms of production, physico-chemical properties and applications. *Renew. Sustain. Energy Rev.* 45, 359–378. doi:10.1016/j.rser.2015.01.050

Karim, M. R., Manshadi, F. D., Karpiscak, M. M., and Gerba, C. P. (2004). The persistence and removal of enteric pathogens in constructed wetlands. *Water Res.* 38, 1831–1837. doi:10.1016/j.watres.2003.12.029

Karunanayake, A. G., Todd, O. A., Crowley, M. L., Ricchetti, L. B., Pittman, C. U., Anderson, R., et al. (2017). Rapid removal of salicylic acid, 4-nitroaniline, benzoic acid and phthalic acid from wastewater using magnetized fast pyrolysis biochar from waste Douglas fir. *Chem. Eng. J.* 319, 75–88. doi:10.1016/j.cej.2017.02.116

Kasozi, G. N., Zimmerman, A. R., Nkedi-Kizza, P., and Gao, B. (2010). Catechol and humic acid sorption onto a range of laboratory-produced black carbons (Biochars). *Environ. Sci. Technol.* 44 (16), 6189–6195. doi:10.1021/es1014423

Kasprzyk-Hordern, B., Dinsdale, R. M., and Guwy, A. J. (2009). The removal of pharmaceuticals, personal care products, endocrine disruptors and illicit drugs during wastewater treatment and its impact on the quality of receiving waters. *Water Res.* 43, 363–380. doi:10.1016/j.watres.2008.10.047

Kauppinen, A., Martikainen, K., Matikka, V., Veijalainen, A. M., Pitkänen, T., Heinonen-Tanski, H., et al. (2014). Sand filters for removal of microbes and nutrients from wastewater during a one-year pilot study in a cold temperate climate. *J. Environ. Manag.* 133, 206–213. doi:10.1016/j.jenvman.2013.12.008

Kholoma, E., Renman, G., and Renman, A. (2016). Phosphorus removal from wastewater by field-scale fortified filter beds during a one-year study. *Environ. Technol.* 37 (23), 2953–2963. doi:10.1080/09593330.2016.1170888

Kizito, S., Luo, H., Lu, J., Bah, H., Dong, R., and Wu, S. (2019). Role of nutrient-enriched biochar as a soil amendment during maize growth: Exploring practical alternatives to recycle agricultural residuals and to reduce chemical fertilizer demand. *Sustainability* 11 (11), 3211. doi:10.3390/su11113211

Kizito, S., Wu, S., Kirui, W. K., Lei, M., Lu, Q., Bah, H., et al. (2015). Evaluation of slow pyrolyzed wood and rice husks biochar for adsorption of ammonium nitrogen from piggery manure anaerobic digestate slurry. *Sci. Total Environ.* 505, 102–112. doi:10.1016/j.scitotenv.2014.09.096

Kołodyńska, D., Wnętrzak, R., Leahy, J. J., Hayes, M. H. B., Kwapiński, W., and Hubicki, Z. (2012). Kinetic and adsorptive characterization of biochar in metal ions removal. *Chem. Eng. J.* 197, 295–305. doi:10.1016/j.cej.2012.05.025

Kołtowski, M., Hilber, I., Bucheli, T. D., Charmas, B., Skubiszewska-Zięba, J., and Oleszczuk, P. (2017). Activated biochars reduce the exposure of polycyclic aromatic hydrocarbons in industrially contaminated soils. *Chem. Eng. J.* 310, 33–40. doi:10.1016/j.cej.2016.10.065

Konczak, M., Oleszczuk, P., and Rozyło, K. (2019). Application of different carrying gases and ratio between sewage sludge and willow for engineered (smart) biochar production. J. CO_2 Util. 29, 20–28. doi:10.1016/j.jcou.2018.10.019

Krueger, B. C., Fowler, G. D., Templeton, M. R., and Moya, B. (2020). Resource recovery and biochar characteristics from full-scale faecal sludge treatment and co-treatment with agricultural waste. *Water Res.* 169, 115253. doi:10.1016/j.watres.2019.115253

Lalander, C., Dalahmeh, S., Jönsson, H., and Vinnerås, B. (2013). Hygienic quality of artificial greywater subjected to aerobic treatment: A comparison of three filter media at increasing organic loading rates. *Environ. Technol.* 34 (18), 2657–2662. doi:10.1080/09593330.2013.783603

Lalhruaitluanga, H., Jayaram, K., Prasad, M. N. V., and Kumar, K. K. (2010). Lead (II) adsorption from aqueous solutions by raw and activated charcoals of melocanna baccifera roxburgh (bamboo)—A comparative study. *J. Hazard. Mater.* 175 (1-3), 311–318. doi:10.1016/j.jhazmat.2009.10.005

Lamichhane, K. M. (2007). On-site sanitation: A viable alternative to modern wastewater treatment plants. *Water Sci. Technol.* 55 (1–2), 433–440. doi:10.2166/wst.2007.044

Lau, A. Y., Tsang, D. C., Graham, N. J., Ok, Y. S., Yang, X., and Li, X. D. (2017). Surface-modified biochar in a bioretention system for *Escherichia coli* removal from stormwater. *Chemosphere* 169, 89–98. doi:10.1016/j.chemosphere.2016.11.048

Li, F., Cao, X., Zhao, L., Wang, J., and Ding, Z. (2014). Effects of mineral additives on biochar formation: carbon retention, stability, and properties. *Environ. Sci. Tech.* 48 (19), 11211–11217.

Li, F., Shen, K., Long, X., Wen, J., Xie, X., Zeng, X., et al. (2016). Preparation and characterization of biochars from eichornia crassipes for cadmium removal in aqueous solutions. *PLoS ONE* 11 (2), e0148132–e0148139. doi:10.1371/journal.pone.0148132

Li, H., Dong, X., da Silva, E. B., de Oliveira, L. M., Chen, Y., and Ma, L. Q. (2017). Mechanisms of metal sorption by biochars: Biochar characteristics and modifications. *Chemosphere* 178, 466–478. doi:10.1016/j.chemosphere.2017.03.072

Li, W., Yang, K., Peng, J., Zhang, L., Guo, S., and Xia, H. (2008). Effects of carbonization temperatures on characteristics of porosity in coconut shell chars and activated carbons derived from carbonized coconut shell chars. *Industrial Crops Prod.* 8, 190–198. doi:10.1016/j.indcrop.2008.02.012

Li, Y., Xu, D., Guan, Y., Yu, K., and Wang, W. (2019). Phosphorus sorption capacity of biochars from different waste woods and bamboo. *Int. J. Phytoremediation* 21 (2), 145–151. doi:10.1080/15226514.2018.1488806

Liang, Y., Wang, Q., Huang, L., Liu, M., Wang, N., and Chen, Y. (2020). Insight into the mechanisms of biochar addition on pollutant removal enhancement and nitrous oxide emission reduction in subsurface flow constructed wetlands: Microbial community structure, functional genes and enzyme activity. *Bioresour. Technol.* 307, 123249. doi:10.1016/j.biortech.2020.123249

Liu, W., Jiang, H., and Yu, H. (2015). Development of biochar-based functional materials: Toward a sustainable platform carbon material. *Chem. Rev.* 115, 12251–12285. doi:10.1021/acs.chemrev.5b00195

Liu, Y., Blowes, D. W., Ptacek, C. J., and Groza, L. G. (2019). Removal of pharmaceutical compounds, artificial sweeteners, and perfluoroalkyl substances from water using a passive treatment system containing zero-valent iron and biochar. *Sci. Total Environ.* 691, 165–177. doi:10.1016/j.scitotenv.2019.06.450

Liu, P., Liu, W., Jiang, H., Chen, J., Li, W., and Yu, H. (2012). Modification of bio-char derived from fast pyrolysis of biomass and its application in removal of tetracycline from aqueous solution. *Bioresour. Technol.* 121, 235–240. doi:10.1016/j.biortech.2012.06.085

Liyanage, A. S., Canaday, S., Pittman, C. U., Jr., and Mlsna, T. (2020). Rapid remediation of pharmaceuticals from wastewater using magnetic Fe3O4/Douglas fir biochar adsorbents. *Chemosphere* 258, 127336. doi:10.1016/j.chemosphere.2020.127336

Lowe, K. S., Tucholke, M. B., Tomaras, J. M. B., Conn, K., Hoppe, C., Drewes, J. E., et al. (2009). *Influent constituent characteristics of the modern waste stream from single source*. Alexandria, VA, United States: WERF and IWA publishers. doi:10.2166/9781780403519

Lu, K., Yang, X., Gielen, G., Bolan, N., Ok, Y. S., Niazi, N. K., et al. (2017). Effect of bamboo and rice straw biochars on the mobility and redistribution of heavy metals (Cd, Cu, Pb and Zn) in contaminated soil. *J. Environ. Manag.* 186, 285–292. doi:10.1016/j.jenvman.2016.05.068

Lu, H., Zhang, W., Yang, Y., Huang, X., Wang, S., Qiu, R., et al. (2012). Relative distribution of Pb2+ sorption mechanisms by sludge-derived biochar. *Water Res.* 46, 854–862.

Lusk, M. G., Toor, G. S., Yang, Y. Y., Mechtensimer, S., De, M., and Obreza, T. A. (2017). A review of the fate and transport of nitrogen, phosphorus, pathogens, and trace organic chemicals in septic systems. *Crit. Rev. Environ. Sci. Technol.* 47 (7), 455–541. doi:10.1080/10643389.2017.1327787

Manga, M., Bartram, J., and Evans, B. E. (2020). Economic cost analysis of low-cost sanitation technology options in informal settlement areas (case study: Soweto, Johannesburg). *Int. J. Hyg. Environ. Health* 223, 289–298. doi:10.1016/j.ijheh.2019.06.012

Manga, M., Camargo-Valero, M. A., and Evans, B. E. (2019). Inactivation of viable Ascaris eggs during faecal sludge co-composting with chicken feathers and market waste. *Desalination Water Treat.* 163, 347–357. doi:10.5004/dwt.2019.24494

Manga, M., Evans, B. E., Camargo-Valero, M. A., and Horan, N. J. (2016). Effect of filter media thickness on the performance of sand drying beds used for faecal sludge management. *Water Sci. Technol.* 74, 2795–2806. doi:10.2166/wst.2016.451

Manga, M., Evans, B. E., Ngasala, T. M., and Camargo-Valero, M. A. (2022b). Recycling of faecal sludge: Nitrogen, carbon and organic matter transformation during Co-composting of faecal sludge with different bulking agents. *Int. J. Environ. Res. Public Health* 19 (17), 10592. doi:10.3390/ijerph191710592

Manga, M., Kolsky, P., Rosenboom, J. W., Ramalingam, S., Sriramajayam, L., Bartram, J., et al. (2022a). Public health performance of sanitation technologies in Tamil Nadu, India: Initial perspectives based on *E. coli* release. *Int. J. Hyg. Environ. Health* 243, 113987. doi:10.1016/j.ijheh.2022.113987

Manga, M., Muoghalu, C., Camargo-Valero, M. A., and Evans, B. E. (2023). Effect of turning frequency on the survival of fecal indicator microorganisms during aerobic composting of fecal sludge with sawdust. Int. J. Environ. Res. Public *Health* 20 (3), 2668. doi:10.3390/ijerph20032668

Manga, M. (2017). *The feasibility of Co-composting as an upscale treatment method for faecal sludge in urban Africa.* Leeds, UK: School of Civil Engineering, University of Leeds. Available online: https://etheses.whiterose.ac.uk/16997 (accessed on June 3, 2022).

Martikainen, K., Veijalainen, A.-M., Torvinen, E., Heinonen-Tanski, H., Kauppinen, A., Pitkänen, T., et al. (2018). Efficiency of private household sand filters in removing nutrients and microbes from wastewater in Finland. *Water* 10 (8), 1000. doi:10.3390/w10081000

Mburu, N., Tebitendwa, S. M., van Bruggen, J. J. A., Rousseau, D. P. L., and Lens, P. N. L. (2013). Performance comparison and economics analysis of waste stabilization ponds and horizontal subsurface flow constructed wetlands treating domestic wastewater: A case study of the juja sewage treatment works. *J. Environ. Manag.* 128, 220–225. doi:10.1016/j.jenvman.2013.05.031

Merrikhpour, H., and Jalali, M. (2012). Waste calcite sludge as an adsorbent for the removal of cadmium, copper, lead, and zinc from aqueous solutions. *Clean Technol. Environ. Policy* 14 (5), 845–855. doi:10.1007/s10098-012-0450-0

Miège, C., Choubert, J. M., Ribeiro, L., Eusèbe, M., and Coquetry, M. (2009). Fate of pharmaceuticals and personal care products in wastewater treatment plants–conception of a database and first results. *Environ. Pollut.* 157, 1721–1726. doi:10.1016/j.envpol.2008.11.045

Moges, M. E., Eregno, F. E., and Heistad, A. (2015). Performance of biochar and filtralite as polishing step for on-site greywater treatment plant. *Manag. Environ. Qual. Int. J.* 26 (4), 607–625. doi:10.1108/meq-07-2014-0101

Mohan, D., Rajput, S., Singh, V. K., Steele, P. H., and Pittman, C. U. (2011). Modeling and evaluation of chromium remediation from water using low cost bio-char, a green adsorbent. *J. Hazard. Mater.* 188 (1–3), 319–333. doi:10.1016/j.jhazmat.2011.01.127

Morató, J., Codony, F., Sánchez, O., Pérez, L. M., García, J., and Mas, J. (2014). Key design factors affecting microbial community composition and pathogenic organism removal in horizontal subsurface flow constructed wetlands. *Sci. Total Environ.* 481, 81–89. doi:10.1016/j.scitotenv.2014.01.068

Mwenge, P., and Seodigeng, T. (2019). Greywater treatment using activated biochar produced from agricultural waste. *Int. J. Chem. Mol. Eng.* 13 (3), 140–145.

Ndung'u, P. W. (2020). *Adsorptive ability of banana stalks biochar in greywater remediation for reuse: A case of university of embu.* Kenya: University of Embu.

Nguyen, T. H., Cho, H. H., Poster, D. L., and Ball, W. P. (2007). Evidence for a pore-filling mechanism in the adsorption of aromatic hydrocarbons to a natural wood char. *Environ. Sci. Technol.* 41 (4), 1212–1217. doi:10.1021/es0617845

Nicholas, H. L., Mabbett, I., Apsey, H., and Robertson, I. (2022). Physico-chemical properties of waste derived biochar from community scale faecal sludge treatment plants. *Gates Open Res.* 6 (96), 96. doi:10.12688/gatesopenres.13727.1

Niwagaba, C. B ., Dinno, P., Wamala, I., Dalahmeh, S. . S., Lalander, C., and Jonsson, H. (2014). Experiences on the implementation of a pilot grey water treatment and reuse based system at a household in the slum of Kyebando-Kisalosalo, Kampala. *J. Water Reuse Desalination* 4, 294–307. doi:10.2166/wrd.2014.016

Oh, T. K., Choi, B., Shinogi, Y., and Chikushi, J. (2012). Effect of pH conditions on actual and apparent fluoride adsorption by biochar in aqueous phase. *Water, Air, Soil Pollut.* 223, 3729–3738. doi:10.1007/s11270-012-1144-2

Oladoja, N. A., and Ademoroti, C. M. A. (2006). The use of fortified soil-clay as on-site system for domestic wastewater purification. *Water Res.* 40 (3), 613–620. doi:10.1016/j.watres.2005.11.031

Oteng-Peprah, M., Acheampong, M. A., and DeVries, N. K. (2018). Greywater characteristics, treatment systems, reuse strategies and user perception—A review. *Water, Air, & Soil Pollut.* 229 (256), 1–6. doi:10.1007/s11270-018-3909-8

Parr, S. W., Hopkins, H. C., and Mitchell, D. R. (1931). Fusain. *Ind. Eng. Chem., Anal. Ed.* 3 (1), 64–65.

Pan, X., Gu, Z., Chen, W., and Li, Q. (2021). Preparation of biochar and biochar composites and their application in a fenton-like process for wastewater decontamination: A review. *Sci. Total Environ.* 754, 142104. doi:10.1016/j.scitotenv.2020.142104

Parshetti, G. K., Chowdhury, S., and Balasubramanian, R. (2014). Hydrothermal conversion of urban food waste to chars for removal of textile dyes from contaminated waters. *Bioresour. Technol.* 161, 310–319. doi:10.1016/j.biortech.2014.03.087

Patnukao, P., and Pavasant, P. (2008). Activated carbon from *Eucalyptus camaldulensis* Dehn bark using phosphoric acid activation. *Bioresour. Technol.* 99 (17), 8540–8543. doi:10.1016/j.biortech.2006.10.049

Peng, P., Lang, Y., and Wang, X. (2016). Adsorption behavior and mechanism of pentachlorophenol on reed biochars: pH effect pyrolysis temperature, hydrochloric acid treatment and isotherms. *Ecol. Eng.* 90, 225–233. doi:10.1016/j.ecoleng.2016.01.039

Peng, S. S., Zhang, D. Q., Huang, H. H., Jin, Z. J., and Peng, X. H. (2019). Ionic polyacrylamide hydrogel improved by graphene oxide for efficient adsorption of methylene blue. *Res. Chem. Intermed.* 45, 1545–1563. doi:10.1007/s11164-018-3689-1

Perez-Mercado, L. F., Lalander, C., Berger, C., and Dalahmeh, S. S. (2018). Potential of biochar filters for onsite wastewater treatment: Effects of biochar type, physical properties and operating conditions. *Water* 10 (12), 1835. doi:10.3390/w10121835

Perez-Mercado, L. F., Lalander, C., Joel, A., Ottoson, J., Dalahmeh, S., and Vinnerås, B. (2019). Biochar filters as an on-farm treatment to reduce pathogens when irrigating with wastewater-polluted sources. *J. Environ. Manage.* 248, 1–10.

Petrov, N., Budinova, T., Razvigorova, M., Parra, J., and Galiatsatou, P. (2008). Conversion of olive wastes to volatiles and carbon adsorbents. *Biomass Bioenergy* 32 (12), 1303–1310. doi:10.1016/j.biombioe.2008.03.009

Pignatello, J., Kwon, S., and Lu, Y. (2006). Effect of natural organic substances on the surface and adsorptive properties of environmental black carbon (char): Attenuation of surface activity by humic and fulvic acids. *Environ. Sci. Technol.* 40 (24), 7757–7763. doi:10.1021/es061307m

Pipíška, M., Krajčíková, E. K., Hvostik, M. V., Ďuriška, L., Černičková, I., Kaňuchová, M., et al. (2022). Biochar from wood chips and corn cobs for adsorption of thioflavin T and erythrosine B. *Materials* 15 (4), 1492. doi:10.3390/ma15041492

Pishgar, R., Morin, D., Young, S. J., Schwartz, J., and Chu, A. (2021). Characterization of domestic wastewater released from 'green' households and field study of the performance of onsite septic tanks retrofitted into aerobic bioreactors in cold climate. *Sci. Total Environ.* 755, 142446. doi:10.1016/j.scitotenv.2020.142446

Qian, L., and Chen, B. (2013). Dual role of biochars as adsorbents for aluminum: The effects of oxygen-containing organic components and the scattering of silicate particles. *Environ. Sci. Technol.* 47, 8759–8768. doi:10.1021/es401756h

Qu, R. J., Li, C. G., Liu, J. Q., Xiao, R. Y., Pan, X. X., Zeng, X. L., et al. (2018). Hydroxyl radical based photocatalytic degradation of halogenated organic contaminants and paraffin on silica gel. *Environ. Sci. Technol.* 52, 7220–7229. doi:10.1021/acs.est.8b00499

Quiñónez-Díaz, M. D. J., Karpiscak, M. M., Ellman, E. D., and Gerba, C. P. (2001). Removal of pathogenic and indicator microorganisms by a constructed wetland receiving untreated domestic wastewater. *J. Environ. Sci.* 36, 1311–1320. doi:10.1081/ese-100104880

Quispe, J. B., Campos, L. C., Mašek, O., and Bogush, A. (2022). Use of biochar-based column filtration systems for greywater treatment: A systematic literature review. *J. Water Process Eng.* 48, 102908. doi:10.1016/j.jwpe.2022.102908

Qurat-ul-Ain, Q., Shehzad, R. A., Yaqoob, U., Sharif, A., Sajid, Z., Rafiq, S., et al. (2021). Designing of benzodithiophene acridine based Donor materials with favorable photovoltaic parameters for efficient organic solar cell. *Comput. Theor. Chem.* 1200, 113238. doi:10.1016/j.comptc.2021.113238

Rahman, S., Navarathna, C. M., Krishna, N., Alchouron, J., Reneau, P., Stokes, S., et al. (2021). High capacity aqueous phosphate reclamation using Fe/Mg-layered double hydroxide (LDH) dispersed on biochar. *J. Colloid Interface Sci.* 597, 182–195. doi:10.1016/j.jcis.2021.03.114

Regmi, P., Moscoso, J. L. G., Kumar, S., Cao, X., Mao, J., and Schafran, G. (2012). Removal of copper and cadmium from aqueous solution using switchgrass biochar produced via hydrothermal carbonization process. *J. Environ. Manag.* 109, 61–69. doi:10.1016/j.jenvman.2012.04.047

Reinoso, R., Torres, L. A., and Bécares, E. (2008). Efficiency of natural systems for removal of bacteria and pathogenic parasites from wastewater. *Sci. Total Environ.* 395, 80–86. doi:10.1016/j.scitotenv.2008.02.039

Román, S., González, J. F., González-García, C. M., and Zamora, F. (2008). Control of pore development during CO_2 and steam activation of olive stones. *Fuel Process. Technol.* 89 (8), 715–720. doi:10.1016/j.fuproc.2007.12.015

Sajjadi, B., Chen, W. Y., and Egiebor, N. O. (2019). A comprehensive review on physical activation of biochar for energy and environmental applications. *Rev. Chem. Eng.* 35 (6), 735–776.

Saltalı, K., Sarı, A., and Aydın, M. (2007). Removal of ammonium ion from aqueous solution by natural Turkish (Yıldızeli) zeolite for environmental quality. *J. Hazard. Mater.* 141, 258–263. doi:10.1016/j.jhazmat.2006.06.124

Santos, J. L., Aparicio, I., Callejon, M., and Alonso, E. (2009). Occurrence of pharmaceutically active compounds during 1-year period in wastewaters from four wastewater treatment plants in Seville (Spain). *J. Hazard. Mater* 164, 1509–1516. doi:10.1016/j.jhazmat.2008.09.073

Schaider, L. A., Balan, S. A., Blum, A., Andrews, D. Q., Strynar, M. J., Dickinson, M. E., et al. (2017). Fluorinated compounds in US fast food packaging. *Environ. Sci. Technol. Lett.* 4 (3), 105–111. doi:10.1021/acs.estlett.6b00435

Semiyaga, S., Nakagiri, A., Niwagaba, C. B., and Manga, M. (2022). "Application of anaerobic digestion in decentralized faecal sludge treatment plants," in *Anaerobic biodigesters for human waste treatment* (Singapore: Springer), 263–281. doi:10.1007/978-981-19-4921-0_14

Shen, Y., and Zhang, N. (2019). Facile synthesis of porous carbons from silica-rich rice husk char for volatile organic compounds (VOCs) sorption. *Bioresour. Technol.* 282, 294–300. doi:10.1016/j.biortech.2019.03.025

Sidibe, M. (2014). *Comparative study of bark, bio-char, activated charcoal filters for upgrading greywater from a hygiene aspect*. Uppsala, Sweden: Swedish University of Agricultural Sciences.

Sim, W. J., Lee, J. W., Lee, E. S., Shin, S. K., Hwang, S. R., and Oh, J. E. (2011). Occurrence and distribution of pharmaceuticals in wastewater from households, livestock farms, hospitals and pharmaceutical manufactures. *Chemosphere* 82, 179–186. doi:10.1016/j.chemosphere.2010.10.026

Simpson, D. R. (2008). Biofilm processes in biologically active carbon water purification. *Water Res.* 42, 2839–2848. doi:10.1016/j.watres.2008.02.025

Singh, K. P., Malik, A., Sinha, S., and Ojha, P. (2008). Liquid-phase adsorption of phenols using activated carbons derived from agricultural waste material. *J. Hazard. Mater.* 150, 626–641. doi:10.1016/j.jhazmat.2007.05.017

Spokas, K. A., Novak, J. M., Masiello, C. A., Johnson, M. G., Colosky, E. C., Ippolito, J. A., et al. (2014). Physical disintegration of biochar: An overlooked process. *Environ. Sci. Technol. Lett.* 1 (8), 326–332. doi:10.1021/ez500199t

Stott, R., May, E., and Mara, D. D. (2003). Parasite removal by natural wastewater treatment systems: Performance of waste stabilisation ponds and constructed wetlands. *Water Sci. Technol.* 48, 97–104. doi:10.2166/wst.2003.0095

Strande, L., Ronteltap, M., and Brdjanovic, D. (2014). *Faecal sludge management: Systems approach for implementation and operation*. London: IWA Publishing.

Stylianou, M., Christou, A., Dalias, P., Polycarpou, P., Michael, C., Agapiou, A., et al. (2020). Physicochemical and structural characterization of biochar derived from the pyrolysis of biosolids, cattle manure and spent coffee grounds. *J. Energy Inst.* 93 (5), 2063–2073. doi:10.1016/j.joei.2020.05.002

Tait, D. R., Shepherd, B. O., Befus, K. M., and Erler, D. V. (2015). Nutrient and greenhouse gas dynamics through a range of wastewaterloaded carbonate sand treatments. *Ecol. Eng.* 82, 126–137. doi:10.1016/j.ecoleng.2015.04.082

Tan, X., Liu, Y., Zeng, G., Wang, X., Hu, X., Gu, Y., et al. (2015). Application of biochar for the removal of pollutants from aqueous solutions. *Chemosphere* 125, 70–85. doi:10.1016/j.chemosphere.2014.12.058

Terzić, S., Senta, I., Ahel, M., Gros, M., Petrović, M., Barcelo, D., et al. (2008). Occurrence and fate of emerging wastewater contaminants in Western Balkan Region. *Sci. Total Environ.* 399, 66–77. doi:10.1016/j.scitotenv.2008.03.003

Théry-parisot, I., Chabal, L., and Chrzavzez, J. (2010). Anthracology and taphonomy, from wood gathering to charcoal analysis. A review of the taphonomic processes modifying charcoal assemblages, in archaeological contexts. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 291 (1–2), 142–153. doi:10.1016/j.palaeo.2009.09.016

Tokwaro, R., Semiyaga, S., Niwagaba, C. B., Nakagiri, A., Sempewo, J. I., Moughalu, C. C., et al. (2023). Application of black soldier fly larvae in decentralized treatment of faecal sludge from pit latrines in informal settlements in Kampala City. *Front. Environ. Sci.* 11, 138. doi:10.3389/fenvs.2023.1118635

Tomczyk, A., Sokołowska, Z., and Boguta, P. (2020). Biochar physicochemical properties: Pyrolysis temperature and feedstock kind effects. *Rev. Environ. Sci. Biotechnol.* 19 (1), 191–215. doi:10.1007/s11157-020-09523-3

Tong, X. J., Li, J. Y., Yuan, J. H., and Xu, R. K. (2011). Adsorption of Cu (II) by biochars generated from three crop straws. *Chem. Eng. J.* 172, 828–834. doi:10.1016/j.cej.2011.06.069

Torrens, A., Molle, P., Boutin, C., and Salgot, M. (2009). Removal of bacterial and viral indicator in vertical flow constructed wetlands and intermittent sand filters. *Desalination* 246, 169–178. doi:10.1016/j.desal.2008.03.050

Trakal, L., Veselská, V., Šafařík, I., Vítková, M., Číhalová, S., and Komárek, M. (2016). Lead and cadmium sorption mechanisms on magnetically modified biochars. *Biores Technol.* 203, 318–324. doi:10.1016/j.biortech.2015.12.056

Tsai, W. T., and Chen, H. R. (2013). Adsorption kinetics of herbicide paraquat in aqueous solution onto a low-cost adsorbent, swine-manure derived biochar. *Int. J. Environ. Sci. Technol.* 10 (6), 1349–1356. doi:10.1007/s13762-012-0174-z

Van Houdt, R., and Michiels, C. W. (2010). Biofilm formation and the food industry, a focus on the bacterial outer surface. *J. Appl. Microbiol.* 109 (4), 1117–1131. doi:10.1111/j.1365-2672.2010.04756.x

Vithanage, M., Rajapaksha, A. U., Zhang, M., Thiele-Bruhn, S., Lee, S. S., and Ok, Y. S. (2015). Acid-activated biochar increased sulfamethazine retention in soils. *Environ. Sci. Pollut. Res.* 22, 2175–2186. doi:10.1007/s11356-014-3434-2

Wang, H., Xu, J., and Sheng, L. (2020). Preparation of straw biochar and application of constructed wetland in China: A review. *J. Clean. Prod.* 273, 123131–131. doi:10.1016/j.jclepro.2020.123131

Wang, H., Gao, B., Wang, S., Fang, J., Xue, Y., and Yang, K. (2015). Removal of Pb (II), Cu (II), and Cd (II) from aqueous solutions by biochar derived from KMnO 4 treated hickory wood. *Bioresour. Technol.* 197, 356–362. doi:10.1016/j.biortech.2015.08.132

Wang, P., Liu, X., Wu, X., Xu, J., Dong, F., and Zheng, Y. (2018). Evaluation of biochars in reducing the bioavailability of flubendiamide in water/sediment using passive sampling with polyoxymethylene. *J. Hazard Mater* 344, 1000–1006. doi:10.1016/j.jhazmat.2017.12.003

Wang, Z., Dong, J., Liu, L., Zhu, G., and Liu, C. (2013). Study of oyster shell as a potential substrate for constructed wetlands. *Water Sci. Technol.* 67 (10), 2265–2272. doi:10.2166/wst.2013.105

Wang, Z., Tian, Q., Guo, J., Wu, R., Zhu, H., and Zhang, H. (2021). Co-pyrolysis of sewage sludge/cotton stalks with K_2CO_3 for biochar production: Improved biochar porosity and reduced heavy metal leaching. *Waste Manag.* 135, 199–207. doi:10.1016/j.wasman.2021.08.042

Weber, K., and Quicker, P. (2018). Properties of biochar. *Fuel* 217, 240–261. doi:10.1016/j.fuel.2017.12.054

Wei, S. U., Ya-ping, Z., Liu-fang, W. E. I., Yan, S. U. N., and Li, Z. (2007). Effect of microstructure and surface modification on the hydrogen adsorption capacity of active carbons. *New Carbon Mater.* 22 (2), 2323–2325. doi:10.1016/j.carbon.2007.06.038

Werner, S., Katzl, K., Wichern, M., Buerkert, A., Steiner, C., and Marschner, B. (2018). Agronomic benefits of biochar as a soil amendment after its use as wastewater filtration medium. *Environ. Pollut.* 233, 561–568. doi:10.1016/j.envpol.2017.10.048

WHOUNICEF (2021). *Progress on household drinking water, sanitation and hygiene 2000-2020: Five years into the SDGs*. Geneva, Switzerland: World Health Organization (WHO) and United Nations Children's Fund (UNICEF).

Williams, M., Martin, S., and Kookana, R. S. (2015). Sorption and plant uptake of pharmaceuticals from an artificially contaminated soil amended with biochars. *Plant Soil* 395 (1-2), 75–86. doi:10.1007/s11104-015-2421-9

Winward, G. P., Avery, L. M., Frazer-Williams, R., Pidou, M., Jeffrey, P., Stephenson, T., et al. (2008). A study of the microbial quality of grey water and an evaluation of treatment technologies for reuse. *Ecol. Eng.* 32, 187–197. doi:10.1016/j.ecoleng.2007.11.001

Xiang, W., Zhang, X., Chen, J., Zou, W., He, F., Hu, X., et al. (2020). Biochar technology in wastewater treatment: A critical review. *Chemosphere* 252, 126539. doi:10.1016/j.chemosphere.2020.126539

Xue, Y., Gao, B., Yao, Y., Inyang, M., Zhang, M., Zimmerman, A. R., et al. (2012). Hydrogen peroxide modification enhances the ability of biochar (hydrochar) produced from hydrothermal carbonization of peanut hull to remove aqueous heavy metals: Batch and column tests. *Chem. Eng. J.* 200, 673–680. doi:10.1016/j.cej.2012.06.116

Yaman, S. (2004). Pyrolysis of biomass to produce fuels and chemical feedstocks. *Energy Convers. Manag.* 45, 651–671. doi:10.1016/s0196-8904(03)00177-8

Yang, K., Peng, J., Srinivasakannan, C., Zhang, L., Xia, H., and Duan, X. (2010). Preparation of high surface area activated carbon from coconut shells using microwave heating. *Bioresour. Technol.* 101 (15), 6163–6169. doi:10.1016/j.biortech.2010.03.001

Yang, X., Flowers, R. C., Weinberg, H. S., and Singer, P. C. (2011). Occurrence and removal of pharmaceuticals and personal care products (PPCPs) in an advanced wastewater reclamation plant. *Water Res.* 45, 5218–5228. doi:10.1016/j.watres.2011.07.026

Yao, Y., Gao, B., Inyang, M., Zimmerman, A. R., Cao, X., Pullammanappallil, P., et al. (2011). Removal of phosphate from aqueous solution by biochar derived from anaerobically digested sugar beet tailings. *J. Hazard. Mater.* 190, 501–507. doi:10.1016/j.jhazmat.2011.03.083

Yin, I. X., Zhang, J., Zhao, I. S., Mei, M. L., Li, Q., and Chu, C. H. (2020). <p>The antibacterial mechanism of silver nanoparticles and its application in dentistry</p>. *Int. J. Nanomedicine* 15, 2555–2562. doi:10.2147/IJN.S246764

Yuan, Y., Yang, B., Wang, H., Lai, X., Li, F., Salam, M. M. A., et al. (2020). The simultaneous antibiotics and nitrogen removal in vertical flow constructed wetlands:

Effects of substrates and responses of microbial functions. *Bioresour. Technol.* 310, 123419. doi:10.1016/j.biortech.2020.123419

Zhang, M., Muhammad, R., Zhang, L., Xia, H., Cong, M., and Jiang, C. (2019). Investigating the effect of biochar and fertilizer on the composition and function of bacteria in red soil. *Appl. Soil Ecol.* 139, 107–116. doi:10.1016/j.apsoil.2019.03.021

Zhang, Y., Cheng, Y., Yang, C., Luo, W., Zeng, G., and Lu, L. (2015). Performance of system consisting of vertical flow trickling filter and horizontal flow multi-soil-layering reactor for treatment of rural wastewater. *Bioresour. Technol.* 193, 424–432. doi:10.1016/j.biortech.2015.06.140

Zhang, Z. B., Cao, X. H., Liang, P., and Liu, Y. H. (2013). Adsorption of uranium from aqueous solution using biochar produced by hydrothermal carbonization. *J. Radioanalytical Nucl. Chem.* 295 (2), 1201–1208. doi:10.1007/s10967-012-2017-2

Zhang, C. M., Xu, L. M., Xu, P. C., and Wang, X. C. (2016). Elimination of viruses from domestic wastewater: Requirements and technologies. *World J. Microbiol. Biotechnol.* 32, 1–9.

Zhao, M., Dai, Y., Zhang, M., Feng, C., Qin, B., Zhang, W., et al. (2020). Mechanisms of Pb and/or Zn adsorption by different biochars: Biochar characteristics, stability, and binding energies. *Sci. Total Environ.* 717, 136894. doi:10.1016/j.scitotenv.2020.136894

Zheng, Y., Wang, B., Wester, A. E., Chen, J., He, F., Chen, H., et al. (2019). Reclaiming phosphorus from secondary treated municipal wastewater with engineered biochar. *Chem. Eng. J.* 362, 460–468. doi:10.1016/j.cej.2019.01.036

Zhou, J., Wang, X. C., Ji, Z., Xu, L., and Yu, Z. (2015). Source identification of bacterial and viral pathogens and their survival/fading in the process of wastewater treatment, reclamation, and environmental reuse. *World J. Microbiol. Biotechnol.* 31, 109–120. doi:10.1007/s11274-014-1770-5

Zhou, X., Wu, S., Wang, R., and Wu, H. (2019). Nitrogen removal in response to the varying C/N ratios in subsurface flow constructed wetland microcosms with biochar addition. *Environ. Sci. Pollut. Res. Int.* 26 (4), 3382–3391. doi:10.1007/s11356-018-3871-4

Zhou, Y., Gao, B., Zimmerman, A. R., and Cao, X. (2014). Biochar-supported zerovalent iron reclaims silver from aqueous solution to form antimicrobial nanocomposite. *Chemosphere* 117 (1), 801–805. doi:10.1016/j.chemosphere.2014.10.057

Zielinska, A., Oleszczuk, P., Charmas, B., Skubiszewska-Zięba, J., and Pasieczna-Patkowska, S. (2015). Effect of sewage sludge properties on the biochar characteristic. *J. Anal. Appl. Pyrolysis* 112, 201–213. doi:10.1016/j.jaap.2015.01.025

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Effectiveness of the Swachh Bharat Mission and barriers to ending open defecation in India: a systematic review

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In 2016, nearly 60% of the population of India practiced open defecation (OD), which was 4 times the global rate, and reducing OD in India will be essential in meeting Sustainable Development Goal (SDG) 6.2 and improving global public health. The government of India launched the Swachh Bharat Mission (SBM) in 2014 with one key goal for all Indian states to achieve OD-free (ODF) status by 2019. Despite reports from the Government of India on the success of SBM, the true ODF status of Indian states is still unknown. A systematic review of peer-reviewed literature was conducted to assess the impact of SBM on OD in India, evaluate the barriers to reducing OD, and provide recommendations for future interventions to reduce or eliminate OD in India. A total of 237 publications were screened, and 22 were selected for inclusion. While the Prime Minister declared India ODF in 2019, studies suggest that the government monitoring system overestimates numbers of ODF villages and toilet coverage. Reasons for households' continued OD practice include financial constraints, lack of water supply, governmental mistrust, cultural beliefs, and personal preference. Community incentives and penalties have been used to encourage proper sanitation practices with varying success. Overarching strategies and approaches that have worked well across study districts to reduce OD include high involvement of district leadership and innovative behavior-change and local community mobilization campaigns.

KEYWORDS

open defecation, Swachh Bharat Mission, water, sanitation, and hygiene (WASH), India, sanitation interventions, open defecation-free

1 Introduction

Open defecation (OD) refers to the practice of defecating or disposing of human feces in fields, forests, bushes, bodies of water, or other open spaces (WHO and UNICEF, 2021). Given its linkages to human health, dignity, and gender equity, eliminating OD has remained a global goal and water, sanitation, and hygiene (WASH) sector priority (Beardsley et al., 2021; Sprouse et al., 2022) manifesting in an international agreement on the human right to water and sanitation and the United Nations SDG 6.2 to achieve by 2030 access to adequate and equitable sanitation and hygiene for all and end OD (United Nations, 2022). Between 2000 and 2020, the World Health Organization/United Nations Children's Fund Joint Monitoring Programme (JMP) reported that the proportion of the global population practicing OD decreased from 21% to 6%; however, an estimated 494 million people still practice OD, of whom 90% live in rural areas of sub-Saharan Africa and Central and Southern Asia (WHO and UNICEF, 2021).

In 2016, an estimated 60% of the population of India practiced OD, which was 4 times the global rate (Alexander et al., 2016). Because India may still be a major contributor to global OD rates, reducing the practice will be essential in meeting the 2030 SDG target 6.2. According to JMP reported data, India is responsible for the largest drop in OD between 2015 and 2020 in terms of absolute numbers among all countries, yet high rates of OD in India persist (WHO and UNICEF, 2021). The JMP estimated that 15% of India's population practiced OD in 2020, with rates varying between 1% and 70% across states (WHO and UNICEF, 2021). India's National Family Health Survey (NFHS) estimated that 19% of India's population practiced OD in 2021 (IIPS and ICF, 2021; WHO and UNICEF, 2021). However, several studies have indicated that rates of OD in India are underestimated. Vyas et al. (2019) found a 20-percentage point higher rate of OD at the individual level than was reported by the NFHS at the household level. Yogananth and Bhatnagar (2018) found that nearly 55% of households in the state of Tamil Nadu practiced OD despite having a household toilet, compared to 38% reported by the 2016 NFHS (IIPS and ICF, 2017).

The JMP estimated that in 2020, 46% of India's population had access to safely managed sanitation services, that is, improved sanitation facilities that are not shared with other households and where excreta are safely disposed of onsite or transported and treated offsite. (WHO and UNICEF, 2021). This estimate of sanitation coverage is similar to other countries regionally—Bangladesh (39%) and Nepal (49%) — as well as globally—including Ecuador (42%) and Albania (49%) (WHO and UNICEF, 2021). However, while these countries have similar estimates of safely managed sanitation coverage, estimates of OD varied. Albania, Bangladesh, and Ecuador were all estimated to have rates of OD less than 1%, compared to an estimated 10% in Nepal and 15% in India, suggested that India is lagging behind in improving defecation practices both regionally and globally (WHO and UNICEF, 2021).

Lack of adequate WASH services and OD are most commonly associated with excreta-related infectious diseases and diarrhea (Cairncross et al., 2010; Manga, 2017; Manga et al., 2022). OD enables disease-causing pathogens to spread from the feces of one person to the mouth of another via contaminated water, food, or fomites (Capone et al., 2022). A systematic review of the health impacts of OD in India and Kenya found associations of OD with soil-transmitted helminth infections, hookworm infestations, poor birth outcomes, poor nutrition, increased risk of sexual violence among women, and psychosocial stress (Saleem et al., 2019). Declines in OD correspond to decreases in the prevalence of diarrheal morbidity (Njuguna, 2016). Reductions in OD, and corresponding reductions in WASH-related morbidity, may be achieved by improving access to basic or improved sanitation services. Improved sanitation facilities hygienically separate excreta from human contact, and basic sanitation refers to the use of improved sanitation facilities that are not shared by other households (WHO and UNICEF, 2021). Safely managed sanitation refers to the use of improved facilities that are not shared by other households, and where excreta are safely disposed of on-site or removed and treated off-site. The JMP estimated that 71% of India had access to basic or safely managed sanitation in 2020 (WHO and UNICEF, 2021).

To accelerate efforts to achieve country-wide sanitation coverage and reduce WASH-related disease in line with SDG 6, the Prime Minister of India launched the Swachh Bharat Mission (SBM) in 2014. One key objective of the SBM was for all Indian villages, districts, and states to improve public health by achieving open defecation free (ODF) status by 2019 based on household-level surveys (Government of India, 2022). ODF is defined in SBM guidelines as no visible feces found in the environment/village and, b) every household as well as public/community institution(s) using safe technology option for disposal of feces, as defined by the Ministry of Drinking Water and Sanitation. However, the effectiveness of SBM in eliminating OD in Indian states is still not well understood.

SBM sought to engage all people in the task of cleaning homes, workplaces, villages, cities and surroundings, in a collective quest. The objectives of SBM included: a) Bring about an improvement in the general quality of life in rural areas by promoting cleanliness, hygiene and eliminating open defecation, b) Accelerate sanitation coverage in rural areas to achieve the vision of Swachh Bharat, c) Motivate communities to adopt sustainable sanitation practices and facilities through awareness creation and health education, d) Encourage cost effective and appropriate technologies for ecologically safe and sustainable sanitation, e) Develop community managed sanitation systems focusing on scientific Solid and Liquid Waste Management systems for overall cleanliness in the rural areas, and f) Create significant positive impact on gender and promote social inclusion by improving sanitation especially in marginalized communities (Government of India, 2018). The strategy for obtaining these objectives included augmenting the institutional capacity of districts to undertake behavior change at the grassroots level, strengthening the capacities of implementing agencies to roll out program components in a timely manner and to measure collective outcomes, and incentivizing the performance of state-level institutions to implement behavioral change activities in communities.

Because large portions of India's population may continue to practice OD—up to 70% of the population in certain states—and lack access to basic or safely managed sanitation facilities, as established by the JMP and NFHS, it is important to evaluate the impact of SBM on OD and sanitation access in India (WHO and UNICEF, 2021). This is the first study to conduct a systematic review of published literature assessing the impacts of SBM on OD practices. The objectives of this review were to 1) assess the impact of SBM on OD, 2) evaluate the barriers to eliminating OD, and 3) provide recommendations for future interventions to reduce or eliminate OD in India. These study findings may be used to inform future initiatives focused on reducing OD following government-wide sanitation hardware campaigns.

2 Methodology

2.1 Search strategy

A systematic review of published literature from PubMed, Scopus, and the Global Health database within EBSCO was conducted. Search terms were related to the Swachh Bharat Mission, open defecation, and states within India. Synonyms of these search terms in addition to other keywords were used. Initial searches including the Swachh Bharat Mission yielded few results; searches were modified to include Swachh Bharat Abhiyan, Clean India Mission, and Nirmal Bharat Abhiyan as well as keywords including by not limited to Rural, Urban, Toilet Construction, and Household Sanitation. A complete list of search terms is available in the Supplementary Table S1.

Database searches were limited to articles published in English in 2014 or later, and the final search was conducted on 8 June 2022. All studies were uploaded to Covidence, a systematic review production online tool, where duplicate studies were removed. Two reviewers screened the remaining studies by title and abstract for relevance. The final selection of studies occurred after a full text review of articles.

2.2 Document selection and eligibility criteria

Studies selected for inclusion must have assessed the impacts of the SBM on OD practices in India. Studies reporting on ending open defecation under other programs and campaigns were excluded. Studies reported in languages other than English were excluded. Commentaries, viewpoints, and other review articles were excluded from this review, as we sought to evaluate primary evidence of rates of OD in India. Study data were then extracted, which included study design, location, sample size, study description, data collection methods, and main findings such as impacts on OD or qualitative factors affecting latrine access and use.

2.3 Quality appraisal

Quality assessment was performed by one reviewer and involved describing the level of evidence (Ackley et al., 2008; Brownson et al., 2009; Manga et al., 2023; Muoghalu et al., 2023) and risk of bias (Sterne et al., 2016; Higgins et al., 2022; Conaway et al., 2023) that were then used to rate the overall certainty of the articles. Quality assessment results are provided in Table 2.

A level of evidence was assigned to studies based on the methodological quality of the article design and applicability. Levels were ranked as A, B, or C, with Level A being the highest level of evidence and Level C being the lowest level of evidence. Level A was reserved for randomized controlled trials (RCTs), as systematic reviews were excluded from this review (Ackley et al., 2008). Other types of peer-reviewed research such as cross-sectional studies were rated at Level B. Level C was assigned to formative research and pilot studies (Brownson et al., 2009).

The risk of bias was evaluated using the risk-of-bias tool (RoB 2) for RCTs (Higgins et al., 2022), and the Risk of Bias in Non-randomized Studies of Interventions (ROBINS-I) tool for other study types (Sterne et al., 2016). The RoB 2 analysis involved the evaluation of bias that arose from the randomization process, bias due to deviations from intended interventions, bias due to missing outcome data, bias in outcome measurements, and bias in selection of the reported results (Higgins et al., 2022). Domains in ROBINS-I that are not included in RoB 2 include bias due to confounding, selection bias, and bias in classification of interventions (Sterne et al., 2016).

Overall certainty ratings imply confidence that the true effects lie near the estimated effect determined in the study. Studies at Level A were initially given a high certainty, studies at Level B were rated intermediate, and studies at Level C were initially rated as low. Overall certainty was then either increased or decreased based on risk of bias estimates. Based on the information obtained through this review, recommendations for future interventions, modifications, and programs were provided.

3 Results

3.1 Study selection

We identified 237 documents from databases including Scopus, PubMed, and Global Health by Ebscohost. After screening for duplicates and excluding documents that did not meet our inclusion criteria, we reviewed the full texts of 53 studies for further assessment. Of these, we further excluded studies that did not describe and analyze primary data, documents that referenced identical data and findings, and documents in which the interventions to reduce OD were not a part of the SBM. In total, 22 of the total 237 documents were included in this review. Figure 1 presents a Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) diagram of the literature screening and article selection process.

3.2 Summary of findings

A detailed summary of the study findings, including study designs, locations, sample sizes, descriptions, data collection methods, and main findings, is shown in Table 1.

3.2.1 Geographic locations of included studies

Thirteen Indian states were represented across the literature. Six studies reported experiences from more than one state, region, or territory in India, so there is overlap among the locations in some studies. Most studies reported experiences from Uttar Pradesh (n = 4, 18%), Bihar (n = 3, 14%), Madhya Pradesh (n = 3, 14%), Rajasthan (n = 3, 14%), and Maharashtra (n = 3, 14%). The remaining studies were conducted in Odisha, Tamil Nadu, Karnataka, Jharkhand, Tripura, Kerala, West Bengal, and Punjab. Figure 2 shows a map highlighting the frequency of study locations.

3.2.2 Quality assessment of included studies

Of the 22 included studies, three (14%) were RCTs rated as Level A, as shown in Table 2. This review also included 10 cross-sectional studies (45%) that were rated as Level B. The remaining nine studies (41%) were formative research or case studies that were ranked as Level C.

According to the Cochrane guidelines, certain study limitations can increase the risk of bias and therefore decrease the overall certainty rating. A low risk of bias score implies confidence that there were no major or minor sources of bias that could have influenced results. An intermediate risk of bias indicates the presence of one major or several minor study limitations, and a high risk of bias indicates the presence of more than one crucial

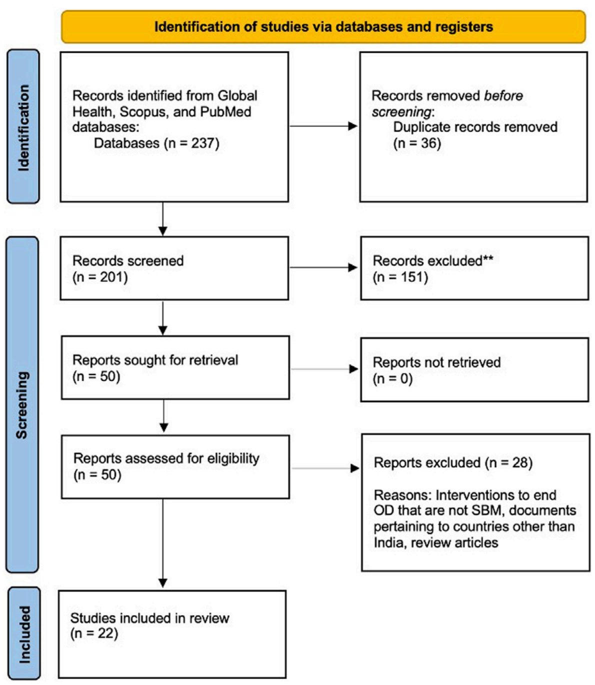

FIGURE 1
Process for selecting studies in this review of the effectiveness of the Swachh Bharat Mission on reducing OD in India.

limitation that may seriously compromise the validity of study findings (Sterne et al., 2016; Anthonj et al., 2020; Higgins et al., 2022).

Seven studies (23%) were scored a low risk of bias. Among these, three were RCTs that had large sample sizes with thousands of participants, randomization via random number generator or lotter, and little to no missing outcome data. Biswas et al. (2020), Exum et al. (2020), Gupta et al. (2020), and Spears and Coffey (2019) conducted cross-sectional studies with large and/or nationally representative sample sizes and adjustments for potential confounders that led to their low risk of bias judgment.

Ten studies (45%) were scored an intermediate risk of bias, among which six were cross-sectional studies with questionnaires or interviews leading to uncertainty in the extent to which participants may be willing to provide truthful answers. The other four studies rated as intermediate risk of bias were formative research or case studies that had hundreds of participants but used purposive sampling techniques for particular populations of interest, leading to the potential for biases in data collection.

Five studies (23%) were scored a high risk of bias, all of which were formative research or case studies. This rating was due to small sample sizes, the use of convenience sampling, self-reported defecation practices, potential for courtesy bias, and the lack of follow-up.

3.2.3 Impacts of SBM on OD

Several studies found that government claims of improved toilet coverage and increases in ODF villages were overreported. While India's Prime Minister declared the country ODF in 2019, assessments of toilet coverage following SBM implementation ranged from 19% in rural Bihar (Jain et al., 2020) to 92% in urban Uttar Pradesh (Jha and Sharma, 2020). India's NFHS reported that 19% of India's total population practiced OD in 2021 (IIPS and ICF, 2021). Andres et al. (2020) found that coverage of improved sanitation among households without toilets increased by 6.8–10.4 percentage points from 2014 to 2019, and open defecation reduced by 7.3 percentage points.

Among households that owned latrines, several studies found that latrine ownership did not necessarily indicate latrine use. Namdev and Narkhede (2020) found that among households in rural Madhya Pradesh, 27.7% of households with toilets at home practiced OD. Caruso et al. (2022) showed that among households in Odisha, only 60.4% of those that received new latrines during the SBM used their latrines. Biswas et al. (2020) found that among all public and community toilets in Mumbai,71%–99% were not in good condition, and toilet infrastructure is not directly correlated with reductions in OD. Exum et al. (2020) found modest reductions in OD in rural Rajasthan between 2016 and 2018, though rates of OD remained high–OD decreased from 63.3% to 45.8% among rural households with latrine access, and households regularly practicing OD despite 21.7% of rural Rajasthan and 12.1% of urban Rajasthan having access to a toilet.

Rates of OD also varied by urban and rural location. Studies conducted in urban locations found higher rates of latrine coverage and lower rates of OD than those conducted in rural areas (Exum et al., 2020; Jha and Sharma, 2020; Datta et al., 2021). Urban latrine coverage was found to be 86% and 92% in urban Tripura and urban Uttar Pradesh, respectively (Jha and Sharma, 2020; Datta et al., 2021). Exum et al. (2020) found that, from 2016 to 2018, main OD practices in rural Rajasthan households decreased from 63.3% to 45.8%, and in urban households from 12.6% to 9.4%.

3.2.4 Barriers to eliminating OD in India

Narayan et al. (2021) conducted key informant interviews to identify barriers to latrine use, and found that unreliable financial support, inadequate planning capacities, and poor community involvement were major factors contributing to continued open defecation. Das and Crowley (2018) also found affordability to be a key hurdle to sanitation program success, though 70% of participants expressed willingness to pay Rs.25-100 ($0.30–1.20 USD) monthly for connection to a networked sewer system. Kumar (2017) found that the current government subsidy of 12,000 rupees ($145 USD) per toilet limits the technologies available to each household, disallowing households from choosing better technology that best fits their local context.

Hutton et al. (2020) conducted a cost-benefit analysis of the SBM based on inputs from household level surveys in which monetized costs (household financial and time investments in building and maintaining toilets, and government's investments on subsidies and campaign activities) were compared to monetized benefits (reductions in medical costs and mortality associated with diarrheal diseases, productive time saved from fewer diarrhea cases and accessing outside defecation options, and increase in the property value of having a toilet). Under ODF scenarios, corresponding to 100% toilet coverage and usage, benefit-cost ratios were 1.7 (household financial perspective), 4.5 (household economic perspective) and 4.0 (societal perspective),

TABLE 1 Summary of included studies' location, sample size, design, data collection methods, and main findings relevant to the impact of the SBM on OD practices in India.

	Citation	Location	Sample size	Study design	Study description	Data collection methods	Main findings: Impact on OD or factors affecting latrine use
1	Caruso et al. (2022)	Odisha	3,723 households in intervention group, 1916 households in control group	RCT	Households that received latrines by the SBM participated in community mobilization activities to engage the whole community to identify problems and increase latrine use among latrine-owning households	Surveys to assess latrine use at baseline and endline	Latrine use increased by 6.4 percentage points among latrine-owning households in the intervention group. 80.5% of households used latrines at the end of the study
2	Narayan et al. (2021)	Tamil Nadu and Karnataka	Expert interviews with 60 participants	Case study	Analysis of the key barriers to sanitation planning in India following SBM implementation	Qualitative and quantitative methods: key informant interviews, participant observations, expert workshops, social network analysis, shit flow diagrams (SFDs), and policy and document analyses	Factors identified as barriers for sanitation: inadequate planning capacities, lack of ownership of city sanitation plans among city governments, poor community involvement, absence of a uniform planning framework, unreliable political and financial support, overlapping jurisdictions, and scheme-based funding
3	Jain et al. (2020)	Bihar	21 participants from 3 villages	Formative research	Exploratory, open-ended discussions, in groups and one-on-one, on sanitation practices, attitudes towards OD, latrine ownership and use, and the reasons for non-adoption and/or non-use despite the financial assistance and social marketing efforts	Surveys and focus group discussions	4 of 21 participants (19%) owned a latrine. Participants were aware of the risks of OD but still practiced OD out of necessity. Key barriers to latrine access included lack of subsidies and perceptions of bias toward rural areas that reinforce governmental mistrust
4	Biswas et al. (2020)	Mumbai	8,417 public and community toilet blocks	Cross sectional	Assessment of toilet infrastructure for squatter settlements of megacity Mumbai, with the help of a data-centric analysis followed by field observations	Field observations to calculate population per toilet seat available. Community surveys to estimate toilet use	Of the 8,417 toilets assessed, 71%–99% were not in good condition. Toilet infrastructure alone cannot eliminate OD.
5	Anuradha et al. (2017)	Tamil Nadu	275 households	Cross sectional	Assessment of knowledge, attitudes, and latrine use practices following SBM implementation in rural India	Structured questionnaire to collect information regarding the demographic characteristics, participants' knowledge, attitudes, and practices towards sanitary latrines usage	62.5% of households had latrines, and 33.1% practiced OD. 87.2% of households were unaware of the potential for disease spread due to OD.
6	Friedrich et al. (2020)	Rural Karnataka	1945 participants from 120 villages with at least 30% latrine coverage	RCT	Risks, attitudes, norms, abilities, and self-regulation (RANAS) approach—a behavior-change intervention—to boost latrine use following implementation of the SBM.	Qualitative interviews and village meetings to identify behavioral factors, visits and phone calls from community health promoters. Self-reported latrine use and spot check observations of latrines	Latrine use increased from 77% at baseline to 97% at endline. The RANAS behavior change approach may be effective in boosting latrine use following toilet construction
7	Hutton et al. (2020)	12 Indian states	>10,000 households	Cost-benefit analysis	Cost-benefit study at national scale based upon the outcomes of implementation of the SBM.	Comparison of monetized costs (household financial and time investments in building and maintaining toilets, and government's investments on subsidies and campaign activities) to monetized benefits (reductions in medical costs and mortality associated with diarrheal diseases, productive time saved from	Under ODF scenarios (100% toilet coverage and usage), benefit-cost ratios are 1.7 (household financial perspective), 4.5 (household economic perspective) and 4.0 (societal perspective), which decrease under partial-ODF scenarios

(Continued on following page)

TABLE 1 (*Continued*) Summary of included studies' location, sample size, design, data collection methods, and main findings relevant to the impact of the SBM on OD practices in India.

	Citation	Location	Sample size	Study design	Study description	Data collection methods	Main findings: Impact on OD or factors affecting latrine use
						fewer diarrhea cases and accessing outside defecation options, and increase in the property value of having a toilet)	
8	Datta et al. (2021)	Urban Tripura	100 participants	Cross sectional	Community-based study to assess knowledge and practices regarding water, sanitation, hygiene, and waste disposal and the key components of SBM in an urban community and determine their associated factors	Individual interviews and quantitative surveys	86% of families had a latrine at home, and no families reported practicing OD. All families without a latrine at home reported the reason as its construction was under progress
9	Curtis (2019)	4 Indian states	17 government actors	Formative research	Employed the framework of Behavior Centered Design (BCD) to understand how the Indian government implemented the SBM.	Interviews with government officials	Political commitment to sanitation infrastructure led to psychological changes in district officials, which led to changed behavior for sanitation programming. SBM claims to have improved the coverage of toilets in rural India from 39% to over 95% of households between 2014 and mid-2019
10	Das and Crowley (2018)	Madhya Pradesh	622 urban households	Cross sectional	Study to explore factors affecting household toilet ownership and use among the urban poor	Survey data from 13 low-income settlements combined with interviews, focus-group discussions, and transect walks in three cities in central India	52.7% of households reported using an individual toilet, and 39.8% reported practicing OD. 70% were willing to pay for sanitation if they had money available
11	Exum et al. (2020)	Rajasthan	20,485 households	Repeated cross sectional	Evaluation of Rajasthan's claims of ODF status under the SMB by measuring OD trends from 2016 to 2018	Repeated cross sectional surveys of household water and sanitation measures. The primary outcome measure was regular OD among households with access to toilet facilities	Between October 2016 and July 2018 main OD practices in rural Rajasthan households decreased from 63.3% to 45.8%, and in urban households from 12.6% to 9.4%. Households with regular OD occurring despite access to a toilet made up 21.7% of rural and 12.1% of urban Rajasthan as of July 2018
12	Mavila and Francis (2019)	Kerala	321 participants	Cross sectional	Study to assess the impact of SBM on sanitation in Kerala and to identify the factors associated with sanitation practices among residents	Semi-structured questionnaire, administered by face-to-face interview to the interviewer, which consisted of a sociodemographic part and a part measuring the awareness, practice, and impact of SBM.	Among those who were aware of SBM, 66% reported that SBM had no impact on the overall sanitation of the community. The community overall already had good sanitation practices, and only one person reported practicing OD.
13	Rengaraj et al. (2021)	Odisha	Village with 65 households	Case study	A 2-year study in a tribal village to understand the reasons for the prevalence of OD in rural India. Human-Centered Design (HCD) incorporates the users' preferences and perspectives into the development of solutions	Research team members resided in the local community to gain an in-depth familiarity of community practices and collaboratively develop solutions	Out of the 65 households, 49 toilets were present, and only 7 households used them. Residents stopped using toilets because they were never instructed on maintenance and use

(Continued on following page)

TABLE 1 (*Continued*) **Summary of included studies' location, sample size, design, data collection methods, and main findings relevant to the impact of the SBM on OD practices in India.**

	Citation	Location	Sample size	Study design	Study description	Data collection methods	Main findings: Impact on OD or factors affecting latrine use
14	Andres et al. (2020)	Rural Punjab	4,800 households	RCT	Evaluation of the SBM's combination of behavior change campaigns, community-led total sanitation approach, and financial incentives for increasing latrine access and reducing OD.	Household, community, and school level surveys to collect data on participants and project implementation	Coverage of safely managed toilets among households without toilets increased by 6.8–10.4 percentage points across various intervention arms, compared with a control group. Open defecation was reduced by 7.3–7.8 percentage points
15	Namdev and Narkhede (2020)	Madhya Pradesh	523 households from 5 villages (approximately 1,000 participants)	Cross sectional	Study of rural villages to determine the prevalence of OD as well as reasons behind the practice of OD.	Trained social workers conducted interviews with adult family members from each household using structed questionnaires	27.7% of study subjects opted for OD practices despite having a sanitary latrine at home. Out of those practicing OD, 76.5% opted due to their habits, 57% for comfort, followed by unawareness (36.4%) and lack of water (34%)
16	Kar and Mistri (2015)	West Bengal	92 households from 7 villages	Cross sectional	Study to understand participants' awareness of hygiene practices, to evaluate the socioeconomic status and health status of the area, and to determine the impact of OD and improper sanitation on human health	Quantitative and qualitative methods: household questionnaires, census reports, and geographic mapping to understand sanitation and hygiene practices as well as rates of disease	17% of households had a toilet, and 85% of households practiced OD. Among households with a toilet, 12% still practiced OD. 20% of participants washed hands with soap after visting the toilet. 50% suffer from symptoms related to waterborne disease, such as diarrhea
17	Patwa and Pandit (2018)	Uttar Pradesh	384 households where toilet was not reported prior to SBM implementation	Formative research	Behavior-change study to complement SBM efforts and to find the reasons for practicing OD from those households who are still practicing it. Educational lessons about benefits of cleanliness, benefits of using toilet instead of OD, details about government subsidiary to construct toilet, awareness about hygiene and sanitation, and pamphlets distribution	Surveys to assess OD practices and associated factors	After SBM implementation, 8% of households did not have a toilet and practiced OD. Financial constraint, waiting for government assistance, spending majority of time away from home due to work, and habit to defecate outside were the major reasons for OD.
18	Vu et al. (2022)	Jharkhand	41 adults	Case study	Study to understand user perspectives on the essential attributes of managed shared sanitation facilities and what role these facilities can play in people's lives	Semi-structured, one-on-one interviews with individuals to understand their sanitation needs, past and present barriers to sanitation access, and their lived experiences defecating in the open and using shared facilities	The percentage of people defecating in the open decreased from 29% in 2015 to 15% in 2020, and the number of people using safely managed toilets rose from 36% in 2015 to 46% in 2020
19	Gupta et al. (2020)	Bihar, Madhya Pradesh, Rajasthan, and Uttar Pradesh	9,812 people (1,558 households from 120 villages)	Cross sectional	Assessment of the impacts of the SBM on reducing OD in Indian states	Rural Sanitation Survey in 2014 and 2018 to estimate household level OD before and after SBM implementation	Between 42% and 57% of rural people over 2 years of age defecate in the open. These findings contrast with government claims that open defecation has been entirely or largely eliminated. In the region as a whole, open defecation declined from approximately 70% of people over 2 years old in 2014, to approximately 44% of people over 2 years old in 2018

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TABLE 1 (*Continued*) Summary of included studies' location, sample size, design, data collection methods, and main findings relevant to the impact of the SBM on OD practices in India.

	Citation	Location	Sample size	Study design	Study description	Data collection methods	Main findings: Impact on OD or factors affecting latrine use
20	Coffey et al. (2020)	Delhi, Uttar Pradesh, Mumbai, Rajasthan, Bihar, Jharkhand, and Maharashtra	Approximately 1,000–3,000 individuals from each of the 7 states	Formative research	Study to assess people's awareness of the existence and purpose of the SBM.	Mobile phone survey to measure opinions on a range of public policies in India, including awareness of the SBM's goal of eliminating OD.	No more than one-third of adults in any state were aware that the SBM intended to promote toilet and latrine use. While the SBM was very active in constructing latrines, the lack of awareness we find suggests that the SBM was less successful in raising the awareness required for large-scale behavior change in promoting latrine use
21	Jha and Sharma (2020)	Uttar Pradesh	5 slums	Case study	Study to assess whether the district of Ghaziabad in Uttar Pradesh is truly ODF following SBM implementation, and if not, the reasons behind it	Survey with questionnaire on toilet availability, water availability, and OD practices	Though government records show all households have a toilet, the survey revealed that toilet availability ranged from 33% to 100%, with an average of 92%. The reasons for lack of toilet availability were lack of funds for construction of toilets due to emergence of new households caused by the separation of joint families
22	Spears and Coffey (2019)	Rural India	Analysis of National Family Health Survey (NFHS), which covers approximately 568,000 households	Cross sectional	Study of patterns of rural open defecation using the NFHS-4, a large-scale nationally representative survey collected between January 2015 and November 2016	Survey data from NFHS-4	NFHS-4 underestimates individual-level OD and offers little evidence that the decline in OD in rural India has accelerated radically in recent years. Despite the high-profile efforts of the SBM, more than half of rural households report OD.

TABLE 2 Quality assessment of studies included in this review of the effectiveness of the SBM in reducing OD practices in India.

	Authors	Study design	Sample size	Level[1]	Risk of bias[2]	Overall certainty rating[3]	Impact on OD in India
1	Caruso et al. (2022)	Randomized controlled trial	3,723 households in intervention group, 1916 households in control group	A	Low (large sample; purposive sampling of participants; extent to which study participants are willing to provide truthful answers)	High Certainty	1 year after community mobilization, 19% of households had a completed latrine across the 50 villages, a marginal increase of 7 percentage points over baseline
2	Narayan et al. (2021)	Case study	Expert interviews with 60 participants	C	High (potential for inherent biases in data interpretation and collection)	Low Certainty	Qualitative only
3	Jain et al. (2020)	Formative research	21 participants from 3 villages	C	High (small sample size; purposive sampling of participants; extent to which study participants are willing to provide truthful answers)	Low Certainty	4 of 21 participants (19%) owned a latrine. Participants were aware of the risks of OD but still practiced OD out of necessity
4	Biswas et al. (2020)	Cross sectional	8,417 public and community toilet blocks	B	Low (large sample, standardized toilet condition assessments)	Intermediate Certainty	Of the 8,417 toilets assessed, 71%–99% were not in good condition. Toilet infrastructure alone cannot eliminate OD.
5	Anuradha et al. (2017)	Cross sectional study	275 households	B	Intermediate (extent to which questionnaire could have yielded truthful answers)	Intermediate Certainty	62.5% of households had latrines, and 33.1% practiced OD. 87.2% of households were unaware of the potential for disease spread due to OD.
6	Friedrich et al. (2020)	Randomized controlled trial	1945 participants from 120 villages with at least 30% latrine coverage	A	Low (large sample, intervention and control were subjected equally)	High Certainty	Latrine use increased from 77% at baseline to 97% at endline. The RANAS behavior change approach may be effective in boosting latrine use following toilet construction
7	Hutton et al. (2020)	Cost-benefit analysis	>10,000 households	C	Intermediate (Assumes ODF status for some cost-benefit scenarios)	Low Certainty	Under ODF scenarios (100% toilet coverage and usage), benefit-cost ratios are 1.7 (household financial perspective), 4.5 (household economic perspective) and 4.0 (societal perspective), which decrease under partial-ODF scenarios
8	Datta et al. (2021)	Cross sectional	100 participants	B	Intermediate (extent to which study participants are willing to provide truthful answers)	Intermediate Certainty	86% of families had a latrine at home, and no families reported practicing OD. All families without a latrine at home reported the reason as its construction was under progress
9	Curtis (2019)	Formative research	17 government actors	C	High (small sample; extent to which study participants are willing to provide truthful answers)	Low Certainty	Qualitative only
10	Das and Crowley (2018)	Cross sectional	622 urban households	B	Intermediate (extent to which study participants are willing to provide truthful answers)	Intermediate Certainty	52.7% of households reported using an individual toilet, and 39.8% reported practicing OD. 70% were willing to pay for sanitation if they had money available

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TABLE 2 (*Continued*) Quality assessment of studies included in this review of the effectiveness of the SBM in reducing OD practices in India.

	Authors	Study design	Sample size	Level[1]	Risk of bias[2]	Overall certainty rating[3]	Impact on OD in India
11	Exum et al. (2020)	Repeated cross sectional	20,485 households	B	Low (large sample)	High Certainty	Between October 2016 and July 2018 main OD practices in rural Rajasthan households decreased from 63.3% to 45.8%, and in urban households from 12.6% to 9.4%. Households with regular OD occurring despite access to a toilet made up 21.7% of rural and 12.1% of urban Rajasthan as of July 2018
12	Mavila and Francis (2019)	Cross sectional	321 participants	B	Intermediate (extent to which study participants are willing to provide truthful answers)	Intermediate Certainty	Among those who were aware of SBM, 66% reported that SBM had no impact on the overall sanitation of the community. The community overall already had good sanitation practices, and only one person reported practicing OD.
13	Rengaraj et al. (2021)	Case study	Village with 65 households	C	High (singular village, extent to which study participants are willing to provide truthful answers)	Low Certainty	OD is prevalent despite the majority of households owning toilets that were built in 2016, under Government of India's Swachh Bharat Mission crusade, that was helping rural communities to become ODF by assisting them in building their own sanitation system
14	Andres et al. (2020)	Randomized controlled trial	4,800 households	A	Low (large sample, extent to which study participants are willing to provide truthful answers)	High Certainty	Coverage of safely managed toilets among households without toilets increased by 6.8–10.4 percentage points across various intervention arms, compared with a control group. Open defecation was reduced by 7.3–7.8 percentage points
15	Namdev and Narkhede (2020)	Cross sectional	523 households from 5 villages (approximately 1,000 participants)	B	Intermediate (extent to which study participants are willing to provide truthful answers)	Intermediate Certainty	27.7% of study subjects opted for OD practices despite having a sanitary latrine at home. Out of those practicing OD, 76.5% opted due to their habits, 57% for comfort, followed by unawareness (36.4%) and lack of water (34%). The present study concluded the prevalence of open defecation at 27.7%
16	Kar and Mistri (2015)	Cross sectional	92 households from 7 villages	B	Intermediate (extent to which study participants are willing to provide truthful answers)	Intermediate Certainty	17% of households had a toilet, and 85% of households practiced OD. Among households with a toilet, 12% still practiced OD.
17	Patwa and Pandit (2018)	Formative research	384 households where toilet was not reported prior to SBM implementation	C	Intermediate (extent to which study participants are willing to provide truthful answers)	Low Certainty	The family survey was initiated in the village in November 2014 where we found that of total 962 households, 384 (39.91%) did not have toilet and were practicing open defecation. Thus, in Bahadarpur village,

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TABLE 2 (*Continued*) Quality assessment of studies included in this review of the effectiveness of the SBM in reducing OD practices in India.

	Authors	Study design	Sample size	Level[1]	Risk of bias[2]	Overall certainty rating[3]	Impact on OD in India
							out of 962 households, only 81 (8.41%) households do not have toilets and practice open defecation
18	Vu et al. (2022)	Case study	41 adults	C	High (small sample of two villages, extent to which study participants are willing to provide truthful answers)	Low Certainty	The percentage of people defecating in the open decreased from 29% in 2015 to 15% in 2020, and the number of people using safely managed toilets rose from 36% in 2015 to 46% in 2020
19	Gupta et al. (2020)	Cross sectional	9,812 people (1,558 households from 120 villages)	B	Low (large sample size; extent to which study participants are willing to provide truthful answers)	High Certainty	Between 42% and 57% of rural people over 2 years of age defecate in the open. These findings contrast with government claims that open defecation has been entirely or largely eliminated. In the region as a whole, open defecation declined from approximately 70% of people over 2 years old in 2014, to approximately 44% of people over 2 years old in 2018
20	Coffey et al. (2020)	Formative research	Approximately 1,000–3,000 individuals from each of the 7 states	C	Intermediate (extent to which study participants are willing to provide truthful answers)	Low Certainty	Qualitative only
21	Jha and Sharma (2020)	Case study	5 slums	C	Intermediate (extent to which study participants are willing to provide truthful answers)	Low Certainty	Though government records show all households have a toilet, the survey revealed that toilet availability ranged from 33% to 100%, with an average of 92%
22	Spears and Coffey (2019)	Cross sectional	Analysis of National Family Health Survey (NFHS), which covers approximately 568,000 households	B	Low (large sample; nationally representative)	High Certainty	NFHS-4 underestimates individual-level OD and offers little evidence that the decline in OD in rural India has accelerated radically in recent years. Despite the high-profile efforts of the SBM, more than half of rural households report OD.

[1]Level A represents randomized controlled trials, Level B represents peer-reviewed research studies (cross-sectional studies, quasi-experimental studies, cohort studies), and Level C represents pilot studies or formative research.
[2]Low risk of bias indicates no limitations that could compromise study findings. Intermediate risk of bias includes studies with minor limitations that would not compromise study findings. A high risk of bias indicates studies with several limitations that may compromise study findings.
[3]Overall certainty ratings imply confidence that the true effect lies close to the estimated effect determined in the study. Studies at Level A were initially given a high certainty, studies at level B were rated intermediate, and studies at Level D were initially rated as low. Overall certainty was then moved either higher or lower based on risk of bias estimates.

which suggest that SBM was highly cost-beneficial when communities are free of OD.

Jain et al. (2020) surveyed rural households to explore perspectives on open defecation and latrine use, and the socio-economic and political reasons for these perspectives in rural Bihar and found that residents perceive a development bias against rural areas that reinforces governmental distrust. While a subsidy can help some households construct latrines, Jain et al. (2020) found that the amount of the subsidy and the manner of its disbursement are key to its usefulness.

Vu et al. (2022) identified structural barriers to sanitation access, including uncertain land rights, lack of space for a toilet, and inadequate water supply. Managed shared facilities could play an important role in helping eliminate OD while preventing adverse outcomes, though having a shared facility does not mean it is accessible. Participants noted having to travel far distances as a barrier to latrine use (Vu et al., 2022). A lack of public participation and poor maintenance led to poor toilet conditions which led to a lack of use by individuals (Biswas et al., 2020; Rengaraj et al., 2021). While studies showed modest

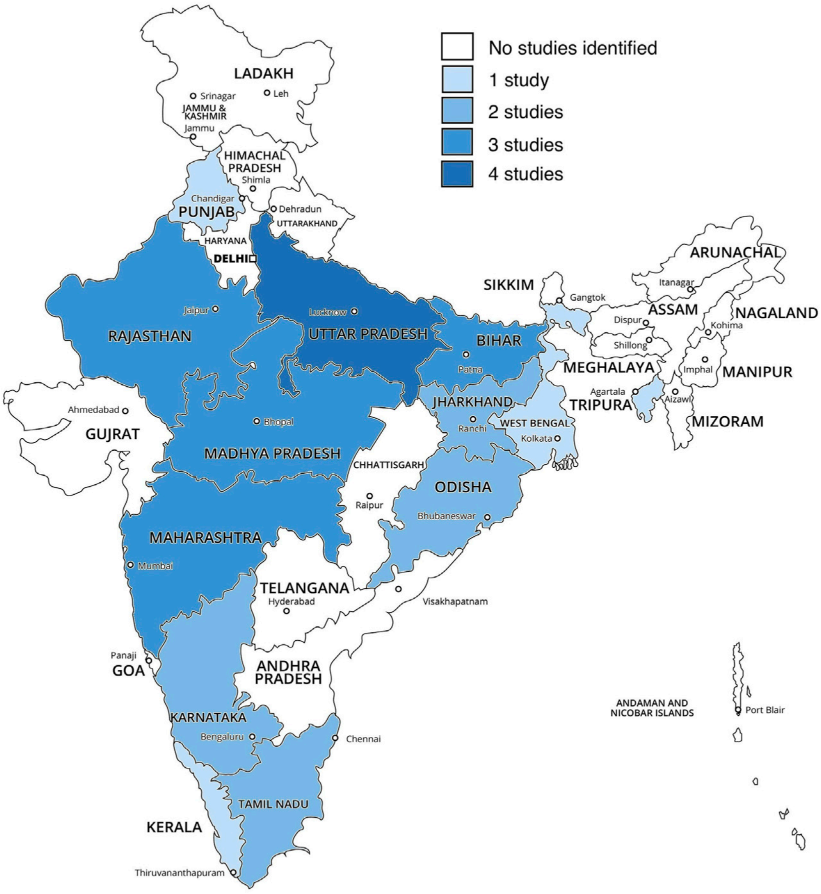

FIGURE 2
Frequency of Indian states/territories that are the study area of focus in articles included in this review. Tripura, Kerala, West Bengal, and Punjab appeared in one study each (4%); Odisha, Tamil Nadu, Karnataka, and Jharkhand appeared in two studies each (9%); Bihar, Madhya Pradesh, Rajasthan, and Maharashtra appeared in 3 studies each (14%); and Uttar Pradesh appeared in 4 studies (18%).

increases in rates of toilet coverage following SBM implementation, toilets were often not appropriately used or maintained. Biswas et al. (2020) showed that nearly all toilets in Mumbai were in poor condition.

Anuradha et al. (2017) found a lack of funds, a lack of interest in latrine construction, and a lack of knowledge about the potential for disease spread as barriers to latrine use. Continued OD may also be due to habit, personal comfort, spending most of the day at work away from home, or cultural beliefs that OD is a form of purity and strength, which is more common in rural areas (Patwa and Pandit, 2018; Namdev and Narkhede, 2020). However, Jain et al. refuted the prevalence of the notion that people open defecate by choice and instead stated that they found most participants vehemently opposed this notion and insisted that they do not wish to OD and instead OD out of necessity (2020).

3.2.5 Interventions for reducing OD following SBM implementation

Three studies conducted behavior-change interventions to boost latrine uptake following the SBM (Friedrich et al., 2020; Rengaraj et al., 2021; Caruso et al., 2022). Caruso et al. (2022) randomly assigned 66 latrine-owning villages to receive either no intervention (control group) or a behavioral intervention involving community meetings and activities, mothers' meetings, household visits, and latrine repairs. Friedrich et al. (2020) conducted qualitative interviews and village meetings to identify barriers to reducing OD, as well as used community health promoter visits and phone calls to encourage latrine use. This demonstrates that while the SBM did provide services, there were more opportunities unaddressed to further encourage latrine usage and additional interventions had to bridge the gap.

After conducting their community mobilization and behavior-change campaign to increase latrine use over roughly 10 months, Caruso et al. (2022) found that latrine use increased from 60.4% at baseline to 80.5% at endline. Friedrich et al. (2020) found that, after 2 years of intervention, latrine use increased from 77% to 97%.

Caruso et al. (2022) suggested that time and cost constraints of the SBM prevented the intervention from addressing all known behavioral factors, notably water access and latrine design. For example, those with government-funded latrines are more likely to open defecate than those with privately constructed latrines due to the design features limited by cost such as smaller pit sizes. Both Caruso et al. (2022); Friedrich et al. (2020) suggested that behavioral campaigns to increase latrine uptake and use should target change-resistant individuals, and behavioral interventions could complement future latrine use promotion in India.

Rengaraj et al. (2021) performed in-depth interactions with community members over 2 years to understand the deeper issues associated with continued OD and developed a water filtration and distribution system to address the root cause of the community's water and sanitation challenges. Rengaraj et al. (2021) determined that longer commitment using a bottom-up participatory and user-centered approach was key in bringing about a higher social impact in reducing OD at the community level.

4 Discussion

Our systematic review sought to identify studies assessing the impact of SBM on OD, evaluate the successes and shortcomings of SBM in reducing OD and the reasoning behind it, and provide recommendations for future interventions to reduce or eliminate OD in India. We found evidence that government claims of India's universal latrine coverage and ODF status were overrepresented, which may be due to the use of household-level data which assumes everyone in the household is using the latrine instead of individual-level data which considers that some members of the household may still be practicing open defecation in government monitoring efforts. There are many households in which some people use the latrine while others defecate in the open, which is especially true of government-provided latrines, which are more likely to be used by only some household members than privately constructed latrines (Spears and Coffey, 2019). We also found variation among studies in reported rates of OD and latrine coverage among Indian states, urban and rural locations, and socioeconomic levels. This suggests that a more robust monitoring system to assess OD at the individual level is needed to adequately assess ODF status.

Many studies found that OD remained prevalent despite SBM, with rates ranging from 15% in Jharkhand (Vu et al., 2022), 30%–40% in Tamil Nadu and Madhya Pradesh (Anuradha et al., 2017; Das and Crowley, 2018; Namdev and Narkhede, 2020), to 44% in a multi-state study (Gupta et al., 2020). Some studies reported no or very little OD, though these had smaller sample sizes and used self-reported data during face-to-face interviews, which may be more susceptible to response bias (Mavila and Francis, 2019; Datta et al., 2021).

Poverty and lack of financial support were identified as key barriers to latrine construction. Government subsidies can help some households construct latrines, dependent on the amount of the subsidy and the method of disbursement, though the current government subsidy scheme is viewed as poor and inadequate (Jain et al., 2020). The current government subsidy of 12,000 rupees ($145 USD) per toilet limits the technologies available to each household, disallowing households from choosing better technology that best fits their local context (Kumar, 2017). The financial aspects of government efforts to reduce OD need to be improved to encourage households to finance latrine construction.

Other barriers to latrine access and use were identified as poor community involvement in SBM implementation, governmental mistrust, and a lack of knowledge about the risks associated with OD. This suggests that, in addition to providing clean, accessible, and affordable sanitation facilities, sanitation programming should also focus on involving communities in implementation to rebuild trust and encourage latrine use. Caruso et al. (2022); Friedrich et al. (2020) conducted community mobilization and behavior-change interventions in villages that received toilets from the SBM to boost latrine use. These interventions resulted in roughly 20 percentage point increases in latrine use, suggesting that targeted behavior-change techniques may be effective in increasing latrine use among households that already have latrines.

Additionally, behavior-change campaigns among government officials may be key to promoting sanitation coverage. Curtis (2019); Bhanot et al. (2017) found that high-level political support for sanitation programming, ambitious SDGs and disruptive leadership changed environments in districts, which led to mindset changes in district officials and contributed to changed behavior in support of the SBM. District officials also reported becoming emotionally involved in the program and felt pride at their achievement in ridding villages of OD (Curtis, 2019). Setting targets and monitoring them is important to hold district leaders accountable for results (Curtis, 2019). Rewarding and recognizing progress can encourage government leaders to continue the promoting sanitation programming.

Hutton et al. (2020) conducted a cost-benefit analysis of the SBM based on cost-benefit model inputs of household-level surveys and found that the program was highly cost-beneficial when communities are free of OD. However, as several studies showed that government claims of improved toilet coverage or an increase in ODF villages were notably overreported, these benefits are likely overestimated.

Community incentives and penalties have been used to encourage proper sanitation practices with varying success. Monetary incentives can be used to encourage household latrine construction, and to repair and renovate nonfunctioning toilets (Jain et al., 2020; Caruso et al., 2022). Furthermore, latrine construction and proper sanitation practices were often accomplished through coercions. Villagers reported guards with sticks being posted to chase people away from common open defecation sites, and local officials often threatened people who did not build latrines (Gupta et al., 2020). It is unknown whether the gains accomplished through coercion will be sustainable.

Overall, preference for OD cannot be solely attributable to material or educational deprivation, as beliefs, values, and cultures also play an important role in people's decisions to reject affordable latrines (Coffey et al., 2016). Many recommendations surrounding drivers of latrine construction focus on the household's enabling environment, though sanitation research should emphasize the need to look beyond these household-level drivers to understand social-structural determinants of latrine uptake (Jain et al., 2020). For example, when examining women's preferences for latrines, a lack of water creates a hesitancy to build; women hesitate to build individual household latrines when sufficient water supply is unavailable because they are the ones who will be burdened with fetching more water from far taps (Mohan, 2017).

While water availability does affect the choice for open defecation, water availability is not the sole factor in determining OD practices, as OD still occurs in households that have access to water (Spears and Coffey, 2019). In one study, 34% of subjects who practiced OD listed lack of water as a reason (Kar and Mistri, 2015). In addition to improving infrastructure, providing educational, community-based services in conjunction with sanitation programming is necessary to encourage households to reduce OD as a sustainable, affordable, and culturally appropriate solution.

In order to meet SDG 6.2 — to achieve access to adequate and equitable sanitation and hygiene for all and end open defecation by 2030 — the United Nations suggests using the proportion of the population using safely managed sanitation services and a hand-washing facility with soap and water as indicators. SDG 6.3.1 also refers to increasing the proportion of domestic and industrial wastewater flows safely treated as an indicator of improving safely managed sanitation (United Nations, 2022). However, as indicated by the JMP, measures of waste containment, storage, and onsite treatment vary widely among countries and among data collection methods (WHO and UNICEF, 2021). For example, in Canada, surveys to assess onsite treatment use "No problems last time pumped, maintained, or inspected" as a measure of containment, while in Nigeria, containment is measured in terms of "No leaks or overflow" (WHO and UNICEF, 2021). For more accurate comparisons among countries, standardized definitions of waste containment, in addition to standard inspection techniques, are needed.

While this systematic review provided a comprehensive overview of the existing peer-reviewed literature on the effectiveness of the SBM in reducing OD and barriers to continued reductions in OD practices, a few limitations were noted. This review was limited by the literature databases to which we had access: PubMed, Scopus, and the EBSCO Global Health database. Searches of other databases, including those containing grey literature and government reports, could have provided a different perspective on OD practices in India. Included studies were also only written in English, and the article search did not include any Hindi journals or publications that could have further informed this systematic review. Additionally, only 13 of the 36 Indian states and territories were represented in the studies in this review. Future work should assess all Indian states and territories to understand the true impact of the SBM on OD practices.

5 Conclusion

While the SBM has improved access to latrines, this systematic review shows that India is yet to be completely ODF. Government reports overestimate the SBM's progress in eliminating OD, and there are substantive gaps in the literature that are not inclusive of all states in India. The studies included in this review show a lack of sanitation planning, adequate financial support, and awareness as major barriers to latrine use and eliminating OD.

Poor community involvement in SBM implementation, governmental mistrust, and a lack of knowledge about the risks associated with OD were additional barriers associated with higher rates of OD. This suggests that, in addition to providing clean, accessible, and affordable sanitation facilities, sanitation programming should also focus on involving communities in implementation to rebuild trust and encourage latrine use. A lack of public participation and poor maintenance led to poor toilet conditions, which in turn led to a lack of use by individuals. While studies showed modest increases in rates of toilet coverage following SBM implementation, toilets were often not appropriately used or maintained.

Behavior-change interventions among communities and government officials may be key to promoting both latrine coverage and use in India. High-level political support for sanitation programming, ambitious SDGs and disruptive leadership changed environments in districts, which led to mindset changes in district officials and contributed to changed behavior in support of the SBM. Setting targets and monitoring them is important to hold district leaders accountable for results. However, for more accurate comparisons among countries to achieve the SDGs, standardized definitions of waste containment, in addition to standard inspection techniques, are needed.

There is a need for research that looks beyond household-level drivers to understand the social-structural determinants of latrine uptake and long-term successful engagement with communities. Overarching strategies and approaches that have worked well across studies include high involvement of district leadership, pivotal role played by local government members and community motivators, innovative promotional methods and local campaigns, and the use of community incentives. In addition to improving infrastructure, providing educational, community-based services in conjunction with sanitation programming is necessary to encourage households to reduce OD as a sustainable, affordable, and culturally appropriate solution.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

AV: Conceptualization; Methodology; Formal Analysis; Investigation; Writing-original draft preparation; Visualization. LS: Conceptualization; Methodology; Formal Analysis; Investigation; Writing-original draft preparation; Visualization. RB: Formal Analysis; Investigation; Writing-Review and Editing; Visualization. SL: Formal Analysis; Investigation; Writing-Review and Editing; Visualization. AS: Investigation; Resources; Writing-Review and Editing; Supervision. MM: Conceptualization; Methodology; Formal Analysis; Investigation; Resources; Writing-Review and Editing; Visualization and Supervision. All authors read and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1141825/full#supplementary-material

References

Ackley, B. J., Swan, B. A., Ladwig, G., and Tucker, S. (2008). *Evidence-based nursing care guidelines: Medical-surgical interventions*. St. Louis, MO: Mosby Elsevier.

Alexander, K., Allton, C., Felsman, C., Hahn, M., Okegbe, T., Palmer, D., et al. (2016). *Ending open defecation in India: Insights on implementation and behavior change for Swachh Bharat Abhiyan*. New Jersey: Princeton University.

Andres, L. A., Deb, S., Joseph, G., Larenas, M. I., and Grabinsky Zabludovsky, J. (2020). *A multiple-arm, cluster-randomized impact evaluation of the Clean India (Swachh Bharat) Mission program in rural Punjab*. India: World Bank Policy Research Working Paper.

Anthonj, C., Setty, K. E., Ezbakhe, F., Manga, M., and Hoeser, C. (2020). A systematic review of water, sanitation and hygiene among Roma communities in Europe: Situation analysis, cultural context, and obstacles to improvement. *Int. J. Hyg. Environ. Health* 226, 113506. doi:10.1016/j.ijheh.2020.113506

Anuradha, R., Dutta, R., Raja, J. D., Lawrence, D., Timsi, J., and Sivaprakasam, P. (2017). Role of community in Swachh Bharat Mission. Their knowledge, attitude and practices of sanitary latrine usage in rural areas, Tamil Nadu. *Indian J. community Med. Official Publ. Indian Assoc. Prev. Soc. Med.* 42 (2), 107. doi:10.4103/0970-0218.205213

Beardsley, R., Cronk, R., Tracy, W., Fleming, L., Ng'ambi, M., Tidwell, J. B., et al. (2021). Factors associated with safe child feces disposal in Ethiopia, India, and Zambia. *Int. J. Hyg. Environ. health* 237, 113832. doi:10.1016/j.ijheh.2021.113832

Bhanot, A., Agarwal, V., Awasthi, A., and Sharma, A. (2017). "Making India open-defecation-free: Lessons from the swachh bharat mission–gramin process evaluation," in *Social marketing* (UK: Routledge).

Biswas, R., Arya, K., and Deshpande, S. (2020). More toilet infrastructures do not nullify open defecation: A perspective from squatter settlements in megacity Mumbai. *Appl. Water Sci.* 10 (4), 96–99. doi:10.1007/s13201-020-1169-4

Brownson, R. C., Fielding, J. E., and Maylahn, C. M. (2009). Evidence-based public health: A fundamental concept for public health practice. *Annu. Rev. Public Health* 30, 175–201. doi:10.1146/annurev.publhealth.031308.100134

Cairncross, S., Hunt, C., Boisson, S., Bostoen, K., Curtis, V., Fung, I. C., et al. (2010). Water, sanitation and hygiene for the prevention of diarrhoea. *Int. J. Epidemiol.* 39, i193–i205. doi:10.1093/ije/dyq035

Capone, D., Barker, T., Cumming, O., Flemister, A., Geason, R., Kim, E., et al. (2022). Persistent ascaris transmission is possible in urban areas even where sanitation coverage is high. *Environ. Sci. Technol.* 56 (22), 15969–15980. doi:10.1021/acs.est.2c04667

Caruso, B. A., Sclar, G. D., Routray, P., Nagel, C., Majorin, F., Sola, S., et al. (2022). Effect of a low-cost, behaviour-change intervention on latrine use and safe disposal of child faeces in rural Odisha, India: A cluster-randomised controlled trial. *Lancet Public Health* 6, e110–e121. doi:10.1016/s2542-5196(21)00324-7

Coffey, D., Gupta, A., Hathi, P., Spears, D., Srivastav, N., and Vyas, S. (2016). "Understanding open defecation in rural India: Untouchability, pollution, and latrine pits,". International Growth Center (IGC), reference no. F-35114-INC-2.

Coffey, D., Spears, D., and Hathi, P. (2020). Assessing high-profile public messaging for sanitation behaviour change: Evidence from a mobile phone survey in India. *Waterlines* 39 (4), 240–252. doi:10.3362/1756-3488.19-00011

Conaway, K., Lebu, S., Heilferty, K., Salzberg, A., and Manga, M. (2023). On-site sanitation system emptying practices and influential factors in asian low- and middle-income countries: A systematic review. *Hyg. Environ. Health Adv.* 6, 100050. doi:10.1016/j.heha.2023.100050

Curtis, V. (2019). Explaining the outcomes of the 'clean India' campaign: Institutional behaviour and sanitation transformation in India. *BMJ Glob. health* 4 (5), e001892. doi:10.1136/bmjgh-2019-001892

Das, P., and Crowley, J. (2018). Sanitation for all: A panglossian perspective? *J. Water, Sanitation Hyg. Dev.* 8 (4), 718–729. doi:10.2166/washdev.2018.011

Datta, A., Somani, A., Karmakar, N., and Nag, K. (2021). A study on knowledge and practices regarding swachh bharat mission among urban population of Agartala city, North East India. *Med. J. Dr. DY Patil Vidyapeeth* 14 (5), 529. doi:10.4103/mjdrdypu.mjdrdypu_65_20

Exum, N. G., Gorin, E. M., Sadhu, G., Khanna, A., and Schwab, K. J. (2020). Evaluating the declarations of open defecation free status under the swachh bharat ('Clean India') mission: Repeated cross-sectional surveys in Rajasthan, India. *BMJ Glob. Health* 5 (3), e002277. doi:10.1136/bmjgh-2019-002277

Friedrich, M., Balasundaram, T., Muralidharan, A., Raman, V. R., and Mosler, H. J. (2020). Increasing latrine use in rural Karnataka, India using the risks, attitudes, norms, abilities, and self-regulation approach: A cluster-randomized controlled trial. *Sci. Total Environ.* 707, 135366. doi:10.1016/j.scitotenv.2019.135366

Government of India (2018). Guidelines for swachh bharat mission. https://jalshakti-ddws.gov.in/sites/default/files/SBM(G)_Guidelines.pdf.

Government of India (2022). Swachh bharat mission: About SBM. https://swachhbharatmission.gov.in/sbmcms/index.htm.

Gupta, A., Khalid, N., Deshpande, D., Hathi, P., Kapur, A., Srivastav, N., et al. (2020). Revisiting open defecation evidence from a panel survey in rural North India, 2014–18. *Econ. Political Wkly.* 55 (21), 55–63.

Higgins, J. P. T., Savović, J., Page, M. J., Elbers, R. G., and Sterne, J. A. C. (2022). "Chapter 8: Assessing risk of bias in a randomized trial," in *Cochrane handbook for systematic reviews of interventions version 6.3* (Canada: Cochrane).

Hutton, G., Patil, S., Kumar, A., Osbert, N., and Odhiambo, F. (2020). Comparison of the costs and benefits of the clean India mission. *World Dev.* 134, 105052. doi:10.1016/j.worlddev.2020.105052

International Institute for Population Sciences (IIPS) and ICF (2017). National family health survey (NFHS-4), 2015-16: India. https://dhsprogram.com/pubs/pdf/FR339/FR339.pdf.

International Institute for Population Sciences (IIPS) and ICF (2021). National family health survey (NFHS-5), 2019-21: India. http://rchiips.org/nfhs/NFHS-5Reports/NFHS-5_INDIA_REPORT.pdf.

Jain, A., Wagner, A., Snell-Rood, C., and Ray, I. (2020). Understanding open defecation in the age of Swachh Bharat Abhiyan: Agency, accountability, and anger in rural Bihar. *Int. J. Environ. Res. public health* 17 (4), 1384. doi:10.3390/ijerph17041384

Jha, P. K., and Sharma, V. (2020). "On ground study of the ODF status of ghaziabad district, UP," in *Solid waste policies and strategies: Issues, challenges and case studies* (Singapore: Springer).

Kar, S., and Mistri, B. (2015). Practice of open defecation and its effect on human health in simlapal block, bankura, West Bengal. *J. Interacademia* 19 (3), 378–390.

Manga, M., Kolsky, P., Rosenboom, J. W., Ramalingam, S., Sriramajayam, L., Bartram, J., et al. (2022). Public health performance of sanitation technologies in Tamil Nadu, India: Initial perspectives based on *E. coli* release. *Int. J. Hyg. Environ. Health* 243, 113987. doi:10.1016/j.ijheh.2022.113987

Manga, M., Muoghalu, C. C., and Acheng, P. O. (2023). Inactivation of faecal pathogens during faecal sludge composting: a systematic review. *Environ. Technol. Rev.* 12 (1), 150–174. doi:10.1080/21622515.2023.2182719

Manga, M. (2017). *The feasibility of Co-composting as an upscale treatment method for faecal sludge in urban Africa*. Leeds, United Kingdom: School of Civil Engineering, University of Leeds. Available at: http://etheses.whiterose.ac.uk/16997/.

Mavila, A. D., and Francis, P. T. (2019). Impact of swachh bharat abhiyan on residents of cochin corporation. *Indian J. Community Med. Official Publ. Indian Assoc. Prev. Soc. Med.* 44, S19. doi:10.4103/ijcm.ijcm_24_19

Mohan, R. (2017). Swachh bharat mission (gramin): Bottlenecks and remedies. *Econ. political Wkly.* 52 (20), 1–5.

Muoghalu, C. C., Semiyaga, S., and Manga, M. (2023). Faecal sludge emptying in sub-saharan Africa, south and southeast Asia: A systematic review of emptying technology choices, challenges, and improvement initiatives. *Front. Environ. Sci.* 11, 158. doi:10.3389/fenvs.2023.1097716

Namdev, G., and Narkhede, V. (2020). Reasons of open defecation behavior in rural households of bhopal, Madhya Pradesh, India. *Natl. J. Community Med.* 11 (03), 103–106. doi:10.5455/njcm.20200116054019

Narayan, A. S., Maurer, M., and Lüthi, C. (2021). The clean plan: Analysing sanitation planning in India using the CWIS planning framework. *J. Water, Sanitation Hyg. Dev.* 11 (6), 1036–1047. doi:10.2166/washdev.2021.130

Njuguna, J. (2016). Effect of eliminating open defecation on diarrhoeal morbidity: An ecological study of nyando and nambale sub-counties, Kenya. *BMC public health* 15, 712. doi:10.1186/s12889-016-3421-2

Patwa, J., and Pandit, N. (2018). Open defecation-free India by 2019: How villages are progressing? *Indian J. community Med. official Publ. Indian Assoc. Prev. Soc. Med.* 43 (3), 246–247. doi:10.4103/ijcm.IJCM_83_18

Rengaraj, V., Simmon, A., Vikash, S., Zel, R., Adhikari, H., Sherpa, P., et al. (2021). "Addressing sanitation and health challenges in rural India through socio-technological interventions: A case study in Odisha," in 2021 IEEE 9th Region 10 Humanitarian Technology Conference (R10-HTC), Bangalore, 30 September 2021.

Saleem, M., Burdett, T., and Heaslip, V. (2019). Health and social impacts of open defecation on women: A systematic review. *BMC public health* 19 (1), 158. doi:10.1186/s12889-019-6423-z

Spears, D., and Coffey, D. (2019). Open defecation in rural India, 2015–16: Levels and trends in NFHS-4. *Econ. Political Wkly.* 53 (9).

Sprouse, L., Liles, A., Cronk, R., Bauza, V., Tidwell, J. B., and Manga, M. (2022). Interventions to address unsafe child feces disposal practices in the asia-pacific region: A systematic review. *H2Open J.* 5 (4), 583–602. doi:10.2166/h2oj.2022.137

Sterne, J. A., Hernán, M. A., Reeves, B. C., Savović, J., Berkman, N. D., Viswanathan, M., et al. (2016). ROBINS-I: A tool for assessing risk of bias in non-randomised studies of interventions. *BMJ Clin. Res. ed.)* 355, i4919. doi:10.1136/bmj.i4919

United Nations (UN) (2022). *Sdg 6: Ensure availability and sustainable management of water and sanitation for all.* New York: United Nations.

Vu, S., Jain, A., Harrison, C., Ghimire, P., and Graham, J. P. (2022). Someone should be there to take care of it": A case study of users' views of managed shared sanitation facilities in Jharkhand, India. *Am. J. Trop. Med. Hyg.* 106 (4), 1135–1140. doi:10.4269/ajtmh.21-0654

Vyas, S., Srivastav, N., Mary, D., Goel, N., Srinivasan, S., Tannirkulam, A., et al. (2019). Measuring open defecation in India using survey questions: Evidence from a randomised survey experiment. *BMJ open* 9 (9), e030152. doi:10.1136/bmjopen-2019-030152

WHO and UNICEF (2021). *Progress on household drinking water, sanitation, and hygiene: 2000-2020, five years into the SDGs.* Switzerland: WHO and UNICEF Joint Monitoring Programme.

Yogananth, N., and Bhatnagar, T. (2018). Prevalence of open defecation among households with toilets and associated factors in rural south India: An analytical cross-sectional study. *Trans. R. Soc. Trop. Med. Hyg.* 112 (7), 349–360. doi:10.1093/trstmh/try064

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