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Structured Approach for Comparison of Treatment Options for Nutrient-Recovery From Fecal Sludge

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The aim of this study is to present a structured approach for comparing possible nutrient-recovery fecal sludge (FS) treatment systems in order to support transparent decision-making. The approach uses a multi-dimensional sustainability assessment of treatment technologies for nutrient recovery from FS, using a typical case of Kampala City, Uganda. A synthesized list of 22 treatment technologies was prepared from literature. This list included wastewater treatment technologies, which could be adapted to treat fecal sludge, and established fecal sludge treatment technologies that are available or potentially applicable in Kampala. Based on the local situation, the list was reduced to eight possible options, which were carried forward into a multi-dimensional sustainability assessment that incorporated input of stakeholders. The technologies included in the final assessment were optimization of the existing system, lactic acid fermentation (LAF), composting, vermicomposting, Black-Soldier Fly (BSF) composting, ammonia treatment, alkaline stabilization and solar drying. Optimization of the existing system performed well against the set criteria and is a recommended short-term solution. This will require e.g., adding narrower screens to remove more trash from the incoming sludge and respecting storage times prior to selling the sludge. To maximize the agricultural value of the recovered product, while respecting the need for safe reuse, a combination of technologies becomes relevant; the use of a combination of BSF, and subsequent ammonia or alkaline treatment of the remaining organic fraction would allow for maximized safe nutrient recovery and can be the aim for long-term sanitation planning in Kampala. The results of this process provide supporting information for a discussion of trade-offs between stakeholder groups as part of a decision-making process within a larger planning context.

Keywords: sanitation, resource recovery, multi-criteria, sustainability assessment, decision-support, wastewater

INTRODUCTION

The world is facing increasing (Koottatep et al., 2005) pressures on both ecological and human environments. Excreta from 60% of the world's population is currently released into the environment untreated (WHO and UNICEF, 2017). In addition, climate change, rapid urbanization, and environmental degradation coupled with economic uncertainty is creating changing conditions that mean that the world cannot continue with business as usual. With this as a backdrop, meeting the targets set out in the Sustainable Development Goals (SDGs), including providing sanitation for all, demands that we reduce long-term dependency on non-renewable resources through the adoption of innovative and adaptive systems that promote recycling and reuse (Cross and Coombes, 2013). An example of this is the on-going paradigm shift (Larsen et al., 2009) to viewing human waste as a resource for the recovery of nutrients, water and energy. In addition to critical energy and water needs, the biogeochemical cycles for nitrogen (N) and phosphorous (P) are part of the critical planetary boundaries that define a safe operating space for humanity and which keeps Earth's environmental system processes in a hospitable balance (Steffen et al., 2015). Closing the loop on the resources found in human waste can therefore contribute to a sustainable future.

In 2015, the world's leaders agreed that a sustainable future includes the provision of safely managed sanitation services for all. However, urban service providers are far from achieving these goals. According to the WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene, 85% of fecal waste is safely managed in Europe and Northern America, while in Latin America the figure is 37% and in Sub-Saharan Africa <20% (WHO/UNICEF, 2019). Sewerage systems currently cover only a small fraction of urban populations (9.5%) in least developed countries (WHO/UNICEF, 2019) and the majority of cities lack fecal sludge (FS) treatment systems that can treat all FS produced from non-sewered systems (Peal et al., 2014). The Greater Kampala metropolitan area in Uganda is no exception; here 98% of the population rely on on-site sanitation and sewerage services serve only 1% of the population (Schoebitz et al., 2016). Rapid urbanization adds to the challenge of service provision as service providers struggle to keep up with growth rates. For example, the urbanization rate in Greater Kampala is over 5% per year, meaning that the city population will double by 2035 (United Nations, 2018). In order to reach the SDGs for safely managed sanitation in Kampala, there needs to be higher allocation of funds for fecal sludge treatment, given that even after implementation of the existing Kampala Sanitation Master Plan (2015) only 31% of Greater Kampala will be sewered by 2040. A recent study in Kampala found that annual per capita costs for the existing FS system are significantly less expensive than the sewage system (McConville et al., 2019). This means that nutrient-recovery technologies can feasibly be added to the FS management options in Kampala, while still keeping costs of treatment per capita lower than for sewage systems.

Rapidly changing urban areas without previously existing sanitation infrastructure also offer opportunities for redesigning and rethinking traditional structures for sanitation management. Expanding centralized sewerage systems to cover all urban inhabitants is expensive and in many cases impractical (McConville et al., 2019). Thus, demand is growing to develop innovative decentralized systems that protect public health and the environment, recover resource flows, and allow for rapid service expansion to underserved populations (Larsen et al., 2013). Many innovations focus on resource-recovery as a way to help offset costs, but also to create win-win scenarios between sanitation and other sustainability goals like clean energy, sustainable consumption and production, and food security. In contrast to conventional wastewater treatment, which solely focuses on removal of nutrients from wastewater, the systems under consideration in this study focus on recovery and reuse of nutrients as valuable products at the same time as they sanitize excreta for the removal of harmful pathogens. This can, for example, be achieved through conversion of waste to protein feed for livestock (Lalander et al., 2014), or agricultural fertilizers (Udert and Wächter, 2012). However, many current sanitation-planning practices do not consider the range of new treatment methods available. Urban sanitation planners need more knowledge regarding innovations and tools for structuring evaluation methods to determine the appropriateness of these innovations for their given context.

Addition of nutrients to agricultural fields, to replace what crops remove, is necessary to maintain soil fertility. Uganda, with its 80 kg/ha of annual nutrient losses, replaces only about 1–1.5 kg/ha of that with fertilizers (MAAIF, 2016). Prior to the recent commission of a phosphate fertilizer factory in the Tororo district, Uganda lacked fertilizer production and has been completely dependent on expensive fertilizer imports. In addition to the factory in Tororo, the National Fertilizer Policy (MAAIF, 2016), specifically mentions massive promotion of local production of fertilizers derived from organic residues as one important step to take to enhance fertilizer availability in Uganda. Recirculation of plant nutrients and organic matter from fecal sludge represents one possibility of local, organically derived fertilizer to avoid soil degradation and increase the affordability and accessibility of fertilizers to farmers.

It is widely recognized that there are several factors that determine if a sanitation system is appropriate and sustainable (Guest et al., 2009), and that these factors are context specific. Indeed, the Sustainable Sanitation Alliance defines a sustainable sanitation system as one that protects and promotes human health by providing a clean environment and breaking the cycle of disease, while at the same time being economically viable, socially acceptable, and technically and institutionally appropriate, while protecting the environment and the natural resource base. Accounting for this diversity of factors can be done using multi-criteria assessment techniques. These techniques can account for quantitative and qualitative assessments of system attributes and allow decision-makers to discuss trade-offs between different sustainability aspects when comparing alternative options (Mendoza and Martins, 2006).

The aim of this study is to present a structured approach for comparing possible nutrient-recovery FS treatment systems. The paper draws on experience with multi-criteria sustainability assessments and participatory planning processes, and links

it strongly to the need to provide information on resource recovery innovations to decision-makers. The specific objectives of this paper are to (i) provide more information regarding the potential of nutrient recovery technologies; and (ii) present a method that can help decision-makers select the most appropriate FS treatment system that can protect public health and the environment, recover resource flows, and do so in an adaptable way that allows for rapid service expansion to underserved populations. The approach uses a multi-dimensional sustainability assessment of treatment processes for nutrient recovery from FS. The approach is illustrated through application of the method in the case of Kampala, a city that relies on on-site sanitation services for over 90% of its population (Schoebitz et al., 2016). The approach is not a stand-alone tool, but should be fitted in the larger urban planning cycle.

METHODS

This paper proposes a structured approach for comparing treatment options for nutrient-recovery from fecal sludge from non-sewered systems. The approach includes a four-step process: (1) Identification of available options; (2) Narrowing the options based on locally identified prerequisites; (3) Multi-dimensional sustainability assessment of the remaining options; and (4) Stakeholder weighting and discussion of the results. The novelty of this approach is its focus on including more innovative nutrient-recovery options in the decision-making process. The basic principle behind this method is that it should start with a process that opens up the range of options to capture possibly interesting new innovations before narrowing down the possible options based on locally-specific criteria. This paper uses a case study approach to illustrate how the first three steps can be performed, while the final step should be done with actual stakeholders within a planning process. This method would be most effective when applied within an actual sanitation planning process in which key stakeholders are involved. Local input from stakeholders will be critical in steps two through four to assure that the decision-making process includes locally specific prerequisites and sustainability criteria. While the example presented in this paper was not embedded within a participatory planning process in Uganda, stakeholder input was solicited in step two as explained below.

Step 1 in this process is to create a large list of potential options. In this study we used the results of two recent reviews (Harder et al., 2019; Johannesdottir S. et al., 2019), which focused on nutrient-recovery from wastewater, to identify a range of potential treatment options. Note that the focus of this study is on treatment technologies for collected FS (e.g., from lined and unlined pit latrines and septic tanks), and not on the entire FS service chain. When creating this list, no judgement was taken on whether the options were locally feasible. This means that the initial list of technologies used in this study could be used as a starting point in any study aiming at nutrient recovery. However, since there is rapid development occurring in the sanitation sector, it is recommended that each new planning process review this starting list and update with emerging technologies. The identified treatment technologies were categorized based on types of treatment process, possible inputs and products recovered.

The following two steps in this methodology aim to narrow down the possible options for decision-making based on the local context. Step 2 applies a list of case-specific prerequisites to the initial list of possible options. This step essentially sets the system boundaries for the decision space. The prerequisites should be case specific, but not too limiting. Relevant prerequisites can be related to the incoming material to be treated, resource(s) to be recovered, or case specific limitations regarding placement, space or applicability to context. For example, a relevant prerequisite would be to specify that the system should enable recovery of nitrogen; however, the form of recovered nitrogen should not be specified at this point. This study uses four prerequisites: (1) the treatment technology should be able to handle raw FS; (2) it should recover a majority of the macro nutrients (N, P, K, and S) from the incoming waste stream; (3) it should have a technical readiness level (TRL) of 6 or higher, meaning that it has been tested in a relevant environment to Uganda; and (4) it should be possible to implement the technology at the existing FS treatment plant. Determination whether the treatment technologies met the prerequisites was based on information available in published literature and, in the case of the fourth prerequisite, on the expert judgement of the authors.

In Step 3, a multi-dimensional sustainability assessment takes place. Selection of the criteria to use should recognize the holistic nature of sustainability, but also be adapted to the local context. In order to ensure a holistic sustainability assessment of sanitation systems, several different criteria are often proposed for use in planning and decision-making processes (Hellström et al., 2000; Balkema et al., 2002; Lennartsson et al., 2009; Molinos-senante et al., 2014; Vidal, 2018). For example, Hellström et al. (2000) proposed assessing a system's sustainability by identifying and evaluating system performance against criteria within five main categories: (1) health and hygiene; (2) social-cultural; (3) environmental; (4) economic; and (5) functional and technical. This broader understanding of sustainability is also reflected in the definition of sustainable sanitation by the Sustainable Sanitation Alliance, mentioned above. In this study, we applied these five main categories as a starting point for the assessment: Health, Financial, Social, Technical and Institutional; however, social and technical were regrouped as socio-technical.

The criteria used in a decision-making process may differ between different contexts and should therefore be adapted to the local context. Several sanitation planning tools encourage stakeholder engagement on different levels to capture different sustainability perspectives (Lüthi et al., 2011; Parkinson et al., 2014). One example is the Open Wastewater Planning method, described in Bodík and Ridderstolpe (2007). On an overarching level it is considered that stakeholder engagement and participation in planning will lead to a better decision-making process where the selected technologies are better

adapted to the local context (Eawag, 2005). A study in Java concluded that consultative and collaborative participation process with the community in a community-based sanitation project increased the progress toward users' ownership of the technology (Roma and Jeffrey, 2010). In a recent interview study of sanitation professionals, the interviewees' emphasized the importance of gender-sensitive and community participation as critical for capturing sustainability issues in the decision-making process (Ramôa et al., 2018). Therefore, it is critical to involve local stakeholders in the selection of criteria to use in the multi-criteria assessment. Stakeholders should also be involved in Step 4, weighting and discussion of the results of Step 3 before final decision-making.

In this specific case, considering nutrient-recovery from a FS treatment plant in Uganda, the most important stakeholders to consult were professionals working with the treatment plant, research institutes and municipality representatives, rather than community members. In order to identify locally relevant criteria, a series of semi-structured interviews regarding important criteria that should be considered for treating FS with the intention to reuse it were held in 2017 and 2018, with representatives from five different municipalities in Metropolitan Kampala, the water and sanitation utility, one ministry, two research institutions and one NGO. Participants in these interviews generally held technical positions within their organization, including managers, engineers, agronomists and technicians. The interviews focused on general decision-making criteria related to on-site sanitation and reuse, with probing questions into specific categories of sustainability. This approach allowed the interviewees to identify by themselves the most important decision-making criteria (see the **Supplementary Material** for details of interview questions). The interviews were recorded and transcribed for post-interview analysis. The interviews were coded and categorized, i.e., grouping and labeling of similar aspects (Flick, 2009), in order to identify locally relevant criteria.

For the purposes of this article, we illustrate the first three steps by applying them in the context of selecting nutrient-recovery technologies for up-grading of a FS treatment plant in Kampala, Uganda. The population of the Greater Kampala metropolitan area is 3.2 million and the majority of the population is using on-site sanitation services. The Kampala Sanitation Master Plan (Government of Uganda/NWSC, 2015) estimates that 35% of the fecal sludge produced in the city is collected, transported, and delivered to the fecal sludge treatment plant (FSTP) at Lubigi. The Lubigi FSTP was commissioned in 2014 with a design capacity of 400 m^3/day, it consists of manual screening, and grit removal followed by covered settling/thickening tanks, covered drying beds and covered storage areas for dried sludge. The liquid effluent from the settling/thickening tanks is co-treated with wastewater in the WWTP at Lubigi, which consists of anaerobic and facultative ponds. The dried sludge is sold to farmers. There is evidence from observations and interviews with the FS treatment plant operators that the recommended storage times for the sludge are not respected, particularly prior to planting season.

RESULTS—ILLUSTRATION OF APPROACH

The results presented are for a hypothetical upgrade to improve nutrient-recovery at the Lubigi FS treatment plant in Kampala. Data collection was primarily based on literature reviews, supplemented with results from student experiments at the plant in 2018 and the research team's qualitative assessments in 2019. The student experiments tested the use of BSF composting, ammonia treatment and lime treatment. Their results provided details on costs, pathogen inactivation, organizational capacity and odor. Further details, including specific references used for scoring, can be found in the **Supplemental Material**.

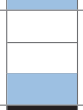
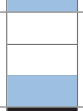
Step 1: Identification of Available Options

Two recent reviews of technologies for nutrient-recovery from domestic wastewater and human excreta provided the basis for developing a broad list of possible treatment options for this case (Harder et al., 2019; Johannesdottir S. L et al., 2019). A synthesized list was developed that includes 22 treatment technologies (**Table 1**). The list includes treatment technologies that can produce a recoverable nutrient product. Complementary technologies such as dewatering were not included at this stage, although they should be included when comparing specific options in step three. The technologies were summarized, including the primary nutrient product recovered and what types of fecal sludge inputs can be used, e.g., raw fecal sludge (TS 1–5%), dewatered fecal sludge (TS>15%), or the filtrate/supernatant water from the dewatering technology. Note, that it is also possible to combine some of these technologies in series, e.g., dewatered FS can be used in fly larvae composting while the filtrate/supernatant can be used in a membrane nutrient-extraction technology. Combinations of technologies are not included in this study.

Step 2: Narrowing the Possible Options

In Step 2, a set of prerequisites was used to narrow down the number of possible options. Determination of whether the treatment technologies met the prerequisites was based on information available in published literature (references provided in Table 2), with the exception of the fourth prerequisite that was based on the expert judgement of the authors. The first prerequisite was that the technology should be able to handle raw or dewatered sludge (there is a dewatering technology already at the existing plant). Based on published literature regarding these technologies, algae production, stripping & capture, and membrane nutrient extraction where deemed inappropriate for treating FS due to the high levels of suspended solids. These three treatment technologies were also deemed non-feasible at the existing plant. Incineration and carbonization technologies failed to meet the prerequisite for macro nutrient recovery since these treatments fully eliminate nitrogen and sulfur. It is noted that hydrothermal carbonization can retain ∼30–60% of the nitrogen in the hydrochar, depending on process temperature and feedstock (He et al., 2015; Wang et al., 2018). However, the high temperatures, high pressure and complex processing needed for this technology are not deemed feasible at Lubigi.

TABLE 1 | Summary of possible treatment technologies for nutrient-recovery from fecal sludge, based on recent review studies that map a variety of treatment processes and products (Harder et al., 2019; Johannesdottir S. et al., 2019).

	Treatment technology	Input	Description	Potential products
Physical	Storage		Prolonged storage, open or enclosed. Degradation of material. Give a stabilized sludge Pathogen reduction is a function of time, temperature, moisture, competition etc.	Stabilized sludge
	Desiccation		Treatment decreasing water content to an extent that the product becomes pseudo stable. Pathogen reduction is a function of low moisture content. Moisture content below 5% required for inactivation of persistent pathogens.	Pseudo stabilized sludge
Biological	Aerobic treatment		Collective name for a number of treatments using aerobic microorganisms to break down biodegradable matter e.g., can be part of wastewater treatment. For composting processes, see below.	Stabilized sludge
	Composting		Aerobic, auto thermal process in which biodegradable matter is decomposed by microorganisms, fungi, and invertebrates. Pathogen inactivation depend on thermophilic temperatures.	Stabilized compost
	Vermicomposting		Aerobic process in which earthworms and microorganisms degrade the organic matter. Worms may be harvested as animal feed. Requires dewatering of sludge or addition of co-substrates.	Stabilized compost, worms
	Fly larvae composting		Aerobic process in which fly larvae and microorganisms degrade the organic matter. Larvae may be harvested as animal feed. Requires dewatering of sludge or addition of organic matter.	Active compost, larvae
	Anaerobic treatment		Collective name to a number of processes in which microorganisms break down biodegradable matter in the absence of oxygen while producing biogas. Pathogen inactivation depend on process temperature dependent on heating.	Stabilized sludge, biogas
	Lactic acid fermentation		Biological, anaerobic process in which the sludge is inoculated with lactic acid bacteria and commonly also a co-substrate. Preserve a majority of the material in a pseudo stable form. Low pH and carboxylic acids are involved in pathogen inactivation.	Pseudo stabilized sludge
	Productive wetland		An artificial wetland or planted drying bed used to treat wastewater, and sludge and produce biomass. Biochemical processes at the plant interface remove pollutants.	Stabilized sludge, biomass (plants)
	Algae production		Cultivation of phototrophic algae in nutrient-rich wastewater flows.	biomass (algae)
	Aquaculture		Rearing of fish in ponds that are fertilized by effluent or sludge. The fish feed on algae and other small aquatic organisms that grow in the nutrient enriched water.	stabilized sludge, fish
	Microbial fuel cells		A bio-electrochemical device that uses microorganisms to convert chemical energy into electrical energy using oxidation-reduction reactions.	Sludge, nutrient solution
Chemical	Precipitation		Nutrient extraction from liquids by converting the substance into an insoluble form or by changing the composition of the solvent to diminish its solubility.	Inorganic precipitate
	Stripping and capture		The transfer of volatile components from a liquid to a gas stream. Can be re-capture in a solvent through e.g., wet scrubbing. E.g. Ammonia can be stripped from conventional wastewater.	Nutrient solution
	Elution		Extraction of nutrients from solid material by washing with an alkaline or acid solvent, e.g., extraction of P from ash. Elution is often followed by membrane separation, sorption or solvent extraction.	Nutrient solution

(Continued)

TABLE 1 | Continued

	Treatment technology	Input	Description	Potential products
	Ammonia treatment		Addition of ammonia, often as urea. Pathogen inactivation is due to ammonia (NH_3) and carbonates. Shall be a closed treatment to minimize ammonia losses.	Pseudo stabilized sludge
	Alkaline stabilization		Addition of highly alkaline chemicals, e.g., lime, caustic soda or ash to increase the pH. Pathogen inactivation depend on a pH over 12 or when using CaO a combination of alkaline pH and heat from the exoterm reaction.	Stabilized sludge
Thermal	Carbonization		Carbonization of organic solids at elevated temperatures in the absence of oxygen. Heat energy may be captured. Non-volatile nutrients remain in the biochar.	Biochar
	Incineration		Combustion of organic substances in the presence of oxygen. Heat energy may be captured while non-volatile nutrients remain in the ash.	Ash
	Pasteurization		Heating of sludge to 65–75°C in order to inactivate pathogens. Often used as a pre-treatment to anaerobic treatment for biogas production.	Pseudo stabilized sludge
	Solar drying		Use of solar radiation to dry and sanitize sludge. Can be done in open or closed beds. Closed beds have been shown to have a higher drying efficiency. Temperature, reduced moisture content and partially UV contribute to pathogen inactivation.	Pseudo stabilized sludge
Physio-chemical	Membrane nutrient extraction		Treatment processes using semi-permeable membranes for selective separation of nutrients from wastewater fractions.	Nutrient solution
	Sorption		Process in which one substance becomes attracted to another, e.g., the capture of nutrients in filter material (zeopeats, P-filters, etc.).	Nutrient-enriched sorbent material

Possible input flows considered in this study are fecal sludge (black), dewatered fecal sludge (brown), and the supernatant from the dewatering process (blue). Potential products are shown for each process with the exception of water recovery.

The remaining treatment technologies do not eliminate one or more of the in-coming macronutrients. Several treatment technologies were deemed to have an insufficient TRL to treat FS solids, due to lack of evidence of their implementation in a context similar to Kampala: aquaculture, microbial fuel cells, stripping & capture, membrane nutrient extraction and sorption (**Table 2**).

Finally, the prerequisite that nutrient-recovery technologies should be feasible to implement as an upgrade of the existing treatment plant led to the exclusion of several other technologies. The exclusion of technologies with this prerequisite was primarily due to the lack of land available at the existing site for expansion of treatment works, e.g., for aquaculture ponds or wetlands, or due to the technology requiring expensive modifications, e.g., construction of heating units for hydrothermal carbonization or thermal technologies. It should be noted that this last prerequisite means that some of the treatment options that are excluded in this step could be interesting for future FS treatment plants in Kampala.

As a result of Step 2, eight possible options were carried forward in to a multi-criteria assessment in step three: storage and desiccation (e.g., optimization of the existing system), composting, vermicomposting, Black-Soldier Fly (BSF) composting, lactic acid fermentation (LAF), ammonia treatment, alkaline stabilization, and solar drying. Optimization of the existing system includes adding narrower trash screens (5 mm) to remove more trash from the incoming sludge and respecting storage times of 6 months prior to selling the sludge. It was deemed that a composting technology for FS would require the additional carbon material to maintain the correct C:N balance, thus further evaluation of this option is based on the assumption that the FS is composted with e.g., organic solid waste. Vermicomposting and BSF composting would need to be performed after a dewatering step. Both would require construction of specialized compartments for batch treatments of FS with the worms/larvae. Lactic acid fermentation is performed in closed containers and would require a pumping system to recirculate the sludge for inoculation of new batches with lactic acid bacteria. Similar to LAF, ammonia treatment should be performed in sealed containers where the urea (a common fertilizer) is added to each batch of FS to be treated. Alkaline treatment in Kampala could be performed with the addition of lime, such as CaOH or CaO. Solar drying could be performed by enclosing the existing drying beds or storage areas to make them greenhouses.

Step 3: Multi-Dimensional Sustainability Assessment

Analysis of the interviews with local stakeholders revealed several sustainability criteria of importance for nutrient recycling from

TABLE 2 | Narrowing the decision space based on prerequisites specific to the Kampala context.

		Prerequisites				
	Treatment technology	**Feasible with FS**	**Recovers nutrients[a]**	**TRL >6[b]**	**Feasible at lubigi[c]**	**References**
Physical	Storage and desiccation (existing system)	X	X	X	X	WHO, 2006; Strande et al., 2014
Biological	Aerobic treatment	X	X	X		Strande et al., 2014
	Composting*	X	X	X	X	Strauss et al., 2003; Strande et al., 2014; Komakech et al., 2015
	Vermicomposting*	X	X	X	X	Strande et al., 2014; Komakech et al., 2015; Bhat et al., 2018
	Fly larvae composting*	X	X	X	X	Strande et al., 2014; Komakech et al., 2015
	Anaerobic treatment	X	X	X		Diener et al., 2014; Strande et al., 2014
	Lactic acid fermentation	X	X	X	X	Anderson et al., 2015; Andreev, 2017; Odey et al., 2018
	Productive wetland	X	X	X		Koottatep et al., 2005; Strande et al., 2014
	Algae production		X	X		Grobbelaar, 2004; Barbera et al., 2018
	Aquaculture	X	X			Strande et al., 2014
	Microbial fuel cells	X	X			Raheem et al., 2018; Lu et al., 2019; Palanisamy et al., 2019
Chemical	Precipitation	X	X	X		Shiba and Ntuli, 2017; Chapeyama et al., 2018; Tarragó et al., 2018; Li et al., 2019
	Stripping and capture		X			Harder et al., 2019
	Elution	X	x	x		Shiba and Ntuli, 2017; Harder et al., 2019
	Ammonia treatment	X	X	X	X	Méndez et al., 2002; Nordin, 2010; Strande et al., 2014
	Alkaline stabilization	X	X	X	X	Bina et al., 2004; Strande et al., 2014; Anderson et al., 2015; Farrell et al., 2017
Thermal	Carbonization	X		X	X	Strande et al., 2014; Harder et al., 2019
	Incineration*	X		X	X	Rulkens, 2008; Diener et al., 2014; Strande et al., 2014
	Pasteurization	X	X	X		Forbis-Stokes et al., 2016; Chapeyama et al., 2018; Septien et al., 2018
	Solar drying	X	X	X	X	Bennamoun, 2012; Strande et al., 2014; Singh et al., 2017
Physical-chemical	Membrane nutrient extraction		x			Harder et al., 2019
	Sorption	X	X			Strande et al., 2014; Harder et al., 2019

*Treatment technologies marked with * are feasible with FS if they have a pre-treatment step of dewatering and/or addition of organic matter (e.g., solid waste).*

[a]Recovers a majority of the macronutrients from the incoming waste stream.

[b]Technical Readiness Level (TRL) 6—System Adequacy Validated in in relevant environments, e.g., must have been tested in relevant environment to Uganda.

[c]By feasible at Lubigi, we mean that the process would be possible on the land available and that the treatment can be implemented without extensive & expensive infrastructure modification of the existing plant. NB: Some of the treatments that disappear in this step could be interesting for future FSTPs in Kampala.

FS, **Table 3**. For practical reasons not all of the stakeholder-identified criteria were included in the assessment. For example, "precision fertilizer" was one criteria not included in this analysis, since the variability in fecal sludge quality is high and production of precision fertilizers will either demand technologies that were eliminated in Step 2, or an upstream approach (e.g., source-separated sanitation systems) not considered in this paper. The request for high pH in the final product is covered in the criteria "agricultural value." The criteria finally used in Step 3 are shown in the right column of **Table 3**. In addition to the stakeholder-identified criteria, the right-hand column includes two criteria in italics pertaining to technology and institutional capacity, namely robustness and organizational capacity. The rationale for including organizational capacity is that without

TABLE 3 | Stakeholder-identified criteria and criteria used in the sustainability assessment.

Dimension	Stakeholder-identified criteria	Criteria used in the assessment
Health	The product must be safe to use in agriculture	Pathogen exposure
Financial	The treatment options should be cost-effective	Capital costs
		O&M costs
	The product must be competitive on the fertilizer market, have a nitrogen content, and be affordable to farmers	Agricultural value—including the product's content of nutrients, organic matter, and pH
Socio-technical	The product should have no odor	Odor—during treatment and the final product
	Concentrated fertilizer to minimize transportation costs	Volume reduction
		Robustness—how well the technology can withstand e.g., shock loads
	Reduced pollution of water sources	
Institutional		*Organizational capacity—complexity of the technology and its demands on skills etc.*
	Need of local regulation for safe reuse	
Recycled product	Important that it has changed appearance into an actual product	
	Precision fertilizers is important	
	High pH to counteract Uganda's acidic soils	Included in Agricultural value—high pH is preferred

NB: criteria in italics were not identified by stakeholders, but added due to their suggested importance from other studies.

an adequate capacity within a utility to operate and maintain a given treatment technology there is a high risk that the system in question will fail (Davis et al., 2019). Systems and technologies that are complicated to operate will demand a higher level of organizational capacity. The introduction of more complicated technologies can therefore be of crucial importance in settings where the organizational capacity is already limited. Furthermore, a system's technical robustness in terms of withstanding, for example shock loads etc., is another important criteria to include to ensure continuous and reliable operation of a treatment method (Andersson et al., 2016).

Each of the eight alternative systems identified in Step 2 was qualitatively evaluated against the eight sustainability criteria. Evaluation was based on data found in published literature, experience gained through student experiments at Lubigi, and expert knowledge within the project team. Full details of the scoring can be found in **Tables S1, S2**. The existing operations at the Lubigi FS treatment plant were used as a reference and the alternatives were scored on the degree to which they improved or reduced the quality of each sustainability attribute, e.g., the degree to which pathogen exposure was reduced compared to the existing operations. The results are shown in **Table 4**.

The most important sustainability criteria from a reuse perspective in this study is health. It is the criterion most often mentioned by the interviewees, e.g., that the product must be safe for reuse (**Table 3**). None of the studied technologies would negatively affect the health criterion of the fecal sludge, but there is a range in the degree to which they would reduce pathogen exposure in the end product. Ammonia treatment, alkaline stabilization and composting (provide that the composting process is thermophilic) provided the greatest reduction in pathogen exposure. If the existing system were to follow World Health Organization recommendations for storage time (WHO, 2006), or if the sludge was desiccated using solar drying the pathogen content of the reused sludge would also be reduced compared to today's system. However, it is judged that vermicomposting, BSF composting and LAF would not change the risk for pathogen exposure. This is due to that fact that these systems do not create thermophilic conditions or chemical inhibitors necessary to result in pathogen reduction. There have been some studies indicating that vermicomposting can reduce fecal coliforms (Rodríguez-Canché et al., 2010), however, since other studies contradict these finding (Monroy et al., 2009), we have chosen to conservatively score vermicomposting as no improvement in hygienic quality of the product. Further treatment of the end-product from these systems would be necessary for safe reuse. Note, the health risks for workers at the treatment plant will depend on how any of the possible technologies are implemented, e.g., how mixing of chemicals or compost is performed. Proper safety equipment and following operational safety standards will be necessary precautions for implementation of any potential technology upgrades.

All of the studied nutrient-recovery options have higher capital costs than the existing system. In particular, vermicomposting and BSF composting are considered to require higher capital investments due to the need for specialized compartments for growing the worms or larvae. Ammonia treatment, LAF and solar drying would also have higher capital costs due to the construction of sealed containers or drying areas to enable optimum treatment. The other systems can be implemented by modifying the existing infrastructure at relatively low costs. Concerning operation and maintenance, the majority of the reuse options are also more expensive to operate. This is particularly the case for alkaline treatment that would require the addition of large quantities of lime to be purchased (∼UD$600,000 per year). Urea treatment would also require significant chemical inputs amounting to ∼UD$90,000 per year. Inputs to other treatment technologies require less expensive additives (e.g., organic solid waste) or additional labor costs (e.g., maintenance of worm and larvae beds or mixing of compost/urea). The exception for O&M costs are the options to optimize the existing plant or solar drying which are judged to have comparable costs to today's system. The high capital investment costs for vermicomposting and composting may be offset somewhat through the higher value of the end product. The worms and larvae produced in these systems can be harvested as

TABLE 4 | Results of the multi-criteria assessment for improving safe, nutrient-recovery from Lubigi Fecal Sludge Treatment Plant, Kampala Uganda.

	Health	Financial			Institutional	Socio-technical		
	Pathogen exposure in end-product	**Capital costs**	**O&M costs**	**Value of product**	**Organizational capacity**	**Odor**	**Robustness**	**Volume reduction**
Current system	Significant coliform die-off. Ascarsis likely remains.	Annualized capital investment for FSTP USD$650,000	Annual O&M costs for FSTP USD$200,000	Contains ~4.6 g P and 23 g N per kg sludge.	Exists	Slightly septic smell	Roofs leak leading to irregular treatment	Total sludge volume reduced ca 85% from incoming sludge.
Optimized existing system	+	−	0	0	0	0	+	0
Composting	++	−	−	+	−−	+	−	+
Vermicomposting	0	−	−	++	−−	+	−−	+
Black soldier fly composting	0	−	−	++	−−	−	0	+
Lactic acid fermentation	+	−−	−	0	−−	−	−	0
Ammonia treatment	++	−−	−	+	−	−	+	0
Alkaline stabilization	++	−	−−	+	−	0	+	−
Solar drying	+	−	0	0	0	0	+	+

Basic information regarding the state of the existing plant is provided. Eight alternatives are qualitatively scored against the reference of the existing plant: Dark green (++) means considerable better, Light green (+) mean better, 0 means the same quality, Orange (–) means worse, Red (– –) means considerably worse. See ***Supplementary Information*** *for scoring cut-offs and details regarding evaluation of performance.*

a protein fodder, which has a higher market value than compost. In addition, both composted and ammonia treated FS would have a higher agronomical value than the current sludge due to the extra organic material and nitrogen content, respectively. Limed sludge is also seen as more valuable than today's product due to its low pH that would improve soil quality in Uganda's acid soils (see **Table 3**).

From an institutional perspective, the biological treatment options would require considerably more organizational capacity. Composting, vermicomposting, BSF composting and LAF require managing biological life cycles of treatment organisms that would require additional training of operators. In the case of composting, the logistics of obtaining clean amendment material for the compost are deemed potentially challenging. Ammonia and alkaline treatments both require additions of potentially hazardous chemicals, thus staff would require additional health and safety training to properly operate these systems. The other options could probably be implemented with existing capacity and are thus similar to today's system.

The results from the socio-technical criteria show a wider variation between potential technologies. Several technologies are judged to have worse odor problems than the existing system. The odors from BSF larvae, fermentation, and ammonia are often perceived as unpleasant. In contrast, the "earthy" smell from composting or vermicomposting is typically perceived as positive. However, since most of these recovered nutrient products are rather new, further studies are needed regarding consumer acceptance and sensitivity to odor and physical appearance of the product. Concerning robustness, the chemical treatments and the solar drying are generally less sensitive to changing environment or inappropriate use, and thus score better than the existing system. Fixing the leaking roofs in the existing system would also improve the robustness of the system. In contrast, the biological technologies are often less robust as the organisms are sensitive to changes in temperature or material composition. This is particularly the case for vermicomposting where maintaining the correct environment for the worms can be challenging. The opposite is true for BSF larvae that have shown to be quite resilient and adaptable to changing conditions and feedstock. Composting, vermicomposting, BSF composting, and solar drying reduce the sludge volume, which is advantageous for subsequent transport of the treated sludge to agriculture. With regard to volume, alkaline stabilization performs worse that the current system since the addition of lime can lead to bulking, in some cases doubling the volume (Bina et al., 2004).

Step 4: Stakeholder Weighting and Discussion of the Results

Step 3 generates an overview of the pros and cons of different treatment approaches, which has merit in itself since it may be possible to use the matrix for choice of treatment technology without further work. In other cases, e.g., for a first step in pre-feasibility studies, the results from Step 3 can be used

for narrowing down which technologies to further investigate. However, there may be times when the criteria identified in Step 3 will have different importance in different contexts. For example, when the recipient is a highly eutrophized lake it may be most important to decrease the release of N, P and organic matter to the recipient. In a setting with water scarcity, it may be most important to consider water consumption. The criteria may also be conflicting and trade-offs between meeting different criteria may be needed. In these cases, there may be a need to introduce a weighting of the identified criteria to show how weight on different criteria may change the outcome of Step 3. This introduction of weights to criteria is introducing subjectivity into the process and therefore it needs to be made in an explicit and transparent manner (Nardo et al., 2005). There are several different ways to assign weights to criteria. In sanitation planning processes it is common to have stakeholders assign weights to the identified criteria (Johannesdottir S. et al., 2019), e.g., by assigning percentage weights to different criteria. It is possible to assign weights when the criteria are defined in Step 3, in which case Step 4 starts in parallel with Step 3. Once the criteria are identified, the stakeholders are asked to put weights on them. It is recommended that the result matrix include both non-weighted and weighted results, to show the effect of weighting of different criteria on the results. It is further recommended to avoid the aggregation of the results, weighted or non-weighted, into a single score and ranking (even though several such methods exist). Rather it is recommended to use the result matrix to highlight each system's pros and cons to facilitate stakeholder discussion on trade-offs prior to decision-making. Important stakeholders to include in this process would be local decision-makers, technicians, engineers and other actors directly affected by the system, e.g., sanitation customers and users of end-products.

DISCUSSION

The aim of the structured process presented in this paper is to provide transparent supporting information for decision-making processes. Within a decision-making process the different criteria need to be weighed against each other in order to find the most acceptable solution given the necessary trade-offs and local constraints. Used in this way, the results can provide decision-making support for both short-term and long-term investments. For example, in the short-term organizational capacity and costs may prohibit implementation of systems that provide the best results regarding nutrient recovery. However, for long-term planning these options may be more relevant and can be linked to citywide sanitation master plans and policy.

Concerning technology selection at the FS treatment plant at Lubigi, Kampala, this structured approach identified several recommendations, depending on how the criteria are weighted. The stakeholders in this study assessed safe reuse (pathogen exposure) as the most important criterion. The most effective solution for reducing pathogen exposure at the lowest cost and with the least need for organization capacity development is to optimize the existing system. This would using narrower screens than today to remove trash and respecting storage times. To assure safe reuse, this option may be complemented with guidelines to farmers regarding proper handling measures for treated fecal sludge and recommendations for crop use. Such guidelines can be developed from World Health Organization for safe reuse of wastewater, excreta and greywater (WHO, 2006) and integrated into Ugandan agricultural extension services. This option is perhaps the most realistic from a short-term perceptive. However, such an improvement of the existing system will not maximize the agricultural value of the product.

To maximize the agricultural value of the recovered product, while respecting the need for safe reuse, a combination of technologies is relevant. Vermicomposting and BSF are the treatment options with the highest increase in value of product since they produce a valuable form of protein and an organic compost that can be used as a soil amendment. Of these two options, the BSF treatment is considerably more robust. However, neither of them is proven to reduce pathogen exposure risks. Lactic acid fermentation, ammonia treatment and alkaline treatment are the options that are assessed as reducing pathogen exposure most efficiently of the studied options. However, LAF is associated with high investment costs and higher need for organizational capacity, which makes it less appealing. Therefore, for maximum reduction of pathogen exposure and maximum nutrient reuse a combination of BSF and subsequent ammonia or alkaline treatment of the remaining organic fraction can be applied. This would mean increased investment costs and an increased demand on organizational capacity, but with unchanged or improved robustness. This combination of technologies can be the aim for long-term sanitation planning in Kampala with a focus on safe nutrient-recovery. With a long-term perspective, it is possible to develop the necessary organizational capacity and plan for financing structures.

The structured approach for comparison of FS treatment options proposed in this paper makes the decision-making process transparent and assures that a variety of possible options are evaluated, hopefully assuring the selection of the most appropriate technologies for a given context. The multi-dimensional sustainability assessment can clearly show the advantages and disadvantages of different options. The results of this process provide important supporting information for a discussion of trade-offs between various stakeholder groups (e.g., between utilities and politicians); a discussion which should be a critical part of the broader process of sanitation planning. The approach needs to be fitted into an actual sanitation planning process in which key stakeholders are involved. Local input from stakeholders is critical to assure that the decision-making process includes locally specific prerequisites and sustainability criteria.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

AUTHOR CONTRIBUTIONS

JM conceived the study, conducted the literature reviews, analysis, and coordinated the writing of this manuscript. EK assisted with structuring the multi-criteria assessment and contributed to the writing of the manuscript. AN, HJ, and CN were involved in the review of the results and proofreading of the manuscript.

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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.2020.00036/full#supplementary-material

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