A system dynamics approach to sustainable waste management in a South African city

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Abstract. Waste management in South Africa is significantly affected by rapid population growth, urbanisation, industrialisation, and poor waste management practices. These have impeded the effectiveness of waste reduction, recovery, and recycling. This study employs a systems dynamics approach to provide a cohesive assessment of the core components of South African waste management to evaluate the impact of systemic bottlenecks on its sustainability. The study employed a qualitative system dynamics methodology and focused on a single city. Data were gathered from interviews, record analysis, and observations, and then thematically coded and mapped using causal loop diagramming. The findings revealed several variable interactions that influence the system, for instance, waste segregation, collection system efficiency, informal pickers mobilisation, recovered recyclables, market demand, income and employment opportunities, regulatory compliance, and policy and governance, which were addressed as enablers influencing sustainability. On the contrary, limited infrastructure, dependence on landfills, lack of incentives and punitive schemes, weak policy enforcement, and poor coordination among public and private stakeholders were identified as barriers to achieving sustainable outcomes. The study demonstrates the value of system dynamics in identifying barriers to sustainable waste management and in designing interventions that foster the uptake of sustainable waste practices.

1 Introduction

Rapid urbanisation in South African cities has led to increased waste generation, placing tremendous pressure on municipal waste management systems [1]. As of 2017, the country generated 55 million tonnes of general waste, of which 89% was disposed of in landfills [2]. In that year, there were approximately 38 million tons of hazardous waste, of which only 7 per cent was recycled. Additionally, an estimated 27.8 million tons of unclassified waste, including slag from mills and foundries, brine, and mineral waste, were generated, further challenging waste management [3]. Landfills are approaching capacity, and South African municipalities are struggling to obtain permits for new landfill sites [4]. These trends reflect global patterns: only 20 per cent of waste was recycled annually, while a substantial portion of global resources is discarded [5].

Sustainable waste management (SWM) is a key factor in achieving Sustainable Development Goal 12 (Responsible Consumption and Production). SWM promotes efficient resource use, waste reduction, and sustainability in the global economy. Waste management encompasses all administrative and operational activities related to the handling, storage, transport, treatment, recovery, recycling, and disposal of waste [6]. Understanding effective, safe, and sustainable waste management practices is crucial, as these processes can be costly. One core approach is recycling, which involves collecting, sorting, and reprocessing waste into new products to reduce its adverse impacts on the environment, health, and aesthetics [7].

Current waste management (WM) in South African cities is unsustainable due to an overreliance on landfilling as the primary waste-disposal method [8]. This approach means that South Africa misses significant economic opportunities that result from SWM [9]. In 2018, approximately 75 per cent of waste was disposed of in landfills, mainly due to inadequate systems for reusing, recovering, and recycling waste [3]. However, municipal waste management in South Africa has evolved significantly over the past thirty years [10]. According to Grand View Research [11], the South African waste recycling services market generated about $1.18 billion in revenue in 2024 and is projected to reach $2.22 billion by 2033. The study highlights ongoing challenges and proposes strategies to improve decision-making by governments, service providers, and policymakers. Moreover, the study demonstrates that sustainable practices will not only mitigate environmental impacts but also generate social and economic benefits for the community.

2 Literature Review

SWM is shaped by the multifaceted challenge posed by the complex interactions among ecological, technological, economic, legal, sociocultural, and institutional dimensions [12–14]. Rapid economic and

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population growth, and urbanisation, significantly influence waste generation patterns, infrastructure development, and policy implementation [12, 13]. Importantly, Waste management is also a source of livelihood, as recycling and collection provide jobs and income opportunities that are key drivers of public participation in sustainability goals [14, 15]. In addition, supportive policy measures, including incentives for segregation and treatment, sustainability initiatives, and public awareness and education campaigns, further reinforce these positive trends as they act as strong enabling drivers [16, 17].

On the challenge side, economic development contributes to more complex waste streams, which in turn necessitate more advanced, large-scale waste treatment facilities, posing significant financial and infrastructural burdens [13]. Weak governance, uncoordinated responsibilities, and inadequate policy enforcement prevent coherent strategies [18]. Infrastructural limitations, including poor collection coverage and limited treatment capacity, further constrain effectiveness [19]. Dependence on informal waste pickers highlights inequities and safety risks, while financial and technological deficits restrict the adoption of advanced systems [14]. Moreover, unmanaged waste disposal, including open dumping and unsafe medical waste practices, continues to pose severe environmental and health threats [20]. Ultimately, these findings show that while the drivers of sustainable practices are increasingly evident, overcoming entrenched structural challenges remains the most significant barrier to transitioning towards sustainability in waste management.

Developed vs. Developing Country Perspectives

There is a divide between developed and developing countries in the management of waste [12]. In developed contexts, advanced collection systems, 4R practices, and technological integration are widely implemented, whereas in developing countries, informal waste sectors, open dumping, and infrastructure challenges predominate. Kumari and Raghubanshi [12] further examined how waste generation is directly affected by population growth, rising community quality of life, unexpected immigration, and rapid urbanisation, particularly in developing countries. Xiao et al. [13] emphasised how rapid economic and population growth in these nations amplify municipal solid waste generation and necessitate large-scale infrastructure and advanced treatment facilities. Their findings highlighted the roles of socioeconomic indicators and demographic policies in shaping municipal waste management strategies. Additionally, poor waste management in these regions, despite growing awareness of sustainable practices such as zero waste, is exacerbated by the absence of adequate policies, public awareness, and necessary technologies, further harming environmental and public health.

Medical and plastic waste streams are among the most affected by the divide between developed and developing countries. Olaniyi et al. [6] examined poor medical WM practices in South Africa, spanning from the initial source of generation to ultimate disposal. Their findings identified the absence of a national policy to regulate the substantial volume of medical waste generated and illegally dumped. Singh and Sharma [16] noted the importance of implementing sustainable WM practices, particularly in developing countries, given the substantial annual plastic production. Furthermore, plastic waste generation, as well as overall waste production, is influenced by multiple interrelated factors, including the level of industrialisation, the pace of urbanisation, the sector of operation, socio-economic activities, and climatic conditions. In contrast, developed countries have adopted more advanced and regulated waste management systems; in these regions, legislation is enforced by municipal and local authorities, thereby promoting waste minimisation strategies such as source-separated collection, recovery, recycling, and reuse. For instance, landfills may serve not only as disposal sites but also as hubs for waste sorting, treatment, and recycling activities. Reuse conserves resources by extending the life cycle of materials. In contrast, recycling converts waste into valuable products, thereby reducing the need for raw materials and minimising the potential waste of useful materials.

Singh and Sharma [16] further emphasised the importance of integrated waste management, which utilises a combination of methods to manage and reduce waste. However, standard waste disposal practices include reuse, recycling, landfilling, and incineration, and strict penalties for non-compliance are crucial to ensure effective implementation. Complementing this, Xiao et al. (2020) concluded that socio-economic dynamics influence the assessment of waste management systems, emphasising that a country's developmental level is directly influenced by the complexity and urgency of implementing effective governmental MSW policies and interventions. The literature further shows that policies aligned with sustainability goals are most effective when they balance environmental objectives with financial and institutional feasibility. Clarifying the complex interactions between population growth, urbanisation, economic development, and waste policy outcomes is critical to supporting more evidence-based decision-making.

Public behaviour emerges as both a constraint and an enabler of sustainable waste management. Studies consistently discuss how public education, enforcement of environmental policies and regulations, widespread awareness among individuals and communities, and incentives can transform waste practices, encouraging source segregation, increased recycling, and reduced reliance on unsafe disposal behaviours [17]. Minelgaitė and Liobikienė [21] asserted that personal attitudes toward waste generation promote a stronger influence on behaviour than general attitudes. Similarly, Pandey et al. (2023) argued that individual behaviour and awareness promote effective waste management and are closely tied to education and national consciousness.

In developed contexts, Kumari and Raghubansh [12] emphasised that household-level segregation and recycling are already well established, whereas in developing countries cultural practices and a lack of incentives often hinder the system's uptake. Singh and

Sharma [16] further stress the importance of governance structures that enforce compliance and incentivise sustainable behaviours. The evidence collectively demonstrates that policy and governance structures are deeply interlinked with public behaviour. Strong policy enforcement and regulations alone cannot succeed without public involvement, while behaviour-change campaigns are unlikely to be effective without adequate infrastructure and governance support.

Soft systems dynamics (in the form of causal loop diagrams) can assist in understanding complex WMSs by clarifying the relationships and feedback mechanisms that shape system behaviour. Xiao et al. [13] explained that causal loop diagrams (CLDs) can illustrate how factors such as economic and demographic development, waste generation, and treatment capacities interact over time. For instance, the diagram of the Shanghai MSW management model indicated that GDP per capita and population growth influenced waste generation, whereas sorting rates and treatment capacities determined overall system performance. These interactions are structured through reinforcing and balancing loops, allowing researchers to visualise systems, identify potential strengths for policy intervention, and explore the possible effects of alternative policy scenarios.

Similarly, Brinton et al. [22] asserted the role of CLDs in demonstrating how stakeholder actions, policies, and external influences interact to create feedback loops that either promote progress or stagnate waste management. Their work showed how institutional policies, enforcement, practices, motivation, and material flows combine to explain why specific pathways (e.g., disposal over recycling) are favoured or discouraged within system structures. In addition to guiding the identification of leverage points, CLDs facilitate stakeholder communication and identify areas where interventions and systemic improvements can be supported. This is achieved by establishing a shared understanding of the system's structure and complexity.

3 Research Methods.

This study employed a qualitative research design, collecting data to examine current WM practices and the strategies that facilitate the integration of sustainability in a South African city. Pathak et al. [23] asserted that qualitative research is particularly well suited to understanding people's beliefs, experiences, attitudes, behaviours, and interactions within waste management systems. It provides a humanistic perspective which captures dimensions of reality not measurable through variables alone and gives voice to participants by ensuring their lived experiences and perspectives are central to the analysis. Moreover, this further allows for a more engaged and less formal researcher–participant relationship, fostering openness during interviews.

3.1 Participant selection

The study focused on two waste management companies in a South African city. The companies were purposefully selected based on several criteria: their willingness to participate in the study; the diversity of waste types managed; the availability and reliability of operational records; the size and scope of their operations; and their sustainability initiatives. The sample comprised six participants, and their profiles are outlined in Table 1.

Table 1. Profiles of the participants who were selected in the study

Participant ID	Gender	Position	Years of Experience
Participant 1	Male	National Manager	11 Years
Participant 2	Female	Branch Manager	13 Years
Participant 3	Female	SHERQ Manager	14 Years
Participant 4	Male	Area Manager	10 Years
Participant 5	Male	Branch Supervisor	Two Years
Participant 6	Male	Health and Safety Officer	Five Years

3.2 Data collection

Before data collection, the researcher obtained ethical approval from the university's ethics committee and permission to collect data from the participant companies. The primary data collection method was semi-structured interviews. All interviews were audio-recorded with permission, and additional notes were taken to ensure accurate documentation of responses for subsequent analysis. The interview durations ranged from 25 to 46 minutes. Further data, in the form of documents, were collected as a triangulation source for the interviews. Observation of operation practices within the participant companies was also done. These were completed before the interviews to provide the researcher with an in-depth understanding of the practices and to prepare for the interviews.

3.3 Data analysis

Initially, audio recordings from the interviews were transcribed verbatim using Microsoft Word's speech-to-text functionality. Each transcript was saved as a separate document, organised under anonymous identifiers (e.g., Participant 1, Participant 2, etc.) and grouped by organisation.

The qualitative interview data were analysed using thematic analysis. First, all six interviews were

transcribed verbatim and repeatedly read to familiarise the researcher with participants' perspectives. Second, systematic coding was conducted in ATLAS.ti 25 through a two-cycle process: initial codes were generated inductively from the data, then refined into more descriptive codes that better represented participants' experiences and insights. Third, codes were examined for recurring patterns and organised into overarching themes and subthemes reflecting commonalities across responses. Finally, these themes and subthemes were reviewed and refined to ensure clarity and alignment with the study's focus on sustainability in waste management practices.

The themes provided the analytical foundation for identifying recurring patterns, causal influences, and interrelationships among system variables. These qualitative insights were subsequently translated into SD variables and synthesised into CLDs. Variables for the SD model were derived from qualitative data obtained through interviews, document analysis, and observations. CLDs were developed using Vensim PLE version 10.3.2

4 Results

4.1 Thematic analysis results

Data analysis uncovered four distinct themes, each reflecting the essential aspects of waste management practices, barriers, and strategies for enhancing sustainability. These themes were further organised into sub-themes, as summarised in Table 2.

Table 2. Themes and sub-themes that emerged from thematic analysis

Themes	Sub-themes
Waste management practices	Waste segregation practices Waste collection and logistics Recycling, recovery, and disposal
Policy, governance, and compliance	Regulatory compliance and monitoring Policy influence, collaboration, and incentive mechanisms
Education and community involvement	Awareness and communication campaigns Community education and participation
Barriers to sustainable waste management	Operational and systemic inefficiencies Economic, social, and behavioural barriers Market and quality challenges Governance and regulatory gaps

4.1.1 Theme 1: Waste Management Practices

The first theme describes current WM company practices, following waste from generation and segregation through collection, treatment, recovery, recycling, and final disposal. It includes three key subthemes: waste segregation practices; waste collection and logistics; and recycling, recovery, and disposal.

Participants noted that waste originates from post-consumer sources, including retailers, manufacturers, distribution centres, households, and non-consumer actors such as informal traders. Commercial and industrial waste is often separated on-site, while household waste usually arrives mixed. Segregation combines manual, mechanical, and collaborative methods to maintain quality and compliance. Two sorting approaches were reported: at the facility using labour and machinery, or at customer sites by staff, allowing separation at source before collection.

> Placing on-site sorters at the customer site to separate at source, which would then be collected. Regarding our facility, we have both labour and mechanical sorting. Still, the most significant contribution for us comes from the on-site sorting employees who are permanently on their site. (Participant 3)

Informal waste collectors complementing formal WM practices. They play a key role in separating recyclable materials from general waste. This mobilisation enhanced recycling rates and created livelihood opportunities.

> Informal pickers collect waste from residential houses, sort it, and transport it to facilities. Mobilising informal waste pickers to collect materials creates livelihoods, which is highly beneficial. (Participant 1)

Mill and facility quality requirements also guided segregation practices. This included weighing and recording incoming waste streams and rejecting nonconforming material, underscoring that waste separation does not depend solely on separating recyclables from general waste but also on compliance with standards and market demands.

Participants stressed municipal collection systems for residential waste often rely on mixed collection, which reduces the effectiveness of source separation and increases the risk of contamination. Some companies' logistics networks also involved the collection of recyclables by informal pickers, who supplied clean recyclables. Furthermore, hazardous waste collection necessitates specialised handling and treatment processes; however, some companies hold licenses only for safe transportation, as explained:

> The company is also permitted, licensed, and equipped to transport hazardous waste, but such transport is not managed at this facility. It's purely transportation only. (Participant 3)

The findings showed that operations covered recycling, recovery, and disposal to ensure each waste stream was processed correctly or safely discarded. Upon arrival, waste was weighed on the facility's weighbridges and then moved to designated storage areas to prevent contamination. Recyclables such as paper, cardboard, plastic, glass, and metals were baled and sent to mills or suppliers; organic waste was sent to composting facilities; and general waste was sent to landfills.

The analysis of organisational records over six months provided solid evidence complementing the interview data. The records verified the monthly operational practices for waste management, which involved receiving, handling, recovering, recycling,

diverting, and landfilling of various waste streams. The records also showed that the waste was classified into multiple categories, including commercial, organics, paper, plastics, glass, metals, bottom ash, electronics, construction, and others.

The findings also illustrate how sustainability metrics are operationalised within these organisations. However, substantial proportions were diverted through recycling, composting, or reuse; however, significant tonnages still ended up in landfills each month, underscoring landfills' continuing dominance, especially in months with recovery rates dipping closer to 40 per cent.

4.1.2 Theme 2: Policy, Governance, and Compliance

This theme highlights how government participation and regulatory frameworks affect operational effectiveness, compliance, and sustainability outcomes, reflecting the role of governance in waste management.

Compliance frameworks such as ISO 14000 and the Environmental Waste Act were reported to play a central role in guiding day-to-day environmental management, particularly in reducing pollution, ensuring safe operations, and meeting regulatory expectations. As one participant highlighted:

> All our branches follow ISO 14000 standards. Three branches are formally accredited. The remaining branches align with the same standard and focus on environmental management, pollution, and emissions. We comply with the Environmental Waste Act. This Act replaced former per-site waste management licenses with norms and standards. We conduct internal and external audits annually. The external audit verifies that our internal processes comply with these rules, including those related to contamination control. (Participant 1

In addition to formal audits, participants reported that continuous monitoring systems reinforced compliance. Specialised software applications were reported to capture and track the entire waste flow, from receipt to diversion, recycling, and final disposal, with real-time visibility for branch managers. This data served as both an internal management tool and an external accountability mechanism, as records were submitted to the city's municipal office for verification. The municipality then issued compliance, trade, and safe-disposal certificates, thereby formalising compliance with waste regulations. As another participant explained:

> The city's municipality is where we send both our recycled waste and the waste that goes to the dumpsite, and, in return, it issues us compliance certificates. We always make sure we have the necessary trade and compliance certificates. They also ensure that hazardous waste is safely disposed of immediately and provide us with waste disposal and safe disposal certificates (Participant 2)

Participants noted that, to determine whether waste is destined for treatment, recovery, or disposal, legislative tools such as landfill bans, landfill levies, and zero-waste compliance targets are crucial. In this context, the recent enactment of policies aimed at prohibiting the disposal of specific waste streams (e.g., high-moisture waste) has been regarded as pivotal to the transition of materials toward recovery practices such as composting or refuse-derived fuel (RDF) facilities. However, participants cautioned that RDF and similar advanced recovery technologies require substantial government support and public–private partnerships to ensure feasibility and long-term success.

The findings suggest that rebates and other financial incentives are essential policy tools for promoting SWM. This was found not only to promote proper sorting but also to strengthen the market value of recyclable streams. Moreover, participants asserted the profitability of recycling when separation quality is ensured:

> The rebates: if they provide clean cardboard, we will offer them $0.20 per tonne, which they can claim back; the rebate structure depends on volume and quality. (Participant 3).

Another participant added,

> Recycling is not expensive. It shouldn't cost you a thing to recycle, but it should give you more. It's more beneficial. If it is well separated, you will sell the waste, and the lower the contamination, the more money you will receive. (Participant 5)

4.1.3 Theme 3: Education and Community Involvement

The findings demonstrate that education and community engagement are key drivers for fostering sustainable waste management practices. Participants emphasised the use of various media platforms, including social media, radio, and television, to maximise outreach and influence behavioural change. Communication serves as an information-sharing tool and as a mechanism to shift recycling practices into tangible benefits for environmental preservation, thereby reinforcing both individual and collective responsibility.

> We maintain an extensive ongoing communication campaign and engage on social media. Our communication department is advertising on Facebook what recycling is." (Participant 4)
>
> 'We need to try and educate everybody via radio and television about the importance of recycling. What we're trying to do is every time we recycle, we save a tree. (Participant 6)

Complementing this, the role of schools and community platforms reflects a more strategic approach, whereas education aims to effect cultural change over the long term. Teaching recycling to students in early stages is described by the participants as "changing the mindset of the whole world," suggesting that schools serve as both hubs for intergenerational influence and as places for knowledge transfer. This aligns with the concept that embedding sustainability education into both formal and informal contexts can assist in standardising source separation and make the public more responsible for their actions, beyond short-term campaigns.

> By educating people or running campaigns, particularly recycling campaigns, we would help people understand that employment can also begin, because once you advertise something, you also need to have it. (Participant 2)
>
> Communities, councils, and the public need to be aware of the risks and hazards associated with landfills compared

with facilities such as this one that divert waste from landfills. (Participant 3)

4.1.4 Theme 4: Barriers to Sustainable Waste Management

Despite the existence of policy frameworks and private sector initiatives, the findings reveal a range of barriers that undermine the effectiveness and sustainability of waste management practices within the studied organisations. These challenges reflect systemic inefficiencies, economic and behavioural constraints, persistent quality and market-related uncertainties, and governance gaps.

A recurring barrier identified among participants was the inefficiency of current municipal waste-handling systems. Although households may attempt to separate waste at the source, weak municipal collection practices often dismiss these efforts. This undermines public participation in source separation and increases the operational burden on private facilities, forcing them to rely heavily on informal waste pickers to recover recyclables:

> There aren't enough means for people to separate waste. In households, waste is separated and placed outside, and a municipal truck collects it and places it in the bin. This is also difficult because once it's mixed, there's a risk of contamination, which affects the recyclability of the materials. So, there's no point in separating it from there. We rely heavily on informal waste collectors to collect waste from residents, separate it, and transport it to facilities like ours. (Participant 1)

Private facilities, in turn, are forced to perform double handling, re-sorting, and prolonged processing times. Participants addressed that sorters often spend days sorting contaminated or mixed waste, a process described as both ‘’time-consuming and labour-intensive”.

The interdependence among household practices, municipal collection, and informal sorting reveals that structural weaknesses at all levels can undermine waste segregation efforts, thereby limiting recycling potential and jeopardising the sustainability of the waste management operations.

Economic pressures further exacerbate the sustainability challenge. Alternative technologies like RDF were described as highly effective but prohibitively expensive:

> RDF is an effective solution for diverting many materials from landfill to an incineration process with energy recovery. If I can qualify, so burning to get something, it's an excellent solution. Unfortunately, the cost is 20 times what landfill is.’’ (Participant 5)

Similarly, zero-waste-to-landfill mandates, though environmentally desirable, were repeatedly described as “very possible but very expensive”, as well as high compliance costs and safety requirements, including external audits and health and safety measures, which exacerbate these pressures, with participants noting that “legal compliance is expensive”. The situation is further aggravated by inflation, which escalates the input costs of materials essential for recycling processes. Investment in sustainable practices is therefore discouraged, as recycling remains economically disadvantaged compared to cheaper landfill disposal.

The participants suggest that households and waste producers are often unwilling to pay for services due to limited awareness of the benefits, with convenience being a strong influence on behaviour. Ultimately, the findings suggest that there is an absence of strong incentive and penalty mechanisms to shift public behaviour, reinforced by the prevailing perception of a finite landfill capacity, and waste will ultimately end up in landfills regardless of individual actions. This perception discourages motivation, as there is no reward or punitive system for recycling. As the participant noted:

> Human behaviour will always dictate parts of the path of least resistance. If it is an effort for me to separate and get it into a recycling stream, I’m just going to mix it and throw it into the landfill. (Participant 1)

Another barrier identified across organisations concerns the stability of recycling markets, where both quality assurance and feedstock are challenging to sustain. Contamination of incoming waste was repeatedly reported as a disruption, with participants underscoring that the presence of glass, metals, and other impurities reduces processing efficiency, thereby causing operational delays and directing considerable volumes to the landfill. As one participant stated:

> Contamination of composting and chipping materials with glass, metal, and wood is prohibited; such contamination disrupts processes and delays our work. There are still unseparated or contaminated waste that is not recyclable or recoverable and will end up in landfills, thereby impacting the quality of work. (Participant 3)

In addition to contamination, seasonal fluctuations in material streams introduce further instability. Packaged waste, for instance, is more abundant in summer but declines in winter as boxes are diverted for household fuel rather than for recycling. Such fluctuations undermine operational planning and exert pressure on labour productivity, as participants observed varying levels of workforce efficiency across seasons. Explained by the participant:

> We also have seasonal packaging as a factor. In winter, we have less packaged waste, since people don't drink much, and boxes are also scarce because people are burning them for warmth instead of recycling them. However, in the summer, we get many of them. (Participant 2)

The organisational records indicate clear seasonal fluctuations in waste volumes, with pronounced peaks in summer, particularly in January, and troughs during the winter months. Monthly variations in waste received and handled reveal a systemic vulnerability to these seasonal patterns, a concern repeatedly highlighted in interviews. The first organisation reported recovery rates varied dramatically, from 45 per cent in lower-performing months to 90 per cent at peak efficiency in February. The second organisation experienced a narrower but still significant fluctuation between 40 per cent and 59 per cent, with the highest recovery also occurring in January. These variations indicate bottlenecks in capacity, workforce, and logistics, which challenge the consistency of operational performance. Although sustainability outcomes are defined by the proportion of waste diverted from landfill, they are not

directly diminished by seasonal volume changes. Reliance on landfill during lower-recovery months highlights the pressures on infrastructure and processes to maintain high diversion rates throughout the year.

4.2 Causal loop diagrams

Fig. 1 shows the graphical representation of the study results. The diagram incorporates the key variables and the cause-and-effect relationships among policy, economic, social, and operational variables within the waste management system, as identified in the thematic results. It also depicts the dynamic interactions between waste segregation, collection efficiency, market demand, governance, technological innovation, and landfill reliance. The developed CLD model combines these relationships into an integrated visual framework that explains the system's behaviour through both reinforcing and balancing feedback loops.

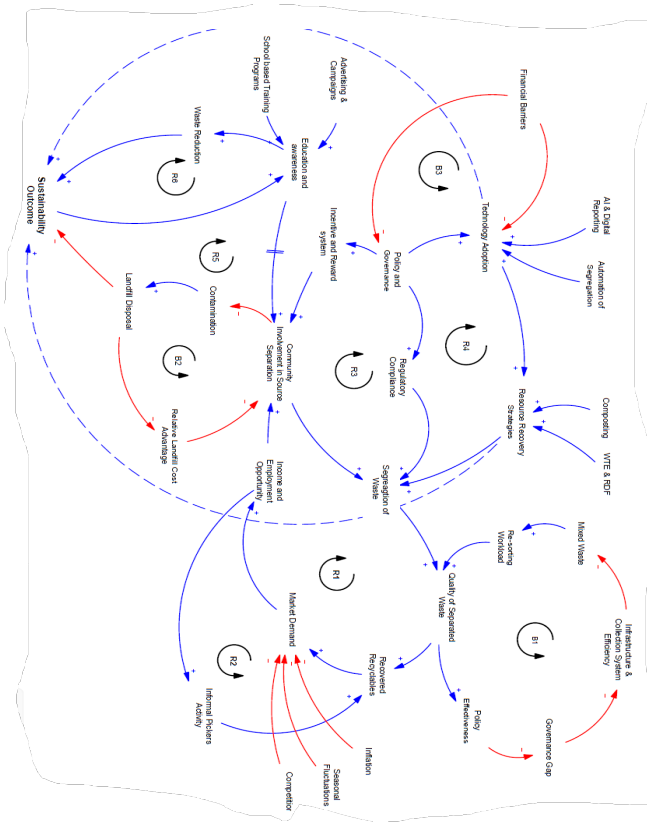

Fig. 1. Causal loop diagram of urban waste management practices, enablers, and barriers in a South African city

Dashed arrows indicate that the causal effects of technology adoption and resource recovery strategies on sustainability outcomes are indirect and long-term, arising due to internal operational practices and system adjustments over time. Double-dashed arrows indicate the delayed effect: improvements in education and awareness take time to produce a tangible change in community behaviour and participation in waste management systems.

5 Discussion

The findings suggest that organisations under study demonstrated how WMS encompasses the following interconnected practices: waste segregation, collection, recycling, recovery, disposal, and regulatory compliance and monitoring. Two main segregation practices were identified: first, manual and mechanical sorting at company facilities, and second, on-site sorting by staff who are permanently at customer premises. Informal pickers also played a critical role in providing recovered recyclables, thus creating livelihood opportunities. These findings align with the broader narrative in the literature on developing nations, as in which informal waste collectors substantially supplement recycling systems [12, 15]. However, mixed waste delivered directly to the facility has posed significant challenges, as separating waste in such instances was labour-intensive, time-consuming, and associated with a high risk of contamination.

Collection and transportation were primarily conducted using organisation-owned trucks, which collected separated recyclables from informal pickers and business clients and delivered them to recycling branches or designated areas within facilities for end users. Upon arrival, all incoming waste was subjected to quality inspection, weighed at weighbridges, baled, and then sent for recycling. Although separation at source was encouraged by placing sorters on-site and recycling bins, companies still faced the risk of receiving mixed waste streams. These contaminated loads were detected and rejected by quality controllers, who redirected them to registered landfills. Moreover, municipal collection systems, particularly in residential areas, relied heavily on mixed-waste collection, thereby undermining source separation and increasing contamination rates. These findings align with the observations of Abubakar et al. [24] who noted that, in developing countries, the mixed collection of household waste and poor transportation systems compromise sustainability, posing significant harm to humans and the environment.

These insights highlight that waste is currently managed through a dual system: private companies operate structured, relatively efficient logistics for business clients. At the same time, municipal collection practices continue to undermine source separation. Furthermore, the findings emphasised that recycling and recovery are central to current waste management practices. Recyclable materials were separated according to buyer and mill requirements, while organic waste was directed to composting facilities. These practices demonstrate structured operational practices aimed at diverting waste from landfills while fulfilling market demands and compliance requirements. Despite these efforts, landfill disposal remains the dominant final endpoint for large waste volumes. Non-recyclables, mixed general waste, and post-treatment hazardous waste were routinely landfilled because landfill gate fees were lower than those for alternative treatments. This factor has reinforced the continued presence of landfills as the primary disposal route. However, the push for more sustainable disposal practices has been strengthened by recent legislative changes governing bidding for the disposal of high-moisture organic waste.

For instance, the literature reports the reliance of developing countries on open dumps as a primary waste-

disposal method, which releases uncontrolled toxic gases [12, 24]. Conversely, the organisations utilised registered and engineered landfills for non-recyclable and mixed waste, indicating more controlled and legally compliant behaviour compared with the illegal dumping practices commonly observed in developing nations. This study suggests that South Africa's system reflects a fragmented structure: on the one hand, formal organisational practices emphasise compliance and environmental responsibility; on the other, informal and often unsustainable practices remain prevalent, as studies have frequently pointed out. Organisational records supported these findings, reporting fluctuations in recovery rates between 40 per cent and 90 per cent across months. Furthermore, the data highlighted variability in the quantities of waste received, recycled, and recovered, driven by external factors such as seasonal fluctuations, inflation, and competition, which influence demand for recyclables.

Additionally, WM practices in South Africa are strongly framed by regulatory frameworks and international standards. Organisations adhere to ISO 14000 standards and the national waste management legislation in their daily operations to ensure safe handling, minimise pollution, and maintain regulatory norms. Importantly, continuous monitoring systems and implementation were adopted to track waste flows and provide verifiable data for municipal scrutiny. Compliance and safe-disposal certificates issued by the city's municipalities reinforced accountability and regulatory compliance. Moreover, companies also adopted brand protection measures to prevent unethical practices and apply carbon footprint reporting to quantify environmental benefits. While some developing nations lack international and formal standards governing waste systems, organisations demonstrate formal compliance with ecological standards and legislation. This finding suggests notable progress toward a more regulated and traceable waste system in South Africa, reflecting a hybrid system that integrates formal compliance mechanisms with ongoing operational inefficiencies.

Several operational and systemic inefficiencies were identified as compromising the system's sustainability. Inflationary pressures increased operational costs related to waste collection, logistics, and processing, forcing organisations to choose landfill disposal of materials that could otherwise be recovered or diverted. Additionally, competition among recyclers has created volatile supply relationships with clients and informal waste pickers. Seasonal variations, driven by changes in consumption behaviour, further affect the material availability and recovery rates. These constraints render landfill disposal more favourable than recycling and recovery practices. This is consistent with the literature, which emphasises that weak policy enforcement, infrastructural and financial constraints, and limited treatment facilities remain dominant barriers in developing countries, particularly in South Africa, underscoring the persistence of these systemic issues [14, 17, 18].

In addition, public resistance to paying for waste services, driven by limited awareness and knowledge gaps about the benefits of recycling, also contributes to inefficiency. Misconceptions regarding finite landfill capacity and the perception that waste inevitably ends up there reinforce unsustainable practices. Collectively, these fluctuations create structural barriers to market stability and growth, ultimately undermining the overall sustainability goal. Similarly, the role of public behaviour identified in this study aligns with the literature linking education, awareness, and policy enforcement to positive attitudes toward sustainable waste management [21]

The visual synthesis of these findings is displayed in Fig. 1. The CLD depicts the operation of the current WMS as a nonlinear, interconnected process that reinforces or constrains one another through feedback loops. The causal links among segregation, recycling, recovery, and informal picker activity are represented through the reinforcing loops R1 and R2. Hence, increased segregation leads to higher recovery rates, which, in turn, increase market demand and income opportunities, thereby fostering further participation. Nevertheless, B2 limits the overall sustainability outcome.

The findings suggest that achieving sustainable WM requires a multipronged and integrated approach. Effective governance requires an integrated regulatory control and incentive mechanisms to drive compliance and positive behaviour. Public-private partnerships are regarded as central to bridging these two dimensions, ensuring that policy objectives are successfully translated into practice. Furthermore, the findings highlighted that the adoption of large-scale recovery technologies, the use of motivational tools and financial incentives such as rebates or reward schemes, and the availability of infrastructure, especially nearby treatment and recycling centres, are key enabling factors to enhance material value, boost market demand for recyclables, and ultimately reach economic sustainability goals. These findings are consistent with the literature, as Chisholm et al. [20] emphasised the role of decision-makers and policy interventions in the adoption of environmentally friendly technologies for treatment and disposal, while also generating economic benefits. Additionally, Singh and Sharma [16] and Nyika et al. [14] emphasised the importance of partnerships, infrastructure development, and incentive-based systems for improving sustainable integration across waste systems.

5.1 Implication of Study Findings

The study identifies three implications for waste management practices in South African cities. First, the findings underscore the importance of source separation in reducing contamination and enhancing recycling potential. Effective collaboration between municipalities and waste management companies is essential to enforce segregation policies. Second, financial incentives and regulatory mechanisms emerge as critical drivers of behavioural change. Instruments such as landfill fees, reward-and-rebate systems, and compliance enforcement can encourage sustainable practices and landfill diversion. Regulatory bodies

should design cohesive incentive schemes and align financial signals with sustainability objectives to improve recycling rates and advance environmental goals. Third, public awareness and education remain key enablers of effective waste management. School-based programs, targeted media campaigns, and community outreach initiatives can influence behaviour, increase compliance, and foster responsible waste practices. These interventions strengthen stakeholder engagement and reinforce sustainability outcomes across the system.

5.2 Limitations

This research was restricted by several limitations that provide direction for future studies. Although the SD approach typically involves both qualitative and quantitative methods, this study focused solely on the qualitative approach, specifically the development of the CLD model. This model served as the initial and conceptual stage of SD model development. However, the absence of quantitative data limited the study's development towards the stock-and-flow diagram (SFD) simulation model. Future studies should extend the CLD model developed from qualitative data into a process-based quantitative SFD simulation model. This model would allow simulation and testing of various scenario situations to examine the ideal situation and adjust all variables to the values that produce the desired outcomes

Although attempts were made to engage a broader range of organisations, only two companies agreed to participate due to the sensitivity of the requested information and confidentiality aspects. This limited the diversity of perspectives and operational settings represented. Nevertheless, the data collected were sufficiently fertile and condensed to support the qualitative system analysis.

6 Conclusion

The study employed a qualitative system dynamics approach to evaluate the sustainability of waste management in a South African city. The study's findings revealed a fragmented dual system. While private organisations demonstrate high formal compliance with ISO 14000 and national legislation, municipal practices often remain inefficient, particularly through mixed-waste collection that undermines source separation. Consistent with literature on developing nations, informal waste pickers were found to be critical to the system, providing essential recovery services and creating livelihoods. However, barriers such as high costs of advanced technologies (e.g., RDF), seasonal fluctuations, and the absence of punitive measures for non-compliance continue to favour landfilling over recovery. The findings suggest three primary implications for enhancing sustainability: (1) municipalities and private firms must align to enforce source separation and reduce contamination, (2) implementing landfill levies and rebate systems is essential to shift behaviour toward recycling, and (3) targeted awareness campaigns and school programs are vital to foster long-term cultural change and responsible waste practices. The causal loop diagram provides a conceptual foundation for future quantitative simulations to optimise urban waste systems.

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