frontiers | Frontiers in Sustainable Cities

TYPE Original Research
PUBLISHED 14 March 2025
DOI 10.3389/frsc.2025.1449868

OPEN ACCESS

EDITED BY
Nitin Goyal,
Central University of Haryana, India

REVIEWED BY
Mehdi Gheisari,
Islamic Azad University, Iran
Sunday Olutayo Fakunle,
Redeemer's University, Nigeria

*CORRESPONDENCE
Vincent Siwawa
✉ vincentsiwawa@gmail.com

RECEIVED 16 June 2024
ACCEPTED 10 February 2025
PUBLISHED 14 March 2025

CITATION
Siwawa V (2025) Assessing waste management performance in smart cities through the 'Zero Waste Index': case of African Waste Reclaimers Organisation, Johannesburg, South Africa.
Front. Sustain. Cities 7:1449868.
doi: 10.3389/frsc.2025.1449868

Assessing waste management performance in smart cities through the 'Zero Waste Index': case of African Waste Reclaimers Organisation, Johannesburg, South Africa

Vincent Siwawa*

Emancipatory Futures Studies (EFS) Programme, University of Witwatersrand, Braamfontein, South Africa

The study investigates waste management performance in Johannesburg, South Africa, focusing on the African Waste Reclaimers Organisation (ARO) within the smart city framework and using the 'Zero Waste Index.' Addressing the challenges of waste management in the Global South, this study evaluates ARO's strategies and the impact of digital technologies on waste diversion practices. A mixed-methods approach was employed, incorporating quantitative data from ARO's annual and monthly waste category records (received via email in 2022) and qualitative insights gathered through direct involvement and participation in the BanQu Project and municipal databases. Data sources were selected based on relevance, reliability, and availability of comprehensive waste management statistics. Key stakeholders, including waste pickers, policymakers, and community members, were considered through documented records from ARO's waste management programs, municipal and government reports. The study found that approximately 9.21% of Johannesburg's total waste is diverted from landfills, with a 'Zero Waste Index' of 0.34, indicating that 33.82% of resources are reclaimed. Analysis of resource substitution values for various waste categories demonstrated the significant contributions of waste reclaimers to material substitution and environmental conservation. The study reveals that digital technologies, such as ICT-enabled platforms and blockchain, play a crucial role in optimising waste diversion practices. These technologies facilitate real-time monitoring, data collection, and transparent transactions, enhancing the efficiency of waste reclaimers and contributing to improved environmental outcomes. Additionally, the research emphasises the importance of integrating informal waste pickers into formal waste management systems to maximise resource recovery and sustainability, recommending innovative policies, public awareness campaigns, and collaborative efforts among stakeholders to achieve zero-waste goals. Johannesburg's commitment to comprehensive waste management strategies, evident in its 'Zero Waste Index,' positions waste reclaimers as leaders in urban sustainability and environmental responsibility, setting a benchmark for other cities aiming for zero-waste objectives.

KEYWORDS

zero waste, circular economy, recycling, waste reclaimers, digital platforms and blockchain technology

1 Introduction and background

Modern cities in the Global South are characterised by climate change crises, deficiencies in service delivery (specifically pertaining to water, sanitation, and waste management), continual urbanisation, and poverty, all of which contribute to a society marked by fragmentation and disconnection (Mata, 2018). The solid waste management (SWM) framework in many South African urban areas primarily involves waste disposal through landfills and outdated end-of-pipe treatment practices. According to the Department of Environmental Affairs (2018), an estimated 90% of the total waste generated in South Africa finds its way to landfills and illegal dumpsites, with only 10% undergoing recycling. This concerning scenario, marked by low levels of recycling, recovery, and reuse in South African cities, prompted the initiation of separation at source programs by 2016. The goal was to "divert 25% of recyclables from landfill sites for reuse, recycling, or recovery" (Godfrey, 2021). However, municipalities fell short of achieving this objective, as those implementing separation at source programs targeted specific suburbs, leaving substantial portions of the municipality boundaries unaddressed (Godfrey, 2021; Godfrey and Oelofse, 2017).

The Second South Africa Environment Outlook Report identified two significant challenges faced by the SWM sector, including a "limited understanding of the main waste flows" and the absence of a recycling infrastructure facilitating waste separation at sources and diverting waste streams to material recovery and buyback facilities (Department of Environmental Affairs, 2018). Additionally, there is a lack of accessible and reliable data on material flows and network dynamics in both formal and informal waste management systems, such as those involving waste pickers (Govender, 2017). The inefficiencies stemming from outdated infrastructures and technologies in the current SWM regime have led to suboptimal recycling levels, prompting a need to enhance material flow and urban symbiosis in South African cities.

According to the Waste Management Strategy 2020, approximately 55 million tonnes of general waste are generated in South Africa, with only 11% diverted from landfills (Department of Environment Forestry and Fisheries, 2020). The increasing urbanisation and consumption in South African cities, coupled with the absence of mandatory and punitive waste reduction measures, are anticipated to escalate municipal solid waste (MSW) generation. Consequently, substantial efforts will be necessary to mitigate the increase in MSW waste generation through waste minimisation strategies, such as diverting waste from landfills to preserve diminishing landfill airspace for municipalities (Greencape, 2021). Additionally, numerous municipalities in South Africa are confronting a shortage of landfill space and are facing the challenge of ensuring compliance with decommissioned landfills, which incurs significant costs. The ramifications of the crisis witnessed in contemporary cities amplify this bleak perspective and underscore the growing enthusiasm for formulating novel city paradigms that offer alternative resolutions to address these challenges.

Embedded within South Africa's comprehensive waste management framework, the 2020 National Waste Management Strategy lays out a strategic roadmap (Thobejane, 2022). Aligned with a zero-waste approach, Target 1 within this framework sets forth ambitious goals, aiming to divert 40% of waste from landfills within a 5-year period, escalating to 55% within 10 years, and achieving a minimum of 70% within 15 years. This concerted effort not only reflects the commitment to sustainable waste management practices but also underscores the nation's dedication to the overarching goal of Zero-Waste to landfill, with a forward-looking perspective extending beyond the year 2035. In South Africa, municipalities have embraced the zero-waste paradigm as an environmentally sustainable alternative for municipal solid waste (MSW), driven by the shortcomings and environmental ramifications associated with landfill and incineration solutions.

The zero-waste concept is defined as a framework that promotes sustainable production and consumption, emphasises optimal recycling and resource recovery, and discourages mass incineration and landfill practices (Zaman, 2014). At the core of resource recovery and recycling efforts are the activities of informal waste pickers, also known as waste reclaimers. These individuals play a crucial role in diminishing the volume of waste in municipal landfills, salvaging discarded materials, and reintegrating waste into value chains to benefit the environment and public health (Gerdes and Gunsilius, 2010). Despite their significant contributions to recycling and environmental enhancement, there is an absence of research focusing on their performance towards the zero-waste goal. This research explicitly links to the Sustainable Development Goals (SDGs), specifically SDG-6, which targets clean water and sanitation, and SDG-11, which focuses on sustainable cities and communities. It contributes to these goals by promoting sustainable waste management practices that improve water conservation and urban resilience. Additionally, the integration of information and communication technology (ICT) and blockchain technologies enhances waste diversion and resource recovery, addressing significant urban challenges like landfill overdependence and environmental pollution.

Given this context, in collaboration with waste reclaimers, South African cities have implemented ICT-enabled solutions and digital platforms for tracking waste collection, monitoring household waste generation, controlling environmental pollution, assessing waste diversion rates from landfills, and generating data for future waste management models. This initiative aims to enhance the efficiency of resource cycling, promote reuse, and facilitate substitution, thereby contributing to the achievement of zero-waste objectives (Alverti et al., 2016). Digital platforms, enabled by information and communication technology (ICT) and built upon blockchain technology, facilitate real-time payment transactions for recyclable materials and implement reward systems for households and waste reclaimers (Rybnytska et al., 2018). Blockchain technology ensures the permanent recording and secure documentation of each transaction in a transparent and immutable ledger that is accessible to all participants in the recycling value chain. In the realm of blockchain technology, data are decentralised, making them accessible to everyone involved in the transactional network.

The integration of the Internet of Things (IoT), blockchain technology, and ICT infrastructure has disrupted traditional waste management systems, providing an inclusive solution for all stakeholders along the recycling value chain in smart cities and thereby contributing to the attainment of zero-waste goals. Against this background, this study seeks to assess the impact of digital technologies on waste diversion and environmental performance, specifically investigating their role in optimising waste diversion practices to decrease landfill usage and enhance overall environmental performance as part of the pursuit of zero waste objectives. The overarching research question guiding this investigation is as follows: To what extent do digital technologies contribute to the enhancement of waste diversion practices, resulting in reduced landfill usage and improved environmental performance within the framework of zero waste goals? The paper begins with an overview of the objectives and methodology, followed by a detailed presentation of the results, which includes comparisons with other global cities like San Francisco and Adelaide. The discussion section interprets these results in the context of urban sustainability and the role of waste reclaimers, while the conclusion summarises the implications of the research and offers recommendations for future studies.

2 Zero waste framework in solid waste management

In contemporary cities, waste is conceptualised as a raw material that requires deliberate reuse, recycling, and composting efforts, ultimately leading to the realisation of an ideal smart city with minimal residual waste (Anagnostopoulos et al., 2017). Transitioning into zero-waste cities, as articulated by Esmaeilian et al. (2018), necessitates a multifaceted approach involving waste prevention, effective waste collection, and the subsequent recovery of value from collected waste. Additionally, the augmentation of the zero-waste concept in cities involves addressing the management of waste reclaimers, implementing improved legislation, and extending producer responsibilities, as identified by Rybova and Slavik (2016) and Al-Khatib et al. (2010). Phillips et al. (2011) articulated the zero-waste objective as a comprehensive approach to succinctly outline targets aimed at minimising the environmental impact of waste. This visionary goal seeks to proactively prevent the generation of garbage, conserve valuable resources, and restore the material's intrinsic value.

Guided by the principles of the zero-waste framework, waste management seeks to curtail further depletion of global resources, mandating sustainable consumption and strategic waste management systems founded on waste avoidance, material efficiency, and resource recovery (Lehmann, 2010). Cities globally, including Adelaide, San Francisco, Vancouver, Johannesburg, Cape Town, and Ethekwini, have embraced zero waste goals within their waste management strategies. This adoption stems from the belief that zero waste stimulates sustainable production and consumption, optimises recycling and resource recovery, and minimises reliance on mass incineration and landfilling. San Francisco's Department of the Environment defines zero waste as the ambition to "send nothing to landfill or incineration" (Zaman, 2014).

Linked to the zero-waste framework, the circular economy seeks to transition from the traditional linear model of extraction and dumping, underscoring the importance of product, component, and material reuse, remanufacturing, refurbishment, repair, and upgrading throughout the product value chain and life cycle (Korhonen et al., 2018). This framework extends beyond optimal recycling or resource recovery, necessitating the elimination of unnecessary waste creation through innovative product design. Circular economy principles prioritise waste avoidance and reduction, highlighting the need for inventive product design and, subsequently, recycling, composting, or waste-to-energy technologies and innovative human strategies (City of Austin, 2018; Zaman and Lehmann, 2013). Despite the universal acceptance of the zero-waste concept, its interpretation and application vary across cities, resulting in diverse outcomes.

Some studies assert the achievement of the zero waste goal through information and communication technology (ICT), such as the Internet of Things (IoT) and Intelligent Waste Systems, while others emphasise human-centric initiatives, including the involvement of animals in waste management, deterrent policies for landfill disposal, and incentives for an effective informal waste reclaimer system. The proposed integrated framework for the zero-waste concept in smart cities comprises three interconnected elements, as outlined by Esmaeilian et al. (2018). This framework includes technology and infrastructure for product lifecycle data collection, facilitating real-time waste separation, collection, and waste generation reduction. Additionally, the zero-waste concept envisions recyclable waste as a raw material for remanufacturing industries, and the current research focuses on integrating waste reclaimers into ICT-enabled waste management systems to enhance efficiency in waste reduction, recovery, and separation.

3 Role of Waste Reclaimers in ero waste

Scheinberg (2011, p. 48) characterised informal waste reclaimers as individuals or entities engaged in private sector recycling and waste management activities that lack sponsorship, financial support, formal acknowledgement, support, organisation, or recognition from formal solid waste authorities. Alternatively, they may operate in contravention or competition with these formal authorities. Wilson et al. (2006) delve into the pivotal yet often overlooked role played by informal waste pickers, particularly in communities that are not yet technologically advanced, where they form the backbone of recycling initiatives and supply raw materials to industries.

Positioned at the lower echelons of the secondary materials supply chain (Wilson et al., 2006), waste reclaimers extract recyclables from household bins, street bins, communal kerbsides, open spaces, and landfill sites. These recovered materials are then transported to local industries or exported globally. Waste reclaimers typically trade their materials at buy-back centres or informal small-scale shops, which, in turn, supply larger centres or directly sell to waste recyclers. This informal value chain involves various intermediaries who directly engage with waste reclaimers, selling materials to buy-back centres or waste recyclers that aggregate the materials for sale to industries. However, this hierarchical structure diminishes the bargaining power of waste reclaimers during material sales, resulting in lower remuneration due to limited technologies for aggregating their recyclable materials.

Waste management poses a global challenge due to its significant environmental repercussions and the substantial expenses associated with waste collection services in developing nations (Le Courtois, 2012). Despite the elevated costs and inefficiencies in collection services, municipal authorities encounter difficulties in coordinating diverse stakeholders involved in waste management and recycling endeavours. Nowakowski (2017) emphasises the indispensability of collecting recyclable waste from households to buy-back centres and other recycling facilities for the success of waste recovery initiatives in the context of a zero-waste smart city. In many developing countries, the primary responsibility for collecting recyclable materials lies in informal waste reclaimers (Wilson et al., 2006). While waste reclaimers play a crucial role in resource recycling and waste collection initiatives, their working conditions and status are threatened by social, health, and environmental challenges (Ardi and Leisten, 2016). Consequently, waste reclaimer recyclable collection through ICT-enabled technologies and the Internet of Things (IoTs) has emerged as a fitting solution for fostering inclusive zero-waste smart cities and sustainable resource recycling.

Several studies have investigated the volume of recyclable waste gathered by waste reclaimers, as evidenced by research conducted by Godfrey (2021), Godfrey et al. (2016). However, akin to the challenges faced in other developing nations, the availability of traceable and accurate waste data regarding the specific contributions of informal waste reclaimers remains limited in South Africa, as highlighted by Godfrey and Nahman (2007). In the present study conducted by Godfrey (2021), South African waste data pertaining to paper and packaging recyclable tonnages collected in 2012 and 2017 were sourced from industry reports(BMi Research, 2012; PETCO, 2016). While data on waste collected by informal waste reclaimers in South Africa are limited, Godfrey (2021, p. 3) contends that "none of the Producer Responsibility Organisations (PROs) was able to provide accurate figures on the percentage of paper and packaging collected by informal waste reclaimers." Plastic SA (2012) reported that waste reclaimers in the informal sector play a pivotal role in the increased collection of recyclable plastic waste, increasing from an estimated 58% in 2012 to 74% in 2017. Notably, the collection of PET plastic by waste reclaimers is particularly pronounced due to its higher market value. It is crucial to acknowledge, however, that these data rely on extrapolation, introducing uncertainties that impact the precision of the actual quantity of recyclable waste amassed by waste reclaimers.

In informal collection systems, both collectors and traders typically lack the practice of maintaining statistics or records regarding their recyclable trade. Their record-keeping is often limited to a simple cashbook documenting purchases and sales to monitor profit changes. This practice results in a dearth of accurate statistical data for China's recycling industry. Researchers and policymakers are compelled to draw conclusions about recycling industry development through estimation due to the absence of precise data. The presence of inaccurate data creates obstacles for waste management policy and circular economy industry development planning. From the government's standpoint, the difficulty in obtaining accurate data hampers policy planning, relegating recycling to an invisible industry within the city. On a business level, inaccurate data render informal collection operations cumbersome and may even lead to their classification being illegal. Informal collection entities face challenges in applying for government subsidies and tax refunds.

In contrast, with the implementation of an intelligent collection system, information and communication technologies (ICTs) play a crucial role in identifying, communicating, and storing various pertinent data. First, the system can pinpoint the location and track the logistic routes of recyclables. Second, the data generated are accurate, traceable, and instantaneous. The intelligent collection system meticulously records all information about recyclables from the moment they are handed over to collectors. The server, in turn, can furnish a comprehensive statistical record of the recyclables collected at any given moment.

4 Digital platforms in the zero waste framework

The shift toward a zero-waste goal is now a strategic focus for municipalities worldwide. Zero waste is regarded as a viable alternative to the linear economy (take–make–waste), operating on the principles of regeneration by keeping materials in use, minimising waste, and reducing pollution (Chauhan et al., 2021). Consequently, scholars posit that the essential aspect of transitioning to zero waste is closely intertwined with the process of digitalisation transformation (Ajwani-Ramchandani et al., 2021). This transformation encompasses the effective utilisation of technologies such as big data, artificial intelligence (AI), blockchain, the Internet of Things (IoT), and cloud computing. There is a consensus among academics that the adoption of zero waste is undeniably linked to digitalisation, as it enables predictive analytics, tracking, and monitoring throughout the product life cycle for organisations (Chauhan et al., 2021).

Numerous studies in the existing body of literature have characterised digitalisation as a catalyst for the transition to zero waste for various reasons. Notably, these digital technologies have the capacity to translate theoretical zero-waste principles into practical and achievable activities (Antikainen et al., 2018; Garcia-Muiña et al., 2018; Blömeke et al., 2020). Specifically, within the realm of zero waste, the application of emerging technologies yields quantifiable benefits. These technologies can complement the skills and capabilities of workers, aiding them in making operational decisions aligned with zero waste (Mboli et al., 2022). Designing for zero waste, guided by data-driven insights, can enhance the economic and environmental sustainability of products by optimising resource utilisation (Garcia-Muiña et al., 2019). Products, their subcomponents, and associated processes can be designed and refined using zero waste principles through the application of predictive and prescriptive machine learning insights (Bressanelli et al., 2018). Historical and real-time data can be used to forecast demand and manage inventory, thereby minimising waste and promoting sustainable operations. Digital technologies also contribute to waste reduction by evaluating optimal practices for remanufacturing and recycling (Wilts et al., 2021).

Simultaneously, advancements in technology, notably within the context of the Fourth Industrial Revolution, are facilitating the emergence of a zero-waste goal. Specifically, blockchain technology has been recognised as a crucial facilitator in addressing challenges associated with transitioning to a circular economy (Kouhizadeh et al., 2019). The establishment of digital networks for transparently disseminating information about materials and supply chains has the potential to enhance circular resource flows, reduce waste, and create an improved database for decision-making in pursuit of a circular economy (ibid.). However, contemporary blockchain technologies face criticism for their high energy consumption, prompting discussions about whether the drawbacks outweigh the promised advantages (Zheng et al., 2018).

The utilisation of blockchain technology in the context of the circular economy intersects with two major trends: digitalisation and sustainability. This intersection represents a nascent field, both in research and practice, with the aim of designing and employing technology to drive a sustainable transformation of the linear economic paradigm. A critical system condition in this context involves establishing an infrastructure for information sharing and platforms for collaboration. This infrastructure is essential for a circular economy, as shared and transparent information forms the foundation for constructing diverse resource and material flows (Derigent and Thomas, 2016). Blockchain technology could serve as this information technology infrastructure. By creating a shared information infrastructure on a blockchain, the technology can facilitate the circular sourcing of renewable inputs, promote resource efficiency, and contribute to the recovery of materials, particularly in refurbishing and recycling processes carried out by manufacturers and consumers. This is achieved through the tracking of material and resource flows across various supply chains and consumption stages.

In the foreseeable future, digital waste management platforms hold more promise in two distinct areas. First, it serves as a complement to the formal municipal solid waste (MSW) collection system, providing a service for separating waste sources. For instance, in China, where the President emphasises waste source separation and reduction on numerous occasions, the Chinese government has introduced the "Implementation Scheme of MSW Separation System," mandating that 46 pilot cities achieve a 35% recycling rate by Xue et al. (2019). Local governments were expected to invest more effort and resources into this initiative. Several prominent digital waste management companies are exploring collaborations with local MSW collection systems to enhance waste separation and achieve reduction targets.

Second, digital waste management platforms can sync with the extended producer responsibility (EPR) framework to establish an exclusive collection system for special or high-resource-value waste, such as waste electrical and electronic equipment (WEEE). The recently unveiled China EPR working plan outlines trials for the EPR framework in four product categories: electronic and electrical products, vehicles, lead-acid batteries, and paper-based beverage packages (Xue et al., 2019; Wu et al., 2022). A digital waste management platform for lead-acid batteries has been tested within the EPR framework in Shanghai (Wu et al., 2022). Moreover, China has initiated 49 national urban mining pilots, and many WEEE recycling plants face supply shortages because the informal sector collects the majority and trades with illegal plants for higher prices (Chi et al., 2014). The integration of digital waste management platforms with EPR provides a potential solution for the recycling of high-resource-value wastes and urban mining towards the zero-waste goal.

5 Materials and methods

Research on the practice-based built environment encompasses modes such as case-based, evidence-based, and performance-based methods (Lee, 2011). This study employs a mixed-methods approach to analyse waste management practices in Johannesburg, South Africa, focusing on the contributions of informal waste pickers affiliated with the African Waste Reclaimers Organisation (ARO). The study incorporated both primary and secondary data sources to ensure a comprehensive understanding of the research context. Secondary data were drawn from existing materials, notably the African Waste Reclaimers Organisation (ARO) annual reports, which provided quantitative data on waste management performance. These reports were classified as secondary sources, given their pre-processed nature. Secondary data collection involved a systematic review of ARO's annual reports, while secondary data were sourced from peer-reviewed literature, government reports, and life cycle analysis databases, including studies like Godfrey (2021) that quantify the impact of waste reclaimers.

A purposive sampling strategy was adopted to select participants directly associated with ARO and the waste management sector. This approach ensured that participants possessed relevant knowledge and experiences. The study utilised an interview guide, detailed in Appendix A, to facilitate structured discussions around challenges and opportunities faced by waste pickers. Interviews were conducted in person, recorded with informed consent, and transcribed verbatim for subsequent analysis. The transcribed interview data were analysed using thematic analysis, a robust qualitative method for identifying and interpreting patterns within data. Key themes were systematically coded and categorized, revealing insights into the challenges and opportunities encountered by waste pickers. To bolster the validity of the study's findings, triangulation was employed. Interview transcripts were systematically compared with data from ARO's reports, ensuring consistency and corroboration. Additionally, the inclusion of the interview guide and questionnaire in Appendix A enhances transparency and facilitates reproducibility, addressing concerns about methodological rigor. This approach enabled a nuanced understanding of their experiences and aligned with the study's zero-waste framework objectives. Themes identified during analysis were cross-referenced with findings from secondary data sources to enhance the validity and reliability of interpretations. These procedures align with ethical research standards and support the credibility of the findings.

The study also examined the BanQu project, which integrates informal waste pickers into formal waste management systems through a software platform that enhances supply chain management. Key stakeholders included representatives from BanQu, local government, and corporate partners like Coca-Cola and Unilever, supporting over 1,400 registered waste pickers. Data analysis combined quantitative methods, determining that approximately 9.21% of Johannesburg's waste is diverted from landfills, with qualitative thematic analysis identifying challenges and opportunities faced by waste pickers. This comprehensive approach highlights the critical role of informal waste pickers in urban sustainability and the effectiveness of integrating them into formal waste management systems. Subsequently, the proposed zero waste index was analysed to assess the performance of waste management systems in the city of Johannesburg.

5.1 Waste diversion rate

The waste diversion rate is currently a pivotal metric employed by municipalities to assess the effectiveness of waste management systems. This rate is defined as the percentage of total waste redirected from disposal at authorised landfills and transformation facilities, such as incineration. Instead, this waste is directed toward reduction, reuse, recycling, and composting programs. The diversion rate can be measured through either a generation-based or disposal-based system. In a generation-based system, disposal and diversion are measured and combined to determine generation. Conversely, in a disposal-based system, while the definition of waste generation remains the same (disposal plus diversion), the method of measurement differs. In this system, waste generation is estimated, and then measured disposal is subtracted from generation to estimate diversion. Therefore, the traditional waste diversion rate can be expressed as per Equation 1.

$$Diversion\ rate = \frac{weight\ of\ recyclables}{Weight\ of\ garbage + Weight\ of\ recyclables} \times 100 \tag{1}$$

Recyclables refer to waste that undergoes processes such as reuse, recycling, composting, or digestion. Garbage encompasses waste that is either landfilled or incinerated, as defined by the City of Toronto in 2012. As of 2011, several cities, including Adelaide, San Francisco, and Stockholm, aspire to become zero-waste cities by achieving a 100% diversion of waste from landfills. However, focusing solely on diversion from landfills and recycling is insufficient for comprehensive zero-waste initiatives. The diversion rate, as defined in Equation 1, does not encompass waste avoidance through industrial design, effective policies, or behaviour change. Consequently, the diversion rate alone falls short in measuring a city's zero waste performance. It serves merely as an indicator of recycling performance, lacking the ability to provide a complete overview of recycling initiatives. It fails to inform us about the recyclability of the entire waste stream, the extent to which all recyclables are recycled, and the overall reduction in generated waste (Marpman, 2011). The diversion rate is inadequate because it fails to consider waste avoidance strategies, such as efforts to promote minimal packaging (Mata, 2018). It also neglects the importance of industrial design, where products are engineered for easier recycling, exemplified by modular electronics (Blömeke et al., 2020). While effective policies, like mandatory recycling laws, can lead to substantial improvements, these are not reflected in diversion metrics (Department of Environmental Affairs, 2018). Furthermore, initiatives aimed at changing behaviour, such as community education programs, can boost recycling participation but are not captured by diversion rates (Chauhan et al., 2021).

To address these limitations, a comprehensive waste management performance tool is essential. Waste avoidance has emerged as a critical aspect that should be integrated into the assessment of a waste management system's performance. Therefore, there is a need for a waste measurement index that goes beyond the diversion rate to thoroughly evaluate waste management system performance. This paper adopts a novel index system called the zero waste index (ZWI), which is designed as an indicator to holistically measure waste management system performance.

5.2 Zero Waste Index

The Zero Waste Index (ZWI) has its origins in foundational studies, specifically those conducted by Zaman and Lehmann (2013) and Zaman (2014), which laid the groundwork for its development. This study does not present the ZWI as an original concept; instead, it has been adopted and adapted from these prior works. The ZWI functions as a performance indicator for evaluating waste management systems. By acknowledging these significant contributions, we reinforce that our methodology is rooted in established research, thereby enhancing the credibility and relevance of our approach to assessing waste management performance. The zero-waste index serves as a tool to assess the ability of zero waste management systems to offset the use of virgin materials. A pivotal objective of the zero-waste concept is to eliminate the depletion of natural resources. Consequently, evaluating the performance of a zero-waste city inherently measures the entire lifecycle of resources from extraction and consumption to waste generation, recycling, recovery, and eventual substitution for virgin materials. The formulation of the zero-waste index is outlined in Equation 2. In contrast, the waste diversion rate fails to indicate the efficiency of the waste management system in replacing virgin materials, a crucial aspect for conserving global natural resources. Therefore, the zero-waste index has emerged as an innovative tool for gauging the substitution of virgin materials by waste management systems. A global adoption of the zero waste index would enable the measurement of the potential offset of virgin materials and the prevention of resource depletion. Furthermore, the ZWI serves as a valuable tool for comparing diverse waste management systems across various cities, offering a comprehensive view of potential demands for virgin materials, energy, carbon pollution, and water within a city. Hence, the ZWI stands as a performance indicator providing an overarching assessment of waste management system performance.

$$Zero\ waste\ index = \frac{\sum potential\ amount\ of\ waste\ managed\ by\ the\ city \times substitution\ for\ the\ systems}{Total\ amount\ of\ waste\ generated\ in\ the\ city}$$

$$ZWI = \frac{\sum_i^n WMSi * SFi}{\sum_i^n GWST} \tag{2}$$

$WMSi$ = amount of waste managed by system i (i.e., i ¼ 1, 2, 3).

n = amount of waste avoided, recycled, treated, etc.

SFi = Substitution factor for different waste management systems based on their virgin material replacement efficiency.

GWS = Total amount of waste generated (tonnes of all waste streams).

The zero-waste index is grounded in the assessment of the material value capable of potentially replacing virgin material inputs. This evaluation extends to the substitution of energy, water, and greenhouse gas emissions, incorporating values derived from various life cycle assessment tools and databases. The substitution values for material, energy, water, and greenhouse gas emissions are sourced from the life cycle database of different assessment tools, reflecting the advancement of technology in material recovery processes. As a result, the substitution value varies for different materials and waste management systems. Although waste prevention is integral to the zero-waste concept, this research does not include a quantitative measurement of waste prevention through behaviour change due to limited scientific quantitative measurement data. Table 1 shows the substitution values for six major waste streams—paper, glass, plastic, metal, organic, and mixed municipal solid waste—considered in this study based on waste data availability in Johannesburg. The selection of these waste streams is informed by their prevalence in the city and the compatibility of data collection systems. The table, adapted from

TABLE 1 Substitution values for the zero-waste index—city of Johannesburg.

Case study city	Waste management systems	Waste category	Total waste managed in the city (tonnes)	Virgin material substitution efficiency (tonnes)	Energy substitution efficiency (GJLHV/tonne)
Johannesburg	Recycling	Metal	41457.1	0.79–0.96	36.09–191.42
		Plastic	34,373	0.90–0.97	38.81–64.08
		Mixed	183,588	0.25–0.45	5.00–15.0
	Composting	Organic	19,466	0.60–0.65	0.18–0.47
	Landfill	Mixed MW[a]	1,032,879	0	0.00–0.8 4[b]
Total			1561337.1		

[a]Average composition of municipal waste.

[b]Energy from landfill facility. A positive value represents savings, and a negative value represents demand or depletion.

various sources, presents the waste volume managed in these cities alongside the corresponding potential substitution values for different waste management systems.

6 Case study of Johannesburg

Johannesburg's waste management is overseen by PikitUp, a municipal-owned entity with an extensive infrastructure that includes 5,035 employees and the service of over 9,000 business properties. The waste management system comprises 13 depots, 42 garden sites, and a fleet of 300+ specialised waste vehicles. The city caters to the needs of 260 informal settlements and operates four operational landfills, two of which are closed. In terms of waste volume, Johannesburg handles 1.4 million tons of waste disposal while successfully collecting 1.6 million tons. Additionally, approximately 200,000 tons of waste are diverted from disposal through various waste management initiatives. Overall, these statistics depict a comprehensive waste management system in Johannesburg, emphasising both collection efficiency and efforts towards waste diversion. The collection of recyclables from residential households and their transport to recycling facilities are crucial components of the recycling process (Nowakowski, 2017). In numerous developing nations, including South Africa, the responsibility for recyclable collection primarily falls on waste reclaimers (Wilson et al., 2006). The positive contribution of waste reclaimers to resource recycling is widely recognised. The African Reclaimers Organisation (ARO), an engaged waste reclaimer organisation in Johannesburg, comprises approximately 6,000 members, including a significant number of foreign nationals, some with proper documentation and others without.

The BanQu Pilot Project in the city of Johannesburg involves a collaborative effort with the African Reclaimers Organisation (ARO), showcasing a commitment to innovation through partnerships. BanQu, a software company operating on a Software as a Service (SAS) model, is primarily utilised in informal supply chains, including waste recycling and agriculture. Initially, focused on agriculture, BanQu connected smallholder farmers with brands such as ABC Index Brewery and Coca-Cola. Functioning as a smartphone app, the BanQu platform is a multitier software designed for precise supply chain management. Users can map any number of tiers (stakeholders) in the recycling supply chain, connecting brands, recycling companies, aggregators, and, eventually, waste reclaimers at the bottom of the recycling chain, resulting in four or seven tiers. Stakeholders are ranked based on their importance, with waste reclaimers positioned on the lower tier of the recycling value chain. BanQu enables waste reclaimers to generate reports on the quantity of recyclable material traded, the prices paid, and the location of the buyback centre.

The data for this research were gathered over a 12-month period, spanning from January 2022 to December 2022. This collection was a collaborative effort that involved local waste management authorities, community waste reclaimers, and the African Reclaimers Organisation (ARO), which supplied valuable waste data from its database. By incorporating these details, we provide a clearer understanding of our methodology, thereby enhancing the transparency and reliability of our assessment of waste management performance. As of 2020, BanQu, in collaboration with PETCO, had registered 10 buyback centres, integrating more than 1,400 waste pickers into the BanQu system. PETCO reported that over 2,350 tonnes of recyclable material have been diverted from landfills and traded on the BanQu platform, representing transactions worth more than R5.7 million (approximately $316,667 USD). Notably, BanQu offers free registration for waste reclaimers and buyback centres, with brands such as Coca-Cola and Unilever taking responsibility for paying annual subscription fees. Table 1 displays the substitution values for waste streams across various waste management systems. This analysis focuses on four primary waste streams—plastic, metal, organic, and mixed municipal solid waste—selected based on the availability of waste data from Johannesburg. Given the substantial differences in waste streams and data collection systems, these six waste streams are chosen for consideration in this study.

7 Results and discussion

The following section presents and discusses the waste management systems in Johannesburg, considering both performance indicators: the diversion rate and the zero-waste index.

7.1 Waste diversion rate

The municipal solid waste diversion rates by waste reclaimers in Johannesburg are provided below, as determined by Equation 1. In Johannesburg, the total waste generated amounts to 1,561,337.1 tonnes. This waste stream is divided into various segments, including composting (19,466 tonnes), recycling (278,884.1 tonnes), diversion from traditional disposal methods (143,594 tonnes), and landfill disposal (1,032,879 tonnes). Calculating the waste diversion rate, which represents the percentage of waste diverted from traditional landfill disposal, reveals that approximately 9.21% of the total waste generated is redirected towards more sustainable practices. By determining the contribution of each segment as a percentage of the total waste generated, we found that composting constituted approximately 1.3%, recycling made up 18.9%, diversion contributed 9%, and landfill disposal accounted for 70.0%. These figures illustrate the distribution of waste management efforts in Johannesburg, emphasising the importance of various strategies to address different waste streams and achieve a more sustainable waste diversion rate (Figures 1, 2).

7.2 Zero Waste Index

Using the formula presented in Equation 2 in Table 1, the zero-waste index for Johannesburg was calculated to be 0.34. This implies that approximately 33.82% of resources were reclaimed from waste management systems relative to the total waste generated. Table 2 illustrates the achievements in terms of resource recovery and waste management systems. The subsequent analysis focuses on the substitution of resources. The calculated zero waste index of approximately 33.82% signifies that waste reclaimers in Johannesburg successfully divert more than one-third of its waste from landfills, showcasing its commitment to sustainable waste management practices. This percentage indicates the effectiveness of recycling, composting, and other waste diversion initiatives within the city. The zero waste index serves as a valuable metric for quantifying the success of these efforts, providing a clear indication of waste reclaimers in Johannesburg's progress toward a more sustainable and environmentally friendly waste management system. As urban areas globally aimed at zero-waste targets, Johannesburg stands as a noteworthy example, demonstrating the positive impact of comprehensive waste management strategies. This ongoing commitment positions waste reclaimers in Johannesburg at the forefront of urban sustainability and environmental responsibility.

In Johannesburg, the resource substitution values highlight the significant impact of waste management systems, particularly in the Metal, Plastic, Mixed, Organic, and Mixed MWa (Landfill) categories. For metal waste, the Virgin Material Substitution, Energy Substitution, GHG Emission Reduction, and Water Savings are estimated at 13,438.88 tonnes, 6,403,507.5 GJLHV, 6,979.02 CO_2e, and 73,183.10 kL, respectively. In the plastic category, the Virgin Material Substitution is calculated at 2,485.81 tonnes, with energy substitution, GHG emissions reduction, and water saving at 868,360.69 GJLHV, 23,142.39 CO_2e, and 0 (indicating water use), respectively. For mixed waste, the Virgin Material Substitution, Energy Substitution, GHG Emissions Reduction, and Water Saving values are 36,117.00 tonnes, 1,835,880.00 GJLHV, 211,226.20 CO_2e, and 1,471,770.00 kL, respectively. In the Organic category, the values for Virgin Material Substitution, Energy Substitution, GHG Emission Reduction, and Water Savings are 973.30 tonnes, 566.22 GJLHV, 9,733.00 CO_2e, and 8,554.64 kL, respectively. Finally, for the Mixed MWa (Landfill) category, the Virgin Material Substitution is not applicable, and there is no Energy Substitution. However, there is a negative GHG emission reduction of 433,865.18 CO_2e, indicating emissions from the landfill and no water savings. Johannesburg's recycling and composting sector features key organizations like the African Reclaimers Organisation (ARO), advocating for informal waste pickers; WastePlan, which emphasizes innovative waste management and landfill waste reduction; Interwaste, providing integrated solutions to lessen environmental impact; and EnviroServ, a leading provider of recycling and composting services that enhance sustainable waste management. These results illustrate the substantial contributions of waste reclaimers in Johannesburg's waste management systems to material substitution and environmental conservation across various waste categories. The positive values signify the potential for reducing the demand for virgin materials, energy consumption, greenhouse gas emissions, and water usage through effective waste management strategies.

In comparing the waste management results of Johannesburg with those of Adelaide, San Francisco, and Stockholm (Zaman and Lehmann, 2013), several notable patterns emerge. Each city's waste management

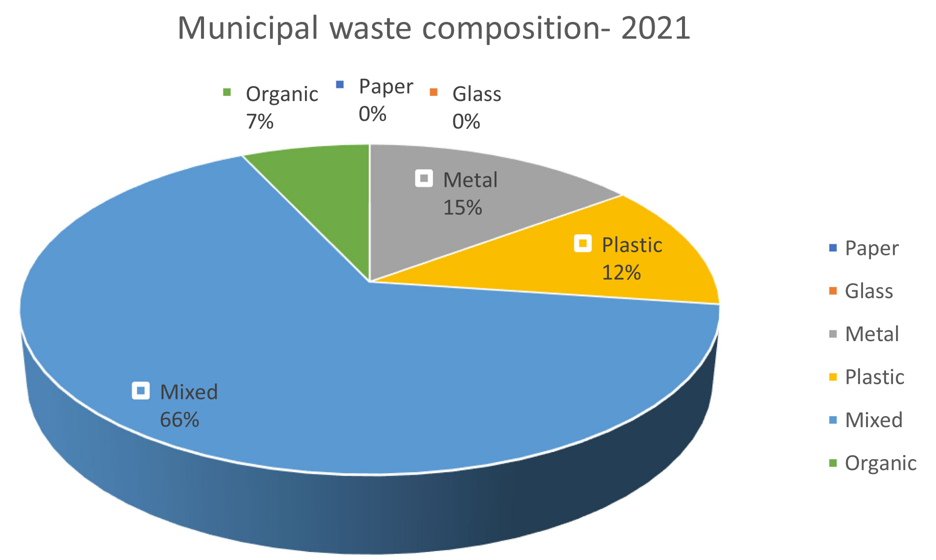

FIGURE 1
Municipal waste composition in the city of Johannesburg (source: African Reclaimers Organisation, 2022).

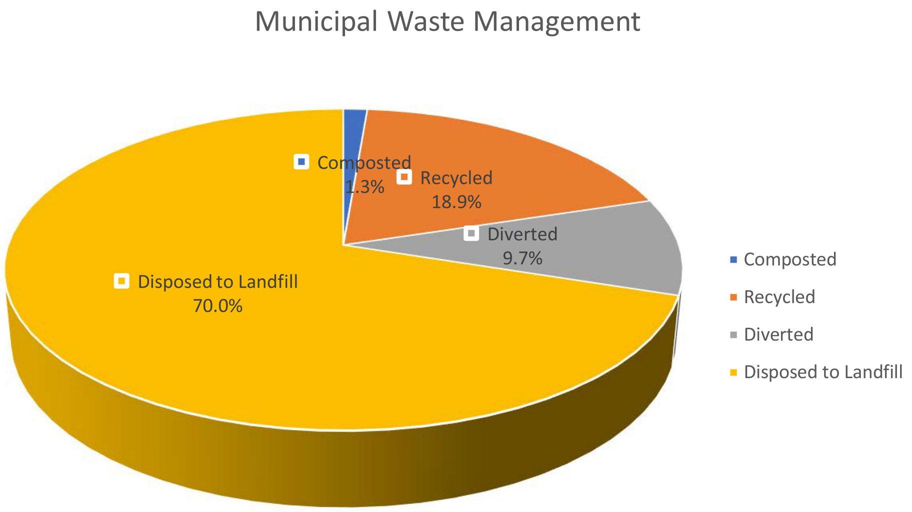

FIGURE 2
Municipal waste management in the city of Johannesburg (source: African Reclaimers Organisation, 2022).

TABLE 2 Potential substitution of resources in the zero-waste index—city of Johannesburg.

Case study city	Waste management systems	Waste category	Total waste managed in the city (tonnes)	Virgin material substitution efficiency (tonnes)	Energy substitution efficiency (GJLHV/ tonne)	GHG emissions reduction (CO2e/ tonne)	Water saving (kL/ tonne)	Zero Waste Index
Johannesburg	Recycling	Metal	41457.1	13,438.88	6,403,507.50	6,979.02	73,183.10	33.82%
		Plastic	34,373	2,485.81	868,360.69	23,142.39	−23,142.39	
		Mixed	183,588	36,117.00	1,835,880.00	211,226.20	1,471,770.00	
	Composting	Organic	19,466	973.3	566.22	9,733.00	8,554.64	
	Landfill	Mixed MW[a]	1,032,879	0	0	−433,865.18	0	

systems exhibit unique strengths and challenges, contributing to variations in waste diversion and zero waste performance. Adelaide's waste management system, with a zero-waste index of 0.23, indicates that approximately 23% of the resources were recovered (Zaman and Lehmann, 2013). While the percentage appears lower than that of Johannesburg, it reflects Adelaide's efforts in material recovery and substitution. A city's focus on energy substitution, greenhouse gas reduction, and water savings per capita signifies a holistic approach to sustainable waste management. Francisco stands out for having a high zero waste index of 0.51, demonstrating a robust commitment to waste diversion and resource recovery (Zaman and Lehmann, 2013). The city's waste management systems excel in substituting materials and energy and reducing greenhouse gas emissions. San Francisco's comprehensive approach to waste reduction, coupled with significant water savings, highlights its leadership in sustainable waste management practices. Stockholm's waste management system achieved a zero-waste index of 0.17, indicating that approximately 17% of the materials were recovered and substituted (Zaman and Lehmann, 2013). While the index may seem lower than that of Johannesburg, Stockholm demonstrates efficiency in energy substitution, greenhouse gas reduction, and water savings per person. A city's waste management practices align with its commitment to environmental sustainability.

Johannesburg positions itself as a city making significant strides in waste diversion, with a zero-waste index falling between the performances of San Francisco and Adelaide. This comparison emphasises the need for a comprehensive understanding of material substitution, energy efficiency, and environmental impact to assess the overall effectiveness of waste management systems. Each city faces unique challenges influenced by local factors such as population density, industrial activities, and infrastructure development. The collective efforts of cities worldwide, including Johannesburg, underscore the importance of adopting sustainable waste management practices to address global environmental concerns. Ongoing collaboration and the exchange of best practices among cities can contribute to the development of effective, tailored waste management solutions on a global scale.

7.3 Challenges and opportunities for waste pickers

The digital transformation of waste management systems has significantly altered the operational dynamics for waste pickers, effectively mitigating numerous challenges they faced prior to the adoption of these technologies. Traditionally, waste pickers functioned within an informal framework marked by inadequate data management practices, where record-keeping was often restricted to basic cashbooks. This limitation resulted in a considerable lack of accurate statistical data regarding recycling activities (Wilson et al., 2006). The absence of reliable data not only impeded the formulation of effective waste management policies but also marginalized the contributions of waste pickers, who frequently received little formal recognition and support from local authorities (Nowakowski, 2017). As a result, their economic stability was jeopardized, with fluctuations in the market value of recyclable materials directly affecting their livelihoods. However, the incorporation internet of waste pickers (ICT-technologies) and block chain technology has enabled the establishment of intelligent collection systems that facilitate real-time tracking and monitoring of waste collection processes, thereby improving data accuracy and informing both operational and policy decisions (Esmaeilian et al., 2018). Moreover, this digital transformation has promoted the formal recognition of waste pickers within the waste management ecosystem, as illustrated by initiatives in South Africa that have successfully integrated waste reclaimers into formal systems, enhancing their status and access to resources (Alverti et al., 2016). Economically, the implementation of digital platforms has empowered waste pickers through mechanisms such as real-time payment transactions for recyclable materials and incentive-based reward systems, which encourage active participation in recycling initiatives (Rybnytska et al., 2018). Additionally, these platforms foster improved collaboration among waste pickers, local authorities, and the wider community, resulting in enhanced waste collection efficiency and increased recycling rates, as evidenced by successful partnerships in cities like Bogotá (Zaman, 2014).

8 Strategies to improve targets towards the zero-waste goal

Waste management strategies in developing countries play a crucial role in addressing environmental challenges unique to each region. One notable example is the city of Indore in India, which has pioneered innovative waste segregation and composting techniques. The implementation of decentralised composting units has proven effective in managing organic waste. The Swachh Indore initiative in India serves as a reference, showcasing how technology adoption can transform waste management practices and contribute to sustainable urban development.

Enhancing collection systems is another key aspect, exemplified by the waste-picker cooperative model in Brazil. Belo Horizonte has successfully integrated informal waste pickers into the formal waste management system, emphasising inclusivity and collaboration. The study by Amorim de Oliveira (2021) provides valuable insights into the impact of cooperatives on waste collection efficiency and recycling rates in Brazil. Public awareness and education campaigns are vital components of waste management initiatives. The "My Clean India" campaign in India exemplifies efforts to raise awareness about cleanliness, sanitation, and waste management. This campaign, promoted by the Swachh Bharat Mission, focuses on community participation and behaviour change, acknowledging the role of education in fostering sustainable waste practices.

Strategic policy and regulation measures are exemplified by Rwanda's nationwide ban on single-use plastic bags, positioning the country as a leader in combating plastic pollution. The regulatory steps taken by Rwanda, as reported by The New Times, highlight the importance of legislative frameworks in shaping sustainable waste management practices. Collaboration and partnerships are crucial for achieving holistic waste management goals. In Colombia, the collaboration of the city of Bogotá with waste pickers has improved waste collection efficiency and increased recycling rates. The partnership, detailed by GIZ, showcases the mutual benefits for both the municipality and informal waste workers, emphasising the significance of collaborative approaches.

Innovation in product design, such as the "Eco Bricks" initiative in the Philippines, demonstrates how repurposing plastic waste can address environmental challenges. The eco-brick exchange initiative promotes sustainable construction by encouraging communities to repurpose plastic waste into building blocks. Monitoring and evaluation technologies, such as the "TrashOut" app developed in Slovakia, empower citizens to report illegal dumpsites and track waste-related issues. Such applications, including adaptations in developing countries, contribute to improved waste monitoring and foster community engagement in waste management practices. These recommendations collectively underscore the diverse strategies adopted by developing countries, emphasising the need for context-specific approaches for addressing waste management challenges and promoting sustainability.

The study highlights the use of key digital technologies, particularly the BanQu platform, a blockchain-enabled software that allows for real-time tracking of recyclable materials and transactions. This platform empowers waste pickers by enabling them to register their activities, monitor collected quantities, and receive timely payments, thus enhancing their economic stability and operational efficiency (Amorim de Oliveira, 2021). Additionally, ICT-based monitoring systems have improved data collection and analysis in waste management. A comparative analysis of waste management conditions before and after the implementation of the BanQu platform reveals that waste pickers faced significant challenges, such as limited market access and tracking difficulties, leading to poorly sorted waste and lower recovery rates (Zaman, 2014). After the platform's adoption, approximately 9.21% of Johannesburg's waste was diverted from landfills, indicating improved efficiency. The integration of these technologies has optimized waste collection processes and empowered waste pickers, who now report greater transaction security and increased earnings due to better market access and transparent pricing (Rybnytska et al., 2018). This demonstrates the transformative potential of digital technologies in enhancing sustainable waste management and improving the livelihoods of informal waste workers.

9 Conclusion

This research provides valuable insights into the waste management performance of waste reclaimers in developing cities, particularly in the context of Johannesburg. The adoption of the zero-waste index and the analysis of resource substitution values contribute to a nuanced understanding of the city's waste management strategies. This discussion underscores the advantage of the zero-waste index over the diversion rate in providing a comprehensive assessment of a city's waste management performance. Achieving a 100% diversion rate from landfills, while a notable milestone lacks insight into resource recovery and substitution. Unlike the diversion rate, the zero-waste index forecasts the recovery and substitution of resources, offering a clearer picture of waste reclaimers and the city's commitment to avoiding further resource extraction.

The findings underscore the importance of ongoing collaboration and the exchange of best practices among cities and waste reclaimers to develop effective, tailored waste management solutions on a global scale. Comparisons with other cities, including Adelaide, San Francisco, and Stockholm, reveal the diverse strengths and challenges of each waste management system. In collaboration with waste reclaimers, Johannesburg positions itself between San Francisco and Adelaide in terms of zero-waste performance, emphasising the need for a comprehensive understanding of material substitution, energy efficiency, and environmental impact. As urban areas strive for zero-waste targets, Johannesburg serves as a noteworthy example of the positive impact of comprehensive waste management strategies, positioning waste reclaimers at the forefront of urban sustainability and environmental responsibility. In the context of this study on waste management in Johannesburg, future research could explore the long-term sustainability of digital waste management platforms. Comparative studies between Johannesburg and other cities embracing similar waste technologies could provide broader insights into scalable best practices. Furthermore, investigating policy frameworks that enhance informal waste pickers' integration could yield more inclusive waste management models. Expanding the evaluation metrics beyond the Zero Waste Index to include social and economic impacts would deepen understanding and inform future sustainable city planning.

Author's note

Vincent Siwawa is a postdoctoral fellow at the Emancipatory Futures Studies (EFS) Programme and a recipient of the Wits Centennial Postdoctoral Fellowship. Vincent Siwawa's research interests include digital smart cities, informal recycling and waste picker integration, digital transformation, the circular economy and environmental sustainability.

Data availability statement

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

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

VS: Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Conflict of interest

The author declares 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

References

African Reclaimers Organisation (2022). Annual and monthly waste category data. South Africa: Johannesburg.

Ajwani-Ramchandani, R., Figueira, S., de Oliveira, R. T., and Jha, S. (2021). Enhancing the circular and modified linear economy: the importance of blockchain for developing economies. *Resour. Conserv. Recycl.* 168:105468. doi: 10.1016/j.resconrec.2021.105468

Al-Khatib, I. A., Monou, M., Zahra, A. S. F. A., Shaheen, H. Q., and Kassinos, D. (2010). Solid waste characterisation, quantification and management practices in developing countries. A case study: Nablus district–Palestine. *J. Environ. Manag.* 91, 1131–1138. doi: 10.1016/j.jenvman.2010.01.003

Alverti, M., Hadjimitsis, D., Kyriakidis, P., and Serraos, K., (2016). "Smart city planning from a bottom-up approach: local communities' intervention for a smarter urban environment." in Fourth international conference on remote sensing and geoinformation of the environment (RSCy2016) (Vol. 9688, pp. 409–420). SPIE.

Amorim de Oliveira, Í. (2021). Environmental justice and circular economy: analysing justice for waste pickers in upcoming circular economy in Fortaleza, Brazil. *Circ. Econ. Sustain.* 1, 815–834. doi: 10.1007/s43615-021-00045-w

Anagnostopoulos, T., Zaslavsky, A., Kolomvatsos, K., Medvedev, A., Amirian, P., Morley, J., et al. (2017). Challenges and opportunities of waste management in IoT-enabled smart cities: a survey. *IEEE Trans. Sustain. Comp.* 2, 275–289. doi: 10.1109/TSUSC.2017.2691049

Antikainen, M., Uusitalo, T., and Kivikytö-Reponen, P. (2018). Digitalisation as an enabler of circular economy. *Proc. Cirp* 73, 45–49. doi: 10.1016/j.procir.2018.04.027

Ardi, R., and Leisten, R. (2016). Assessing the role of informal sector in WEEE management systems: a system dynamics approach. *Waste Manag.* 57, 3–16. doi: 10.1016/j.wasman.2015.11.038

Blömeke, S., Mennenga, M., Herrmann, C., Kintscher, L., Bikker, G., Lawrenz, S., et al. (2020). "Recycling 4.0: an integrated approach towards an advanced circular economy." in *Proceedings of the 7th international conference on ICT for sustainability*. pp. 66–76.

BMi Research. (2012). Recycling assessment report 2012. Unpublished report 2013 [courtesy of Packaging SA].

Bressanelli, G., Adrodegari, F., Perona, M., and Saccani, N. (2018). Exploring how usage focused business models enable circular economy through digital technologies. *Sustainability* 10:639. doi: 10.3390/su10030639

Chauhan, A., Jakhar, S. K., and Chauhan, C. (2021). The interplay of circular economy with industry 4.0 enabled smart city drivers of healthcare waste disposal. *J. Clean. Prod.* 279:123854. doi: 10.1016/j.jclepro.2020.123854

Chi, X., Wang, M. Y., and Reuter, M. A. (2014). E-waste collection channels and household recycling behaviours in Taizhou of China. *J. Clean. Prod.* 80, 87–95. doi: 10.1016/j.jclepro.2014.05.056

City of Austin (2008). Zero Waste Strategic Plan. City of Austin, Austin, TX.

Department of Environment Forestry and Fisheries (2020). National Waste Management Strategy 2020. Available at: https://www.dffe.gov.za/sites/default/files/docs/2020nationalwaste_managementstrategy1.pdf (Accessed June 18, 2021).

Department of Environmental Affairs (2018). South Africa state of waste report. A report on the state of the environment. Available at: https://soer.environment.gov.za/soer/UploadLibraryImages/UploadDocuments/141119143510state%20of%20Waste%20Report_2018.pdf (Accessed June 18, 2022).

Derigent, W., and Thomas, A., (2016). End-of-life information sharing for a circular economy: existing literature and research opportunities. Service orientation in holonic and multiagent manufacturing, pp.41–50.

Esmaeilian, B., Wang, B., Lewis, K., Duarte, F., Ratti, C., and Behdad, S. (2018). The future of waste management in smart and sustainable cities: a review and concept paper. *Waste Manag.* 81, 177–195. doi: 10.1016/j.wasman.2018.09.047

Garcia-Muiña, F. E., González-Sánchez, R., Ferrari, A. M., and Settembre-Blundo, D. (2018). The paradigms of industry 4.0 and circular economy as enabling drivers for the competitiveness of businesses and territories: the case of an Italian ceramic tiles manufacturing company. *Soc. Sci.* 7:255. doi: 10.3390/socsci7120255

Garcia-Muiña, F. E., González-Sánchez, R., Ferrari, A. M., Volpi, L., Pini, M., Siligardi, C., et al. (2019). Identifying the equilibrium point between sustainability goals and circular economy practices in an industry 4.0 manufacturing context using eco-design. *Soc. Sci.* 8:241. doi: 10.3390/socsci8080241

Gerdes, P., and Gunsilius, E., (2010). The waste experts: Enabling conditions for informal sector integration in solid waste management: Lessons learned from Brazil, Egypt and India. GTZ.

Godfrey, L. (2021). Quantifying economic activity in the informal recycling sector in South Africa. *S. Afr. J. Sci.* 117, 138–144. doi: 10.17159/sajs.2021/8921

Godfrey, L. K., and Nahman, A. (2007). Are developing countries ready for first world waste policy instruments? Pretoria: CSIR.

Godfrey, L., and Oelofse, S. (2017). Historical review of waste management and recycling in South Africa. *Resources* 6:57. doi: 10.3390/resources6040057

Godfrey, L., Strydom, W., and Phukubye, R. (2016). Integrating the informal sector into the south African waste key findings. Pretoria: CSIR.

Govender, K.D., (2017). Circular economy design visioning: Exploring industrial and urban symbiosis in south African cities University of KwaZulu Natal. (doctoral dissertation).

Greencape (2021). Waste: Market intelligence report 2020. Available at: https://www.green-cape.co.za/assets/2021_DIGITAL_WASTE-MIR.pdf (Accessed June 15, 2021).

Korhonen, J., Honkasalo, A., and Seppälä, J. (2018). Circular economy: the concept and its limitations. *Ecol. Econ.* 143, 37–46. doi: 10.1016/j.ecolecon.2017.06.041

Kouhizadeh, M., Sarkis, J., and Zhu, Q. (2019). At the nexus of blockchain technology, the circular economy, and product deletion. *Appl. Sci.* 9:1712. doi: 10.3390/app9081712

Le Courtois, A. (2012). Municipal solid waste: turning a problem into resource. *Priv. Sect. Dev.* 15, 1–28.

Lee, L. (2011). An integrated design strategy for South Australia: Building the future. Department of the Premier and Cabinet.

Lehmann, S. (2010). Resource recovery and materials flow in the city: zero waste and sustainable consumption as paradigms in urban development. *Sustaina. Dev. L. Pol'y* 11:28.

Marpman, A., (2011). Does your diversion rate really reflect your recycling efforts. Environmental Leader.

Mata, A.M., (2018). Is smart city an utopia? Lessons learned and final reflections. Smart and sustainable cities for innovative urban planning in Mexico; editorial Academica Espanola: Beau Bassin, Mauritius, pp.198–207.

Mboli, J. S., Thakker, D., and Mishra, J. L. (2022). An internet of things-enabled decision support system for circular economy business model. *Softw. Pract. Experience* 52, 772–787. doi: 10.1002/spe.2825

Nowakowski, P. (2017). A proposal to improve e-waste collection efficiency in urban mining: container loading and vehicle routing problems–a case study of Poland. *Waste Manag.* 60, 494–504. doi: 10.1016/j.wasman.2016.10.016

PETCO (2016). Future focus: A review of PETCO activities. Available at: https://petco.co.za/wp-content/uploads/2017/05/PETCO-2016-Annual-Review_web-version.pdf (Accessed March 2022).

Phillips, P. S., Tudor, T., Bird, H., and Bates, M. (2011). A critical review of a key waste strategy initiative in England: zero waste places projects 2008–2009. *Resour. Conserv. Recycl.* 55, 335–343. doi: 10.1016/j.resconrec.2010.10.006

Plastics SA. (2012). Plastics recycling survey 2012. Unpublished report 2013 [courtesy of Packaging SA].

Rybnytska, O., Burstein, F., Rybin, A. V., and Zaslavsky, A. (2018). Decision support for optimising waste management. *J. Decis. Syst.* 27, 68–78. doi: 10.1080/12460125.2018.1464312

Rybova, K., and Slavik, J., (2016). "Smart cities and ageing population-implications for waste management in the Czech Republic." in *2016 smart cities symposium Prague (SCSP)*. pp. 1–6. IEEE.

Scheinberg, A., (2011). Value added: Modes of sustainable recycling in the modernisation of waste management systems. Wageningen University and Research.

Thobejane, P.M., (2022). Evaluating the implementation of the south African National Waste Management Strategy goals by local government (Doctoral dissertation, North–West University (South Africa)).

Wilson, D. C., Velis, C., and Cheeseman, C. (2006). Role of informal sector recycling in waste management in developing countries. *Habitat Int.* 30, 797–808. doi: 10.1016/j.habitatint.2005.09.005

Wilts, H., Garcia, B. R., Garlito, R. G., Gómez, L. S., and Prieto, E. G. (2021). Artificial intelligence in the sorting of municipal waste as an enabler of the circular economy. *Resources* 10:28. doi: 10.3390/resources10040028

Wu, W., Xie, L., and Hao, J. L. (2022). An integrated trading platform for construction and demolition waste recovery in a circular economy. *Sustain. Chem. Pharm.* 25:100597. doi: 10.1016/j.scp.2022.100597

Xue, Y., Wen, Z., Bressers, H., and Ai, N. (2019). Can intelligent collection integrate informal sector for urban resource recycling in China? *J. Clean. Prod.* 208, 307–315. doi: 10.1016/j.jclepro.2018.10.155

Zaman, A. U. (2014). Measuring waste management performance using the 'zero waste index': the case of Adelaide, Australia. *J. Clean. Prod.* 66, 407–419. doi: 10.1016/j.jclepro.2013.10.032

Zaman, A. U., and Lehmann, S. (2013). The zero waste index: a performance measurement tool for waste management systems in a 'zero waste city'. *J. Clean. Prod.* 50, 123–132. doi: 10.1016/j.jclepro.2012.11.041

Zheng, Z., Xie, S., Dai, H. N., Chen, X., and Wang, H. (2018). Blockchain challenges and opportunities: a survey. *Int. J. Web Grid Serv.* 14, 352–375. doi: 10.1504/IJWGS.2018.095647

Appendix A: Interview Guide

Section 1: Background information

1. Can you describe your role within the African Waste Reclaimers Organisation (ARO)?
2. How long have you been involved in waste reclaiming activities, and what motivated you to join this sector?
3. What types of waste do you primarily collect in your daily activities?

Section 2: Data collection and tracking

4. How do you track the amount and types of waste you collect on a daily or monthly basis?
5. Can you describe how digital platforms, such as BanQu, assist in data recording and quantification of waste types?
6. What challenges do you face in maintaining accurate records of waste collection and transactions?

Section 3: Impact on income and livelihoods

7. Have you observed any improvements in your income since using digital tools for waste tracking and management?
8. How has access to digital platforms affected your ability to negotiate prices or receive fair compensation?
9. What additional features or support would you like to see in these platforms to improve your livelihood?

Section 4: Challenges in waste reclaiming

10. What are the main barriers you encounter in accessing formal waste management systems or infrastructure?
11. How do societal perceptions of waste pickers affect your work and opportunities?
12. Are there specific policy changes that you believe would improve conditions for waste reclaimers?

Section 5: Opportunities and future directions

13. What changes would you like to see in the waste management system that could better support waste pickers and enhance progress toward zero waste?
14. How do you envision the future of waste management and your role as a waste picker in relation to zero waste goals in your community?