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ABSTRACT

The performance of waste management systems in cities has to improve to cope with rapid urbanisation and population growth trends. It is, therefore, necessary to develop a more in-depth understanding of how potential interventions may impact and improve the performance of waste management systems. This is particularly the case for countries in the Global South, in their pursuit of further progress towards sustainable development. This paper develops a system dynamics model to evaluate interventions in the solid waste management system of Accra, where rapid urbanisation and population growth will place its waste management system under increasing strain over the next decades. The model is used to evaluate interventions as to whether they can increase circular waste flows, reduce disposal to landfills and, thus, improve system performance in upstream source separation, midstream waste collection, and downstream waste treatment. The findings reveal that the government's planned expansion of waste recovery capacity in Accra addresses only part of the challenge and will be inadequate to manage the city's accelerating waste generation. The simulation results underscore the necessity of adopting an integrated approach to improve system performance and achieve progress toward sustainability goals. This involves educational interventions for raising awareness and infrastructural interventions across the whole value chain. This analysis improves our understanding of the critical bottlenecks and synergistic effects of upstream, mid-stream and downstream interventions. It also supports policy and decision-making by drawing attention to the delays and potential negative trade-offs involved between interventions.

Keywords: Waste management system, System dynamics modelling, Circular economy, Global South.

JEL: Q53, O13, Q01, C61, R11.

1. Introduction

Urbanisation, economic growth, and rising consumption contribute to unprecedented volumes of municipal solid waste, and turn waste management into one of the most pressing priorities of sustainable development for the twenty-first century (UN, 2024). Today, the world generates about 2.3 billion tons of solid waste annually, a number that is expected to grow by over 70 per cent by 2050 (UNEP, 2024). In developing regions, particularly in Sub-Saharan Africa, waste generation rises faster than the capacity of local systems to manage it safely. More than 90 per cent of waste in low-income contexts is still disposed of in unregulated dumpsites or burned in open air (Kaza et al., 2018; World Bank, 2022). These practices have far-reaching social, economic, and environmental consequences, and they underscore the urgent need to design sustainable and adaptive Solid Waste Management (SWM) systems that can cope with rapid urban and demographic growth.

In response to this need, many policy interventions in the Global South have been implemented but remain short-term and fragmented. They often prioritise visible, end-of-pipe solutions, such as landfill expansion or sporadic collection upgrades, instead of addressing the structural inefficiencies that exist along the SWM value chain (Salvia et al., 2021). This reinforces path-dependent behaviours and institutional inertia in the system, and as a result, dumping and uncontrolled landfilling remain socially and politically legitimate (Abubakar et al., 2022). This linear regime of "collect-and-dispose" hinders the adoption of Circular Economy (CE) practices that could transform waste from an environmental liability into a source of material recovery, job creation, and urban resilience.

The transition from linear to circular SWM systems requires systemic interventions that span the entire value chain, from upstream waste prevention and source separation, to midstream collection and logistics, and downstream treatment and recovery (Geissdoerfer et al., 2017; Xiao et al., 2020). A transformation of this scope calls for an integrated approach that balances technical feasibility, financial sustainability, and social acceptability (Abdel-Shafy & Mansour, 2018). CE provides a guiding framework for this shift, which aligns with the principles of Integrated Solid Waste Management (Asefi et al., 2020; Marshall & Farahbakhsh, 2013) on how to minimise landfill use, reduce virgin material consumption, and maximise environmentally sound recovery of materials and energy (Arena & Di Gregorio, 2014). Yet, in practice, the dynamic interdependencies and feedback mechanisms in these systems remain poorly understood, particularly in the fast-growing cities of the Global South (Tomai et al., 2024).

Against this backdrop, the objective of this study is to explore potential pathways for the design of sustainable SWM systems in developing countries so that they can cope with increasing volumes of waste, while transitioning into a CE mode of operations. This study utilises a mixed-method approach that combines participatory System Dynamics (SD) and modelling and simulation to examine how population and waste-generation trends influence Accra's SWM system performance up to 2040. SD modelling is well suited to capture the non-linear feedbacks, time delays, and accumulations that characterise complex socio-technical systems (Sterman, 2000). Building on stakeholder interviews, focus-group discussions, and participatory workshops in the Greater Accra Metropolitan Area (GAMA), the model simulates five "what-if" scenarios (Sterman, 2015; Sterman, 2012) that test alternative interventions across three critical stages of the value chain: (i) upstream waste separation at the source, (ii) midstream collection efficiency, and (iii) downstream treatment and diversion to landfill.

The analysis contributes to the literature on SD-based circular-economy transitions in the Global South by showing how demographic pressures and system feedback interact to shape urban waste outcomes. The findings demonstrate that the expansion of waste-recovery capacity alone will be insufficient to manage Accra's rising waste generation in the coming decades. Instead, a combination of educational and infrastructural interventions across the value chain, is necessary to strengthen system resilience, enhance resource circularity, and support progress toward sustainability goals.

The remainder of this paper is structured as follows: Section 2 outlines the methodological framework and data sources; Section 3 provides the methodology; Section 4 describes the model development process; Section 5 presents the scenario design and simulation results; Section 6 discusses policy implications and research limitations; and Section 7 concludes.

2. Transitions and urban waste challenges in the Global South

2.1 Sustainability Transitions in the Global South

Sustainability transitions are complex, non-linear processes that are driven by the interplay of environmental, technological, economic, and socio-political factors (Köhler et al., 2019). Yet, in the context of Global South, transitions exhibit an even higher degree of complexity that stems from pervasive informality, institutional and financing constraints, policy discontinuities, heterogeneous stakeholder incentives, and pronounced exposure to climate and socio-economic shocks, which differentiate transition trajectories from those typically observed in the Global North (Tomai et al., 2024). While the goals of sustainability transitions in Western economies are often framed as 'carbon neutral, 'blue-economy', and 'zero-waste', the challenges in the Global South concern the lack of clean water, increasing waste production and dumping, heavy pollution from energy systems, and inefficient mobility are just a few of the grand sustainability challenges developing countries are facing today (Oates, 2021). In this context, contemporary realities urge us to push the boundaries of sustainability transitions research to capture the realities, complexities, and nuances of transition dynamics across diverse regions of the world.

Solid waste management in developing countries is a long-standing problem. In many countries, the SWM system still operates under a linear economy-based traditional approach (i.e., 'take, make, use and dispose of') where materials are discarded at the end of their life cycle, and only a small portion undergoes limited processing to regain value and re-enter the system (Guerrero et al., 2013; Zhang et al., 2024). Moreover, the rapid population growth and urbanisation outpace countries' capacity to collect, treat, and dispose of waste safely (ISWA, 2024; UNEP, 2024). These results, among other things, to overflowing dumpsites, open-air burning, and leakage into waterways, and underscore the urgency of moving away from short-term, reactive waste management practices and quick fixes, toward integrated, sustainable systems that address the root causes of inefficiency and promote long-term resilience.

In a circular economy frame, waste is seen as a set of material and nutrient sources to be retained, reprocessed and upgraded rather than disposed of. This opens several possibilities for rapidly urbanising, resource-constrained regions. First, it enables a shift from end-of-pipe waste services to material stewardship regimes in which cities function as "urban mines," with secondary resources systematically mapped, certified, and utilised as inputs to local industry, potentially easing foreign-exchange pressures tied to imported raw materials (Hadfield et al., 2025; Márquez et al., 2025). Second, product-service system logics (leasing, repair, remanufacturing) expand the design space for firms and municipalities to align incentives around longevity and recoverability, creating new roles for informal and micro-enterprise actors in refurbishment and reverse-logistics (Conlon et al., 2021). Third, circularity provides a coordinating framework for industrial symbiosis and bio-circular pathways (e.g., organics to soil carbon and waste-to-energy), linking sanitation, food systems, and climate mitigation under shared metrics (Rezania et al., 2023; Wei et al., 2022). Finally, a circular lens foregrounds distributional and governance questions, suggesting research avenues on inclusive formalisation, price-stabilisation mechanisms for recyclables, and policy mixes that decouple material consumption from welfare without reproducing environmental injustice (Friant et al., 2020).

2.2 System dynamics modelling for sustainability transitions

The complexity and interconnectedness of elements within a socio-technical system, such as the SWM system, require methodological approaches that can account for the nonlinear feedbacks, time delays, trade-offs, and regime lock-ins within the system (Köhler et al., 2019). Previous studies emphasise the need for adaptive frameworks and case-based inquiry that draw out learning from situated practices, rather than imposing universal models or metrics (Hadfield et al., 2025; Tomai et al., 2024).

SD is an appropriate tool for the study of system behaviour and the relationships between key variables of interest (Forrester, 1961). It is a modelling approach and methodology for analysing large-scale, complex systems and phenomena (Sterman, 2000). SD modelling provides a language to map causal links in a system, examine the endogenous dynamics that enable, accelerate, slow down, or block change in a system (Richardson, 2011), and explore different scenarios of system change with plausible interventions and outcomes. This makes the System Dynamics methodology an appropriate approach for the study and exploration of transition pathways in this context.

SD includes two complementary forms: qualitative modelling, which focuses on creating causal loop diagrams (CLDs) to illustrate dynamic interactions among factors (Luna-Reyes & Andersen, 2003; Wolstenholme, 1990), and quantitative stock-flow models (SFM), which simulate the dynamic effects of these interactions over time. Qualitative modelling involves participatory processes in an interview or workshop setting with problem stakeholders (Andersen et al., 1997; Andersen et al., 2007; Vennix, 1996). Quantitative modelling builds on the qualitative conceptualisation by establishing mathematical relationships between variables to model the system behaviour and resource levels over time. The SD fundamental structural elements include: stocks, flows, causal chains (information links) that create feedback loops, and converter variables, which represent constants, limiting factors, or auxiliary operations (Richardson, 2011).

SD has been widely employed to analyse the complexities of sustainability transitions and to inform policies designed to manage these processes effectively (Holtz et al., 2015; Köhler et al., 2018; Papachristos, 2014, 2019). The strengths of SD modelling in this context are that it: (i) captures feedback loops and unintended policy consequences over extended timeframes, (ii) allows for the simulation of various policy scenarios through computer modelling, and (iii) identifies leverage points where small adjustments can yield substantial effects on system behaviour. SD models are created in graphical user interfaces that make the structure clear and accessible to non-modellers (Black, 2013; Ghaffarzadegan et al., 2009).

SD models have provided valuable insights for managing sustainability transitions across various domains, including the shift from fossil fuels to renewable energy sources (Laimon et al., 2022), sustainable transportation systems (Rees et al., 2017), sustainable agriculture and land use (Walters et al., 2016; Wang et al., 2022), sustainable built environment (Chen et al., 2025; Liu et al., 2025; Papachristos, 2020) and natural resource management (Turner et al., 2016). In the specific fields of SWM and CE transitions, SD is extensively employed for optimal policymaking and scenario analysis. Notably, Guzzo et al. (2022) present an SD-based framework for examining CE transitions and facilitating decision-making processes. Xiao et al. (2020) explore the effects of various policies on the performance of SWM systems using an SD approach, while Wiman et al. (2023) identify high-impact intervention points for plastic recycling. Additionally, there are some applications of SD models in developing countries, though these are more limited in scope (Chaudhary & Vrat, 2020; Dianati et al., 2021; Sufian & Bala, 2007).

3. Methods

This section provides some necessary background to the case of Accra and details why it is a compelling case study for the investigation of how urbanisation and other socioeconomic trends are likely to shape the performance of the SWM system in the coming years.

3.1. Study area

The Greater Accra Metropolitan Area (GAMA) is Ghana’s administrative and economic capital. It is the country's most densely populated region, home to approximately 5 million residents, which contributes around 25% to Ghana’s gross national income (Addae & Oppelt, 2019). GAMA consists of 26 Metropolitan, Municipal, and District Assemblies (MMDAs), with the most prominent being the Accra Metropolitan Area (AMA), Tema Municipal Area (TMA), and the Ga West, East, South, and North Municipal Areas (see

Figure 1). This region is also strategically important, as it hosts Ghana’s only international airport and one of the country’s two seaports.

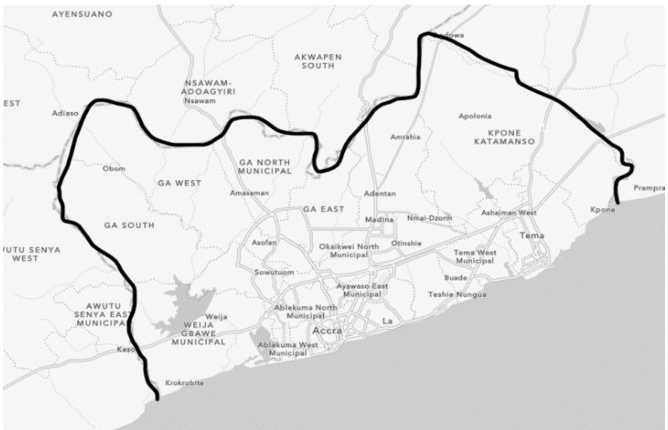


Figure 1. The area of Greater Accra Metropolitan Area (GAMA) of Ghana (Source: Map generated from Arcgis)

GAMA has experienced rapid urban population growth from 3.6 million in 2013 to 4.7 million in 2020 (World Bank, 2020) (see **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**a). According to Ghana’s 2010 population and housing census, 50.9% of the country’s population lives in urban areas, with the Greater Accra region being the most urbanised at 90.5%. GAMA’s population is projected to double by 2037 (WHO, 2023) and reach 10.5 million by 2040 (Addae & Oppelt, 2019; Ghana Statistical Service, 2024; Quartey, 2023). This rapid growth is placing enormous strain on urban infrastructure, public services, and the natural environment (Korah et al., 2025). Nevertheless, this trend mirrors broader urbanization patterns across Africa and Ghana, both of which are projected to experience significant increases in urban population over the coming decades (see **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**b).

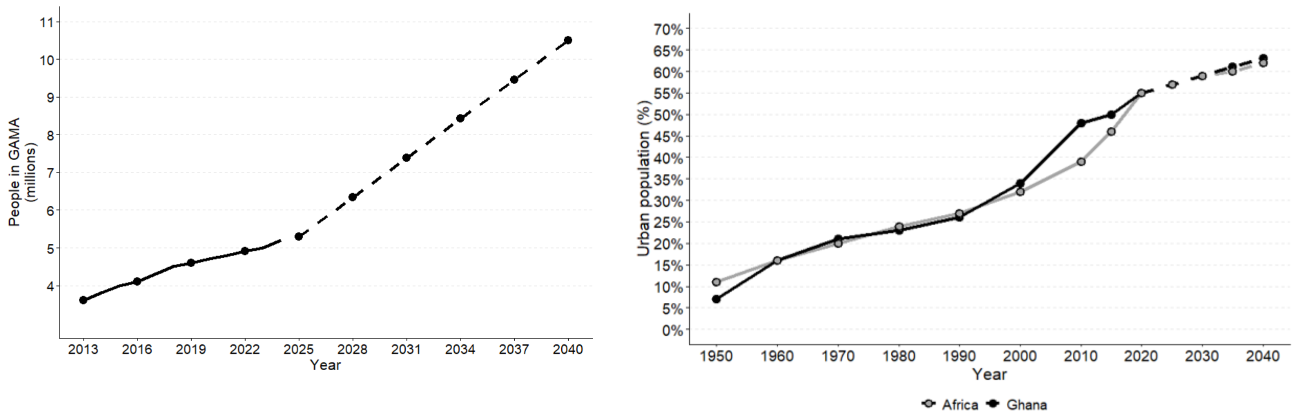


Figure 2. Population and urbanisation trends: (a) population growth in GAMA (left), (b) urbanisation growth in Africa and Ghana (right). (Source: Africapolis database)

In Ghana, municipal waste management falls under the purview of two key government ministries: the Ministry of Sanitation and Water Resources and the Ministry of Environment, Science, Technology and Innovation (Keesman, 2019). The country’s waste management framework is guided by the National Environmental Sanitation Policy (2010), the National Environmental Sanitation Strategic Action Plan (NESSAP), and the National Plastic Waste Policy. Based on these policies, service delivery priorities for the SWM system in GAMA include: (i) universal waste collection to eliminate indiscriminate waste disposal and eradicate open burning in the long term, (ii) systems for efficient and effective waste treatment and processing[1] and (iii) infrastructure for safe waste disposal (Amankwaa & Boafo, 2021). In correspondence to these priorities, policy interventions and investments have been made over the past two decades, including the privatisation of waste collection operations and significant investment in waste transfer, waste treatment and landfill facilities (World Bank, 2017).

The GAMA region is currently served by two main SWM facilities: IRECOP and ACARP, with a processing capacity of 400 and 600 tons per day, respectively (Darteh et al., 2021). In these facilities, municipal waste, which consists of household and commercial waste, is sorted into compostable organic matter, recyclables such as plastics, paper/cardboard, metals, and residual waste destined for landfills (Sarquah et al., 2023). This process aims to recover organic materials for composting and reclaim valuable recyclables. Bulky items, metal scraps, cardboard, and glass are removed, while bags are opened to prevent blockages. Organic waste is separated mechanically using trommels and then processed into compost through biological treatment. Ferrous metals are extracted via magnetic separators. Any remaining waste is classified as residual and is transported to adjacent landfill sites for disposal.

The role of the informal sector in the SWM system is crucial, especially in managing waste flows and improving resource recovery. About 24% of Accra's total workforce is employed in the informal waste management sector (UNFCCC, 2024). These workers are on the frontline of the day-to-day waste collection and recovery operations, collecting about 51% of waste in GAMA (Mensah & Agyabeng, 2024; Oteng-Ababio, 2024).

3.2 Data types and sources

The model development for Accra's SWM system was informed by a three-month fieldwork in Ghana, which included thirty-two semi-structured interviews with key informants, along with extensive field observations and a one-day stakeholder workshop. To capture the breadth and depth of participant engagement, qualitative data were collected based on systems thinking principles (Luna-Reyes & Andersen, 2003). Data were

[1] See the Ghana Clean-up Project: https://smepprogramme.org/project/riverrecycle-oy/

gathered through structured observation protocols that documented participant interactions, use of systems language, and engagement with key concepts such as feedback loops and leverage points. In-session artefacts, including system maps, causal loop diagrams, and behaviour-over-time graphs, served as tools that helped us capture participants' knowledge and understanding of the system, its key mechanisms and problematic behaviour.

Interviewees included municipal assemblies, service providers, researchers, government officials and citizens (see Table A.1 in the Appendix). This provided a diverse range of perspectives and enhanced the reliability and richness of the data collected. The interview insights were instrumental in defining problematic system behaviour, constructing the dynamic hypothesis, and developing the model. During a final workshop held in Accra, participants provided input for the scenarios that were later simulated in the model.

Primary data played a critical role in revising the system structure and enhancing its granularity, ensuring that the model more accurately reflects local realities and stakeholder perspectives. Where specific data were unavailable, assumptions were made based on regional or national-level information, and these are also documented. In addition to primary data from interviews and workshops, secondary data sources were used to build and parameterise the model. These sources included peer-reviewed scientific publications, policy documents, datasets from the Ghana Statistical Service, and reports from international organisations. Detailed data inputs, including values, units, and sources, are provided in the Appendix (Table A.2). Literature-based data supported the development of the initial structure of the SWM system in Accra.

4. SD model development

This research followed the five-step process in Sterman (2000) for SD modelling and simulation: 1. Problem Articulation, 2. Formulation of the Dynamic Hypothesis, 3. Formulation of a Simulation Model, 4. Model Testing, and 5. Policy Design and Evaluation. These five steps are further complemented by domain-specific knowledge for the CE transition (Guzzo et al., 2022). This section outlines the development of GAMA's SWM system using the SD methodology and the five steps. The first four steps are detailed in the subsequent subsections, while the fifth step, focused on designing policies and strategies based on the outcomes of the model under various scenarios, is addressed in Section 4. The dynamic behaviour of key problem variables and trends was elicited and validated during the model development process. Modes of validation used include comparison to statistical data from the Ghana Statistical Service, literature, and expert judgment.

4.1. Problem articulation and sub-model structure

In the first step, the dynamic behaviour of key problem variables and trends was elicited and validated with stakeholders during the model development process. The SWM system of GAMA follows a linear mode with limited circular flows integrated into its operation. The system's problematic behaviour is evident in three places: (i) upstream where the rate of waste separation at the household level is close to zero, (ii) midstream where waste collection coverage is sub-optimal and ranges from 40 to 60%, and (iii) downstream where there is low-value generation from End-of-Life (EoL) waste treatments, such as recycling.

The average waste generation rate for households is about 0.70 kg per capita, with low-income areas generating 0.51 kg per capita, and high-income areas 0.91 kg per capita (AMA, 2020). Studies report varying results with regards to collection coverage, with some evidence suggesting an average of 75% (Oduro-Appiah et al., 2017), while experts in the field estimate it to be lower, ranging between 40-60%. Overall, collection coverage has increased during the last decade, mainly due to the involvement of the private sector and the introduction of the public Public-Private Partnership (PPP) franchise agreements (Adedara et al., 2023; Oduro-Kwarteng & van Dijk, 2013) (see Figure .a). Approximately 62% of waste is disposed of in controlled landfills, while the reported recycling rate of 5% reflects both poor measurement practices and limited commitment to diverting waste from landfills (Darteh et al., 2021; Oduro-Appiah et al., 2017). Source separation remains minimal, with rates near zero, while the only reported cases are found to be pilot projects operated in a few selected neighbourhoods in GAMA (Figure 3.b.).

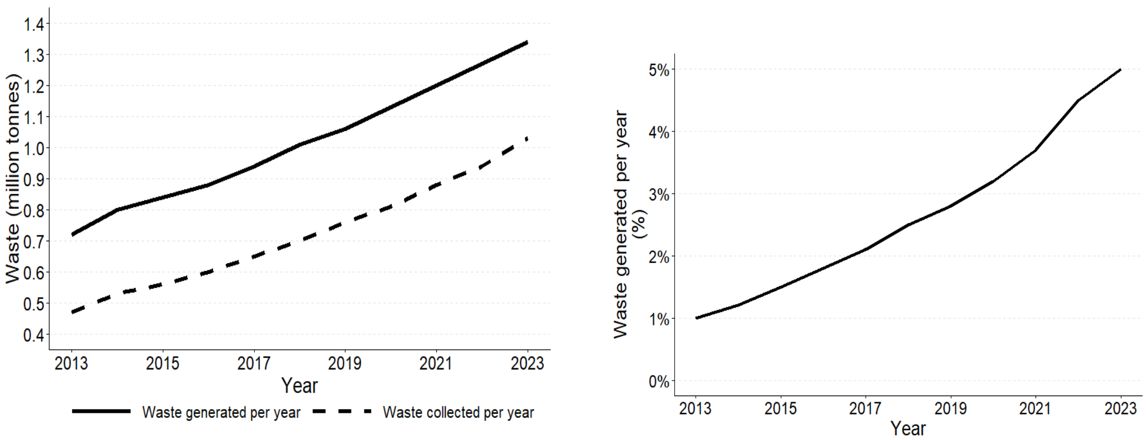


Figure 3. Trends over time for key variables of interest in GAMA (a) waste generated and collected per year (left), (b) Separation rate at source per year (right)

The structure of GAMA's SWM system consists of three interconnected sub-systems, as illustrated in

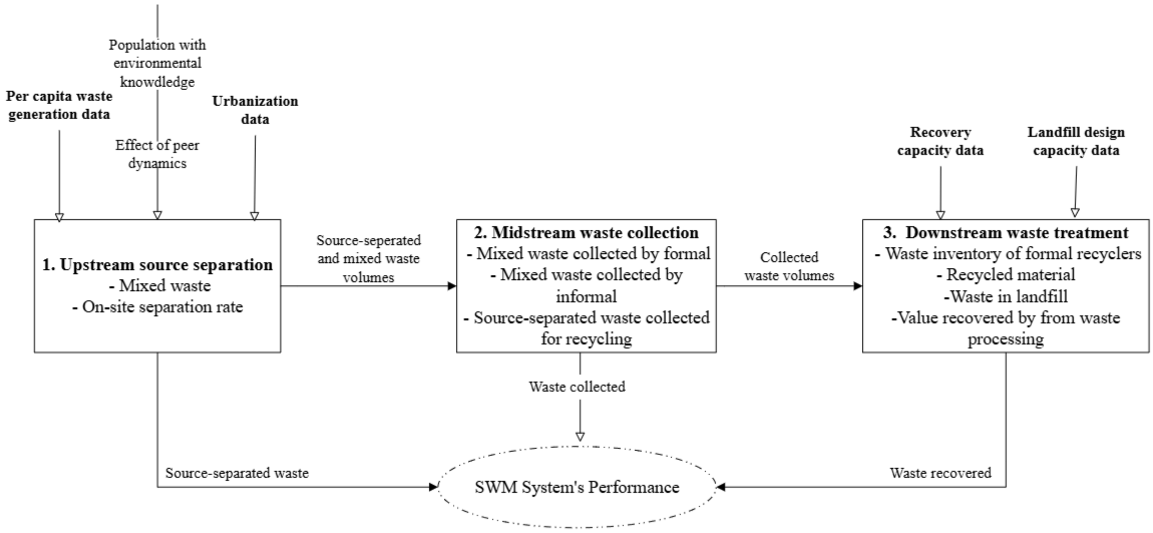


Figure . These sub-models represent the core structure of the SWM system, as it has been derived from this analysis and collectively depict the interconnected challenges and opportunities for transitioning towards a more circular waste management model. The Upstream Source-separation sub-system (1) covers waste generation and sorting rates at the household level. This sub-system focuses on how waste is initially produced and managed, with an emphasis on sorting practices, or lack thereof, at the source. It is directly influenced by population dynamics that drive waste generation rates and place increasing pressure on the system as the city continues to become more urbanised (Akubia et al., 2020). It also encompasses variables related to the population's environmental knowledge, which significantly influences waste management practices (Kanhai et al., 2021). The Mid-stream waste collection sub-system (2) outlines the waste collection process, involving services provided by both the formal and informal sectors. Lastly, the Downstream waste treatment sub-system (3) encapsulates all value-creation activities within the system, such as recycling and composting. This sub-system also tracks waste that is either landfilled or dumped, which has not been processed for recovery. The processes and flows of each sub-model are explained in further detail in section 4.3.

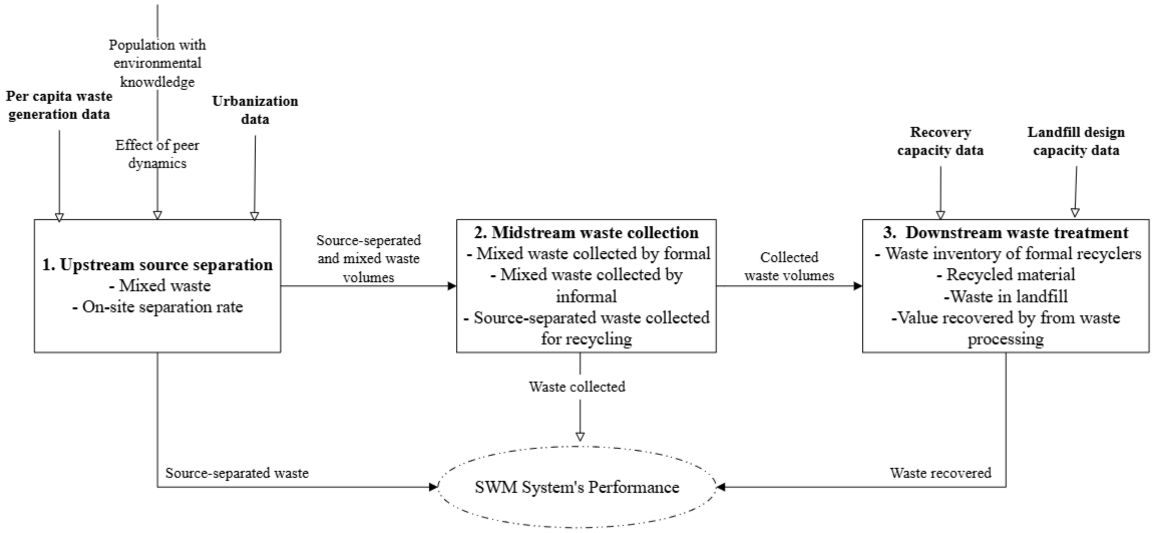


Figure 4. Structure of the full model. Boxes represent the three submodules with their key processes. Arrows represent exogenous data inputs (bold) and information exchange between modules.

Stakeholders identified three primary metrics as the most significant to evaluate the system's performance:

i. On-site Separation Rate (upstream source separation): This represents the proportion of waste separated at the source. In the model, it is calculated as the ratio of source-separated waste to the total waste generated each year.

ii. Collection Coverage (midstream collection): This reflects the total waste collected by both formal and informal workers as a percentage of the total waste generated annually.

iii. Recovery Efficiency (downstream treatment): This metric focuses on different end-of-pipe treatment methods and measures the effectiveness of waste recovery activities in the system. It is calculated as the volume of waste successfully recovered relative to the total waste generated each year.

4.2. Causal loop diagram of GAMA's SWM system

The next step is the development of a provisional theory that explains how endogenous dynamics give rise to a particular problem (Richardson, 2011). This step provides a conceptual system representation, which is refined by engaging with stakeholders in the system (Cabrera et al., 2008). CLDs are central to this step, helping to visualise the dynamic interactions and feedback mechanisms that shape system behaviour (Sterman, 2000). The corresponding CLD encapsulates the main reinforcing and balancing loops that characterise the system's behaviour and explain the linear performance of Accra's SWM system, as outlined below, and depicted in

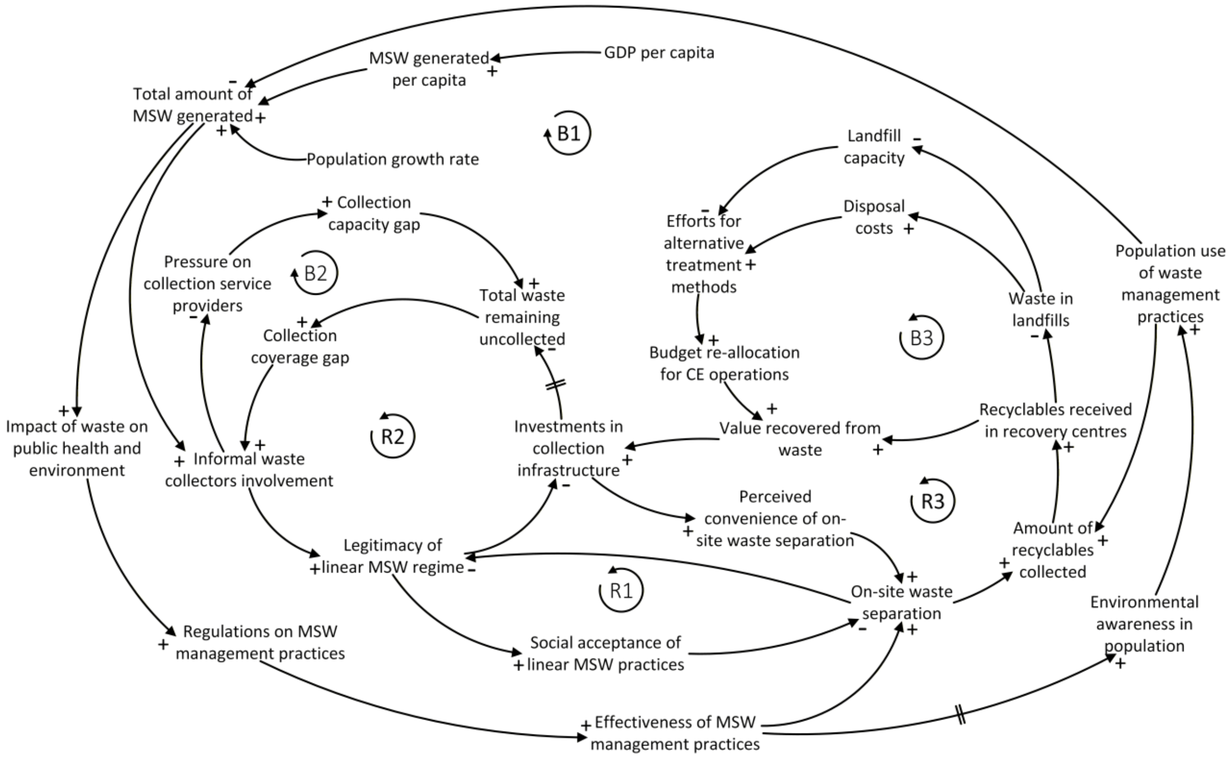


Figure .

R1. *Legitimacy of the linear regime*. The prevalence of linear (unsustainable) behaviours fosters greater *Social acceptance of MSW practices* through peer effect dynamics. As a result, there is a decline in *on-site waste separation* rates as unsustainable habits become normalised.

R2. *Deferred Investment Reinforcement*. The sporadic and unregulated involvement of the informal sector in waste management reinforces the *Legitimacy of linear SWM regime*. This reduces the perceived urgency for long-term solutions, leading to a widening waste *collection coverage gap* due to insufficient investments in sustainable infrastructure.

R3. *Recyclables Value Activation*. As on-site waste separation rates improve, more recyclables are collected and treated, leading to greater *Value recovered from waste*. This incentivises further *Investments in waste collection infrastructure*, which in turn enhances on-site waste separation, creating a reinforcing cycle of improved waste management.

B1. *Public Pressure–Policy Shift*. The increasing *Total amount of MSW generated* in Accra intensifies public health and environmental concerns, prompting growing dissatisfaction among residents. Over time, this public pressure compels policymakers and authorities to respond by introducing stricter *Regulations on MSW management practices* in the system. These policy shifts gradually raise *Environmental awareness in population* and influence public attitudes toward more sustainable practices. As such, this balancing loop helps counteract the reinforcing dynamics of waste accumulation by promoting behavioural and institutional change.

B2. *Collection capacity gap*. As the amount of uncollected waste increases, the gap between waste generation and collection capacity widens. In the short term, the informal sector helps reduce this gap by expanding coverage, particularly in underserved areas. This alleviates some of the pressure on formal waste collectors, who are then able to concentrate their efforts more effectively within their assigned districts. While this dynamic temporarily balances the system, it also highlights the structural limitations of relying on informal actors without formal integration or support.

B3. *Landfill Pressure Recycling*. As landfill capacity nears its limit, it triggers a push for alternative waste treatment methods such as recycling and composting. These efforts divert waste from landfills, extending their lifespan and reducing reliance on traditional disposal methods.

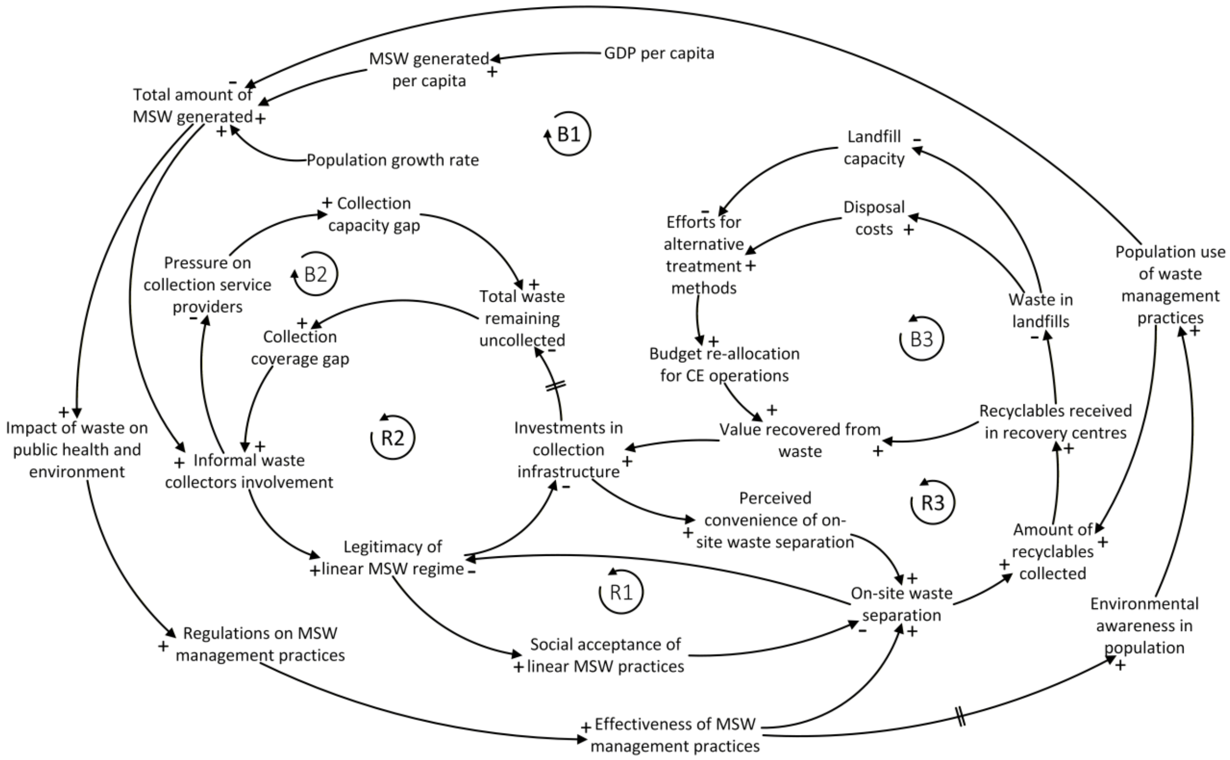


Figure 5. Causal Loop Diagram of the SWM in Accra, with reinforcing (R) and balancing (B) loops. Causal connections with double dashed bars indicate that there is a time delay between cause and effect.

Leverage points in the SWM system were identified through the qualitative systems analysis process, using the developed CLD and based on stakeholder input. More specifically, these leverage points represent strategic areas where targeted interventions could disrupt reinforcing loops of inefficiency and enable significant improvements in system performance, particularly by reducing landfill dependency and increasing circular waste flows (see Table 1). They are centred around critical intervention points across the three SWM sub-systems, targeted at upstream source separation, mid-stream waste collection, and final treatment sub-systems.

Table 1. Main dynamics identified from the stakeholder engagement process

Sub-systems	Problematic dynamics	Loops	Leverage points
Upstream /	1. Deeply rooted littering and waste disposal habits, not-	R1, R3, B1	L1. Environmental education in schools

Waste generation	in-my-backyard syndrome, and socio-cultural influences 2. Misperceptions and lack of knowledge on waste-related issues		L2. "System Literacy", through advanced communication strategies that inform about the short and long-term impact of waste
Midstream / Waste collection	3. Low-profit margin of waste collection operations diverts resources to other ancillary activities 4. Unregulated informal sector operations	R2, B2	L3. Targeted financing to boost the capacity of local authorities L4. Integration and monitoring of the informal sector operations in the system
Downstream / Waste treatment	5. Monopolistic power managed by powerful private companies limits new entrants with CE alternatives	B3	L5. Policy arrangements to support social enterprises engaged in CE to enter the market

4.3. Model development

Following the CLD development, this subsection documents the development of the simulation model. The model is a quantitative representation of the system structure and feedback relationships identified in the CLDs into accumulations (stocks) and rates of change (flows) and forms the basis for simulation and scenario analysis.

4.3.1 Population

The *Population module* simulates the demographic dynamics and the corresponding environmental awareness of the population over time. It employs a standard aging chain with a co-flow structure, informed by (Sterman, 2000). Co-flow structures allow for system attributes, in this case, environmental knowledge, to travel through the stock and flow structure of the system.

The population aging chain has four stocks, which represent four age cohorts: cohort 1 (0-19 years), cohort 2 (20-39 years), cohort 3 (40-59 years), cohort 4 (60+ years). This level of aggregation of the aging chains was judged to best represent the relevant environmental interventions and knowledge dynamics of different age groups. The birth inflow was defined as a function of the total population at each time step (year) and the fractional birth rate. People move from cohort to cohort with a delay equal to the span of the cohort. Death outflows in each stock of the population aging chain simulate the number of people who die every year in that age group. The urbanisation inflow is calculated only for cohort 2 (age 20-39 years), as this age group predominantly moves to cities for studies and work opportunities.

We modelled the level of environmental knowledge for each age cohort as the product of aging in the overall population and the average impact of educational campaigns and interventions on each group, along with the natural knowledge decay that exists. The initial level of environmental education of each cohort in the population is estimated using stakeholder inputs, survey results from the Green Academy project (see Appendix), and adjustments based on related studies in Ghana. For instance, Kanhai et al. (2021) found low population awareness of waste-related health hazards in Ghana. Despite a high prevalence of airborne diseases, 87% of surveyed households dismissed the idea that anyone in their household could have contracted waste-related illnesses. Disparities in environmental education access persist, with rural and underserved communities in GAMA often lacking the necessary resources and infrastructure for effective learning.

Public awareness campaigns and clean-up exercises, such as the operation ‘Clean Your Frontage’, take place regularly in Ghana (Agyabeng et al., 2024). These efforts have intensified since the 2014 cholera outbreak, and citizens are required to participate. Their estimated effect on environmental knowledge ranges between 25%–45%, amplifying the environmental attribute. While the effect of these activities on cohorts 2-4 is constant, the impact of environmental education interventions follows a different trend. Results from the Green Academy project indicate that short-term educational interventions temporarily boost students’ knowledge, which then decays rapidly once the intervention ends. To simulate this dynamic, PULSE and DELAY functions were introduced in the model. A second-order information delay was used to model the effects of environmental interventions on students’ knowledge.

4.3.2 Upstream waste separation sub-system

The *upstream waste separation module* (Figure) models the dynamics that determine the volume of waste entering the SWM system, including the quantity and rate of segregated versus mixed waste. It receives inputs from the Population module about the population in GAMA at each time step and the average environmental attributes of the population.

The *on-site separation rate* at the household level is calculated as a function of two mechanisms: (i) the *Effect of population with Environmental Knowledge*, ii) the *Peer Effect Dynamics* of the population that adopts the behaviour of waste separation. These two components capture the individual and peer-to-peer dynamics that have been identified as most prominent in driving unsustainable practices in the waste generation sub-system.

The rationale is that individuals may take action based on their own environmental knowledge, but they may also take action as a result of peer pressure. The first component, the Effect of population with Environmental Knowledge, is modelled as the product of the total weighted Average Environmental Attribute of the population and the percentage of people with environmental knowledge who would actively engage in waste separation. Households with higher environmental knowledge are more likely to participate in activities that promote good environmental practices, such as waste segregation (Odonkor et al., 2020). Specifically, in the case of Ghana, studies show that if environmental knowledge increases from zero to one (ceteris paribus), the probability of engaging in good environmental practices increases by 7.19% (Amoah & Addoah, 2021).

The second component, the *Peer Effect Dynamics*, captures the peer pressure on households when more people in the area engage in waste separation. Based on the Theory of Planned Behaviour, individual actions are strongly influenced by subjective norms, or the perceived social pressure to conform to behaviours deemed acceptable by peers and important referents (La Barbera & Ajzen, 2020). In the model, peer effect dynamics are represented as a function of the proportion of source-separated waste in the system at each time step. This comes under the assumption that as more people separate their waste, the proportion of separated over mixed waste increases, and that is gradually becoming more evident to more people, who receive this peer pressure to engage in waste separation.

The key output of this upstream module is the percentage of on-site separated waste. A higher separation rate improves the quality of materials collected and reduces the energy and labour required for downstream processes (Feil et al., 2017; Murray, 1999; Zhuang et al., 2008). This is especially critical for materials such as plastics and paper, which are easily contaminated by other waste components, like food waste, rendering their recovery processes significantly more challenging. Similarly, the efficiency of incineration or energy recovery processes for biodegradable waste is heavily dependent on the fraction of source-separated (Tomai et al., 2024).

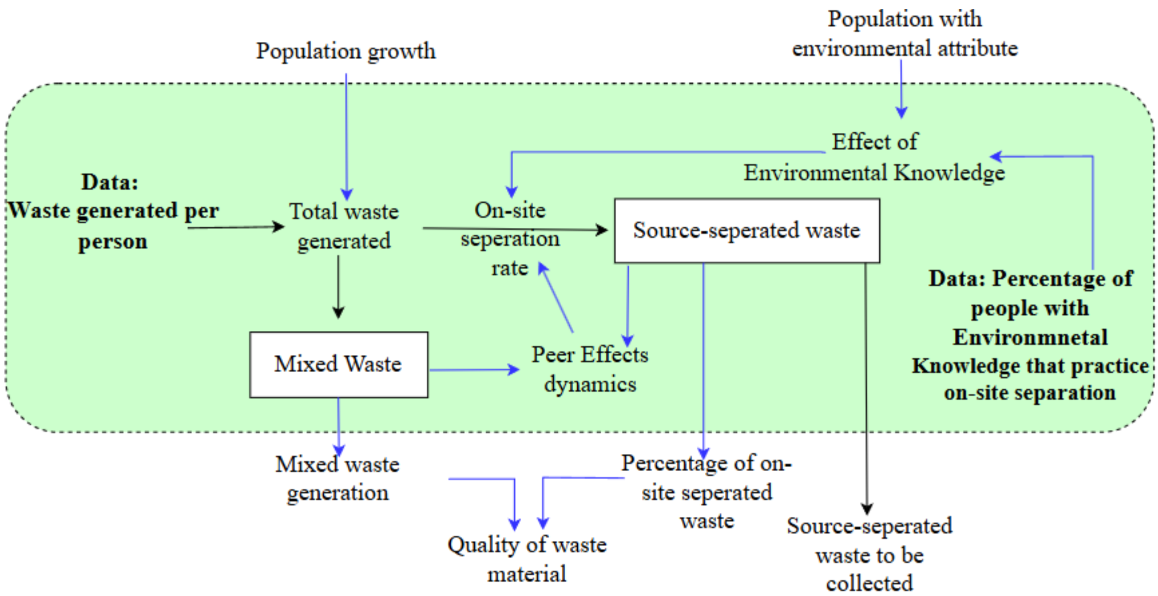


Figure 6. Structure of the Upstream Waste Separation Module

Note: The dashed box represents the module boundary. Boxes are stock variables. Blue arrows represent information flows. Black arrows represent the flow of waste within the system. Variables in bold are exogenous data inputs, and variables in normal font are endogenously calculated.

4.3.3 Midstream collection efficiency sub-system

The *Midstream collection efficiency module* (Figure 7) simulates the dynamics that influence waste collection coverage in GAMA. Source-separated waste, shown at the top of the figure, follows a distinct pathway from mixed waste. Source-separated waste is typically collected in full and processed directly by private recyclers. In contrast, mixed waste is managed through three pathways: a portion is collected by formal service providers, another portion by informal collectors, and the remainder remains uncollected.

The *collection rate by formal workers* is calculated based on a baseline contracted collection rate, which represents the amount formal service providers are obligated to collect, based on their contractual agreements with the districts. This rate is supplemented by additional collection capacity that grows asymptotically with resource gains reinvested into the system from waste recovery activities (see Diminishing returns - equation 6 in Wibbens (2021b) and equation 12 in Wibbens (2021a)).

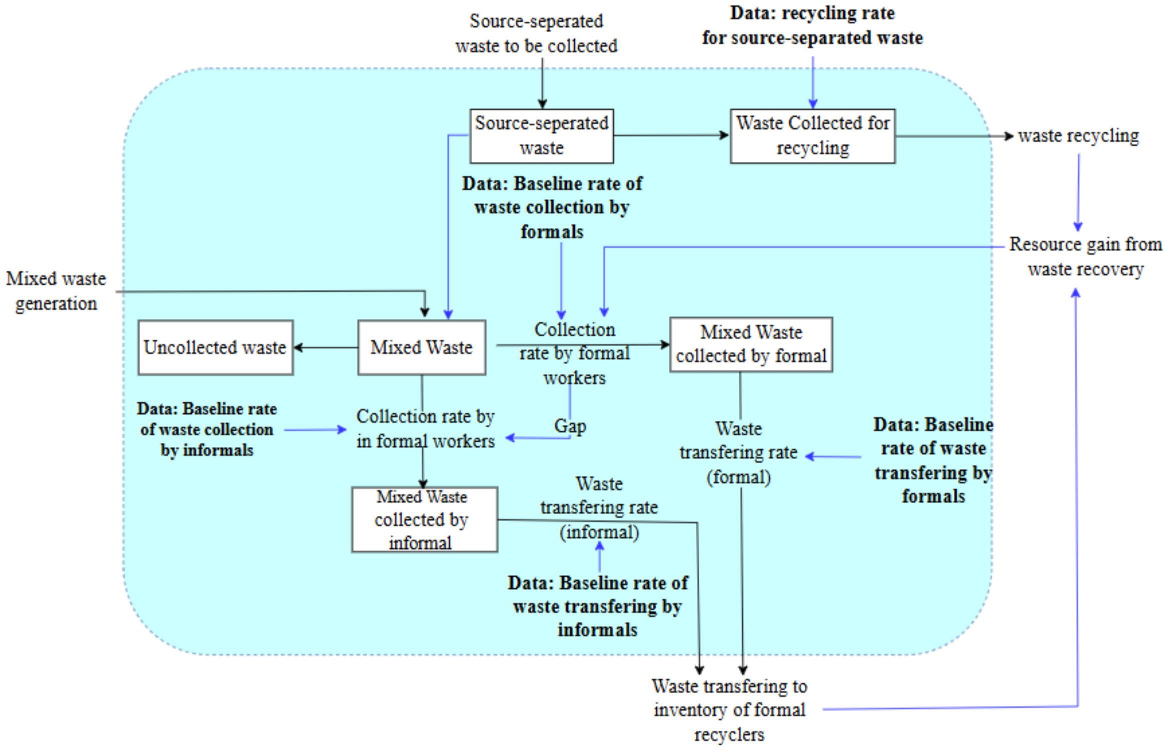


Figure 7. Structure of the Midstream Collection Efficiency Module.

Note: The dashed box represents the module boundary. Boxes are stock variables. Blue arrows represent information flows. Black arrows represent the flow of waste within the system. Variables in bold are exogenous data inputs, and variables in normal font are endogenously calculated.

The *collection rate by informal workers* is governed by a goal-seeking function, which compares the current level of formal collection to the desired (full) collection target. Informal collectors tend to increase their activities when formal systems fall short of their responsibilities. Although a large number of households rely on informal waste collectors, the physical stock of waste they collect is smaller than that of the formal collectors, due to the small capacity of their tricycles (Ampong et al., 2024). Additionally, a third collection and disposal method is available through public communal containers, strategically placed in low-income areas and informal settlements (Abdulai et al., 2015). These containers are managed exclusively by formal service providers and are, therefore, not represented by a separate stock in the model, but rather incorporated into the formal collection stock of mixed waste.

4.3.4 Downstream waste treatment sub-system

The Downstream *Waste Treatment Module* (Figure 8) represents the final stage of waste management, modelling the recovery processes and the proportion of waste diverted to landfills and dumpsites.

Waste collected by formal and informal service providers in GAMA flows into the *Waste Inventory – Formal Recyclers* stock. This stock represents the physical infrastructure of GAMA's two primary treatment facilities, ACARP and IRECOP, alongside several smaller transfer stations distributed across the region. Waste from this inventory is processed based on the capacity of material recovery facilities. The portion that is recovered, generates value from recycling and other waste treatment activities, while the remainder is sent to landfills. The "*recovery rate*" variable represents the capacity for processing. In each flow, waste is either processed at the full capacity rate or at what is available in the preceding stock. This logic is expressed with MIN function (capacity, stock/unit of time).

Additionally, the recycled material from the source-separated waste collected by formal service providers is directly processed without capacity constraints. For instance, ACARP can accept unlimited amounts of sorted recyclable or organic waste, bypassing the capacity limitations of material recovery facilities, which are constrained by their design capacity (World Bank, 2018).

The fraction of waste that cannot be processed in recovery facilities is directed to landfills. GAMA's only purpose-built landfill is the Kpone landfill, located in Tema. It was initially designed to handle 700 tons per day, but regularly received more than twice this volume (Salifu, 2019). Due to overflows, the Kpone landfill was decommissioned between 2020 and 2021. While plans for constructing a new landfill have been announced, a site has yet to be selected, and funding remains uncertain (GSS/EPA, 2020). In addition to Kpone, Nsumia landfill, located close to GAMA has also been receiving a small volume of waste from the region from 2014 to 2019 (Mudu et al., 2021), and has also been included in the model. Since 2021, waste not processed by recovery facilities has been diverted to nearby dumpsites.

When landfill capacity is exceeded, the resulting overflow creates pressure on the system to search for alternative treatment and disposal methods. This dynamic initiates a feedback loop which triggers efforts to expand recovery capacity. However, this is at the same time constrained by monopolistic structures within the sector, which limit opportunities for entrepreneurs to enter the market, ultimately capping increases in the recovery capacity of the system. The two stocks of *Mixed waste collected* by the formal and informal sectors are then directed towards the *Inventory of formal recyclers* for further processing.

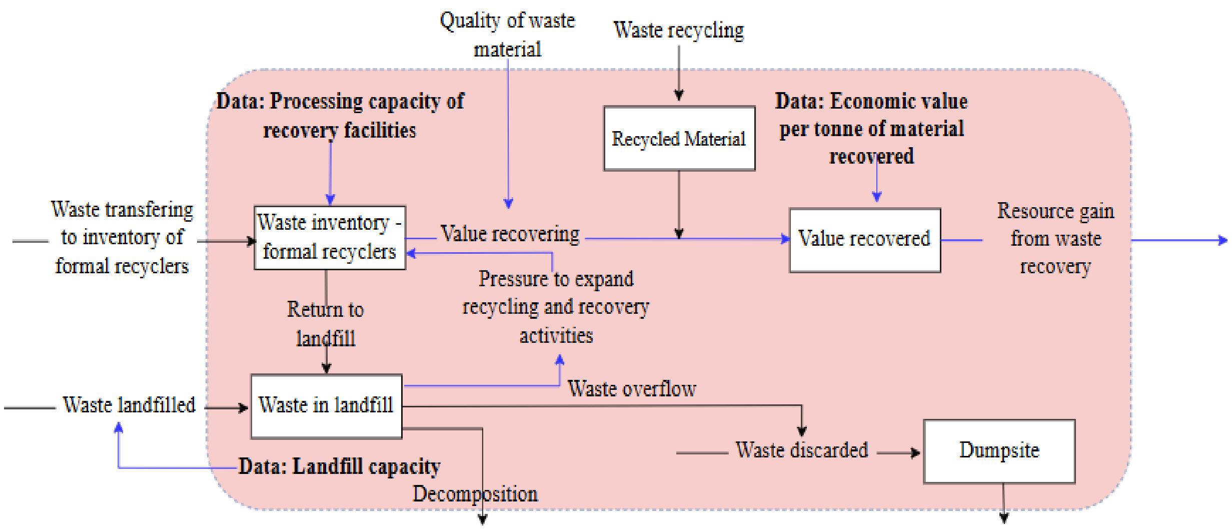


Figure 8. Structure of the Downstream Waste Treatment Module

Note: The dashed box represents the module boundary. Boxes are stock variables. Blue arrows represent information flows. Black arrows represent the flow of waste within the system. Variables in bold are exogenous data inputs, and variables in normal font are endogenously calculated.

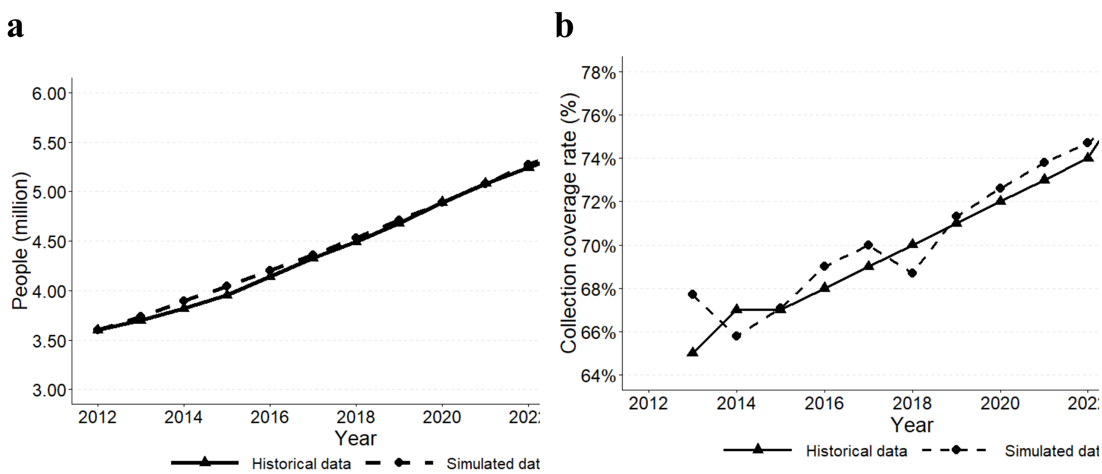
4.4. Model calibration and validation

The fourth step involves calibrating the SFM's behaviour against available data. This is an iterative process that occurs across different stages of modelling to enhance model validity (Barlas, 1996; Forrester & Senge, 1980; Oliva, 2003). Modes of validation used include comparison to statistical data from the Ghana Statistical Service, literature, and expert judgment. Throughout this process, reference modes captured by Business as Usual (BAU) scenarios help the calibration of the model and serve as a comparison with the outcomes of different scenarios.

Confidence in the SD model increases as more tests are performed and new points of correspondence between the model and the empirical reality are identified (Senge & Forrester, 1980). Therefore, structural validity tests were performed, including boundary adequacy, structure verification and extreme conditions tests. The results of these tests are further detailed in Appendices 3 and 4.

The model is calibrated by setting parameter inputs to optimise the fit of the simulation outputs to historical data on population trends, collection coverage, and landfill receiving volume of waste. The model simulates interactions among factors that influence the performance of Accra's SWM system, with a time horizon spanning from 2013 to 2040. The calibration was made based on time-series data collected from the literature from 2013-2023 for the first two variables and from 2013-2019 for the last one, since the landfill was decommissioned in 2021. Each submodule is first calibrated individually (Homer, 2012), followed by a final round of full model calibration and evaluation to ensure consistency with historical data is maintained with the complete set of between-module feedbacks active. Parameter estimates are selected based on literature studies, expert opinions, local empirical data or, if information sources are not available, best estimates by the modellers.

The squared error between simulated and observed time series is used as a payoff function in the parameter estimation process, and results are evaluated quantitatively, using Theil Inequality Coefficients (Sterman, 1984), following the formulations available on Sterman (2000), p.875, table 21-5[2]. Summary statistics for the calibration results are presented in **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**A.4, in the Appendix. Our calibration results show an overall acceptable fit to available data. Most importantly, the model captures the general trends of increasing population and growing burden on the management of waste imposed on the system. Most of the errors are caused by unequal covariance between the observed and simulated time series (81% and 53% for collection rates and landfill receiving waste, respectively). This indicates a low level of systematic error and provides confidence that the model is capable of replicating the dominating behaviour trends in the SWM system. A possible explanation for the relatively high U^M of the population is that simplifying assumptions were made during the model design and calibration, which, however, do not compromise the model (Sterman, 1984). The results of the quantitative behavioural validations are illustrated in Figure 9. A complete list of calibration inputs and outputs is given in **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**, in the Appendix.



[2] For these tests, the SD fit statistics module by Peter Hovmand (2020) is used in STELLA software

c

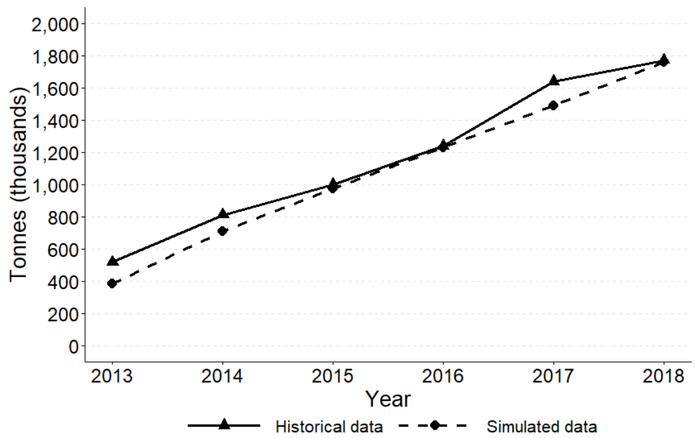


Figure 9. Model behavioural validation on (a) the population, (b) collection coverage rates, and (c) the total waste placement accumulated in Kpone landfill.

A significant driver of the system behaviour is that of population growth. Since that is exogenous to the model, this is not tested under different scenarios. However, the model simulations align with official projections, indicating that GAMA's population will surpass 6 million by 2030 and reach approximately 10 million by 2040 (Armoo et al., 2024). The younger demographic is expected to remain the largest segment of the total population over the next decade.

5. Results

In this section, five scenarios are explored into the likely future developments in the dynamics of waste management in GAMA. The scenarios are constructed based on the strategic priorities set by experts in the participatory workshop in Accra and correspond to five leverage points, as described in Table 1.

Scenario 1: The *Business-as-Usual* (BaU) assumes no major changes in behavioural interventions or technological advancements. A 10% increase in the waste recovery capacity is projected by 2040, in line with expected population growth. With the closure of existing landfills, this scenario assumes that no further efforts towards CE are made, and priority is given to the existing regional plans to develop landfill and transfer facilities, as outlined under the Greater Accra Resilient and Integrated Development (GARID) project and the Greater Accra Sustainable Sanitation and Livelihoods Improvement project (GASSLIP) (Darteh et al., 2021).

Scenario 2: The *Household interventions* scenario focuses on enhancing upstream processes through source separation activities at the household level. This involves implementing mandatory policies and guidelines to promote waste segregation, coupled with efforts to increase environmental awareness among adults. This scenario assumes that the effectiveness of environmental awareness campaigns increases by 50% (low degree – scenario 2a) and that it doubles (high degree - scenario 2b) by 2040, improving people's environmental knowledge, in line with ongoing efforts by civil society and international organisations in Ghana[3] (leverage point L2. "System Literacy"). Additionally, school-based CE educational programs are assumed to have a more enduring impact on students' environmental knowledge. That is tested through an extension in the duration of school-based environmental interventions from the usual 5–6 months to 9-10 months (leverage point L1. Environmental education in schools) over the next years. Other parameters follow the BAU scenario.

Scenario 3: The *Infrastructure Upgrade* scenario focuses on enhancing mid-stream waste collection operations across GAMA by testing two critical strategies. First, it assumes a gradual improvement in material recovery efficiency under ideal conditions (leverage point L3. Targeted financing), which is reflected by an increase in the maximum growth rate (g) parameter, from 0.05 to 0.10. This rate represents the upper limit on growth in the efficiency of investments in CE activities for collection over the baseline, considering diminishing returns (Wibbens, 2021b). This would enable the expansion and improvement of collection infrastructure, including the procurement of additional vehicles and the establishment of buy-back centres. Second, the scenario assumes a greater sensitivity to the collection gap by informal collectors. This implies closer coordination between the private and informal sectors, which results in a more adaptive and responsive informal sector, stepping in to address existing collection gaps (leverage point L4. Integration and monitoring of the informal sector). Other parameters follow the BAU scenario.

Scenario 4: The *Increase Capacity* scenario focuses on increasing downstream recovery capacity through enhanced end-of-pipe treatment methods, which would allow the final treatment and recovery of a greater

[3] For example, C40: https://www.myjoyonline.com/13-c40-cities-including-accra-commit-to-boosting-public-health/

volume of waste (L5. Policy arrangements to support social enterprises engaged in CE). It tests a single intervention aimed at increasing the recovery capacity of waste treatment facilities in GAMA. It first assumes a doubling of recovery capacity from the current 800 to 1600 tonnes per day over a time span of 5 years (scenario 4a), and then an increased capacity that reaches 2,400 tonnes per day, again over a time span of 5 years (scenario 4b). This scenario is built based on the ongoing efforts of the Ghanaian authorities to extend the capacity of ACARP from 800 tonnes per day to 2,000 tonnes per day[4] (Darteh et al., 2021). Other parameters follow the BAU scenario.

Scenario 5: The *Circular City* scenario integrates the best implemented conditions from the previous scenarios.

A summary of the specific parameter adjustments for each scenario is presented in **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**2.

Table 2. Test parameters and their values for different scenarios

Note: underlined values are those that change compared to the BAU (scenario 1)

Scenarios / **Test parameters**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Time effect of environmental education	0.5	0.9	0.5	0.5	0.9
Boost effect of environmental campaigns	0	0.5 (a) 1 (b)	0	0	1
Recovery Efficiency Growth Rate	0.05	0.05	0.1	0.05	0.1
Informal collectors' sensitivity to the collection gap	0.6	0.6	0.8	0.6	0.8

[4] https://thebftonline.com/2021/10/22/akufo-addo-inaugurates-e-20m-2nd-phase-acarp/

Processing capacity in recovery facilities (tons/day)	800	800	800	1600 (a) 2400 (b)	2400

5.1. Scenario results

The *Household Interventions* (Scenario 2) simulates ongoing efforts in GAMA to enhance environmental knowledge among the population. Overall, the expected share of people with environmental knowledge is projected to increase steadily over time, driven by global educational initiatives, technological advancements, and growing awareness of climate and ecological challenges (Tian et al., 2024). Yet, the results show that knowledge diffusion within the population takes time to manifest. Assuming no other simultaneous interventions occur, the proportion of the population with environmental knowledge is projected to rise from 23% in 2023 to approximately 30% by 2040 (Figure 0.a). The oscillations observed in the graph indicate temporary boosts in knowledge from short-term interventions, followed by declines when efforts aren't sustained over a longer period of time.

Nevertheless, these interventions have a limited impact on actual waste separation rates, which increase from 8% to 11% (Figure 0.b). This can be attributed to two endogenous mechanisms in the model. First, while households may possess the knowledge and willingness to separate their waste, very few will actually engage in separating their waste at source. Studies conducted in Ghana have found that "all else held constant", if environmental knowledge increases from zero to one, the probability of engaging in good environmental practices will increase by 7.19% (Amoah & Addoah, 2021). Second, the dynamics of peer effects slow down the overall impact. The population practising waste separation has not yet reached the critical mass needed to influence others positively, so, assuming a perfect mix in the population with those that separate waste and those that don't separate, peer effects work in the opposite direction. These findings align with studies in Ghana, which demonstrate that despite households' willingness to separate waste, the actual fraction of source-separated waste remains minimal (Alhassan et al., 2020).

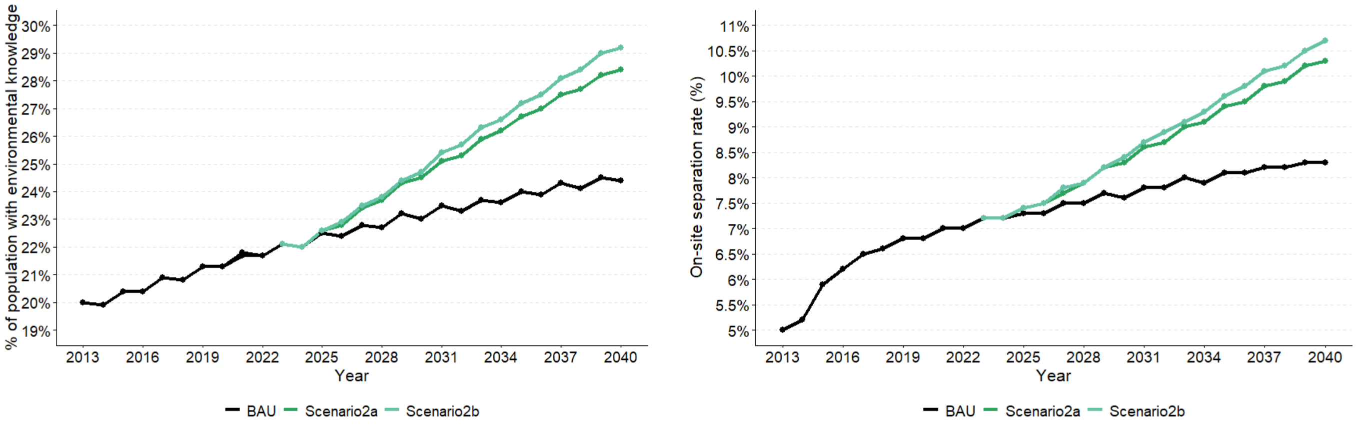


Figure 10. Comparison of results in business as usual (BAU) vs. Scenario 2

a. population with environmental knowledge (left panel), b. on-site separation rate (right panel)

Under scenario 2, the increase in environmental knowledge among GAMA's population does not lead to any noticeable improvement in waste collection coverage. However, it does have a measurable impact on the quantity of materials recovered through formal and informal processes, which rises from 8% under the BAU scenario to 11% by 2040. Based on these projections, the monetary value of the recovered materials was estimated to be \$5 million USD by 2040 (Figure 11), generated by the increased environmental knowledge that enables more waste to be separated and recovered, resulting in a 22% increase in annual recovery gains, assuming no additional interventions. The monetary value is estimated taking into account the final off-taker prices for plastics and other recovered materials in Ghana range between 1,000 and 1,500 Ghana cedis per tonne, equivalent to approximately \$100 USD (Amankwaa & Boafo, 2021).

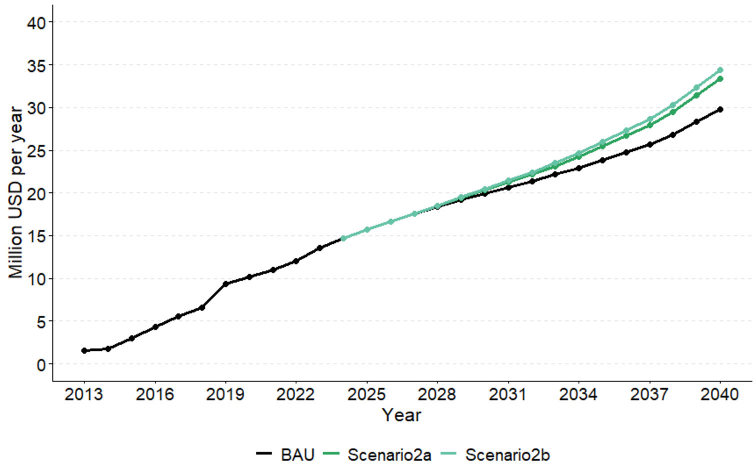


Figure 11. Value recovered in $ million per year in business as usual (BAU) and Scenario 2

The *Infrastructure Upgrade* (Scenario 3) serves as an intermediate scenario, focusing solely on interventions targeted at the mid-stream waste collection, to assess their impact on the system's performance. Figure 12 shows the trends associated with the collection coverage and projected contribution of the informal sector in the system.

As anticipated, collection coverage improves significantly under this scenario, rising from approximately 80% in the BaU scenario to nearly 89% under scenario 3 by the end of 2040. Notably, the majority of this improvement is attributed to the informal sector, which is more responsive to the collection gap left by the formals and scales up their operations. In this scenario, the informal sector collects between 40-46% of the mixed waste generated in GAMA, while the formal service providers collect almost half. Despite the increase in the efficiency of investments and the informal sector's participation, these interventions are not sufficient to achieve universal collection coverage in the region by 2040, as envisioned by the Government of Ghana.

An additional benefit of the increased waste collection under Scenario 3 is the positive impact it has on the recovery capacity of facilities in the region. With a larger volume of waste being collected and directed to these facilities, the demand for recovery and treatment rises, stimulating further investment and innovation in waste management technologies and infrastructure

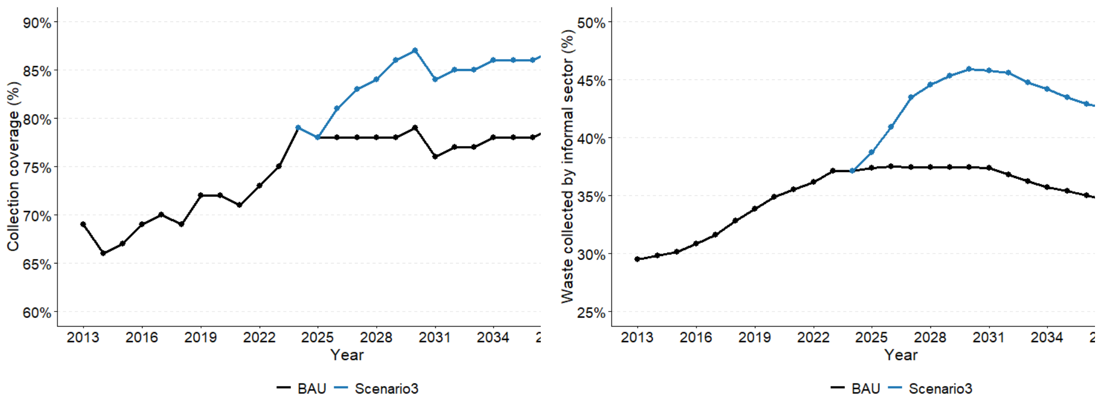


Figure 12. Comparison of results in business as usual (BAU) vs. Scenario 3

a. collection coverage (left panel), b. % of waste collected by the informal sector (right panel)

The *Increase Capacity* (Scenario 4) is the most ambitious goal for GAMA's SWM system, as it simulates a 100% and 200% increase in ACARP's treatment capacity, a strategic priority for the authorities and local experts. The results reveal a significant initial increase in the percentage of waste processed through the recovery facilities; however, this impact diminishes over time, at around 2030 (Figure 3.a). This decline is primarily attributed to the rapid growth in waste generation driven by population increases, which ultimately outpaces the expanded recovery capacity. Similarly, while the volume of waste diverted from dumpsites and landfills decreases substantially in 2024, following the introduction of the enhanced treatment capacity, this effect gradually wanes as the facilities approach their maximum processing limits, which remain lower than the inflow of waste requiring treatment (Figure 3.b). In both cases examined under Scenario 4, the system exhibits a temporary peak in performance following the capacity expansion in 2024, but the magnitude of this improvement gradually diminishes over time. Nevertheless, Scenario 4 demonstrates a notable time-delay effect, as the system takes significantly longer to revert to BAU performance levels. While this underscores the importance of capacity enhancement, it also highlights the need for complementary interventions to sustain long-term improvements.

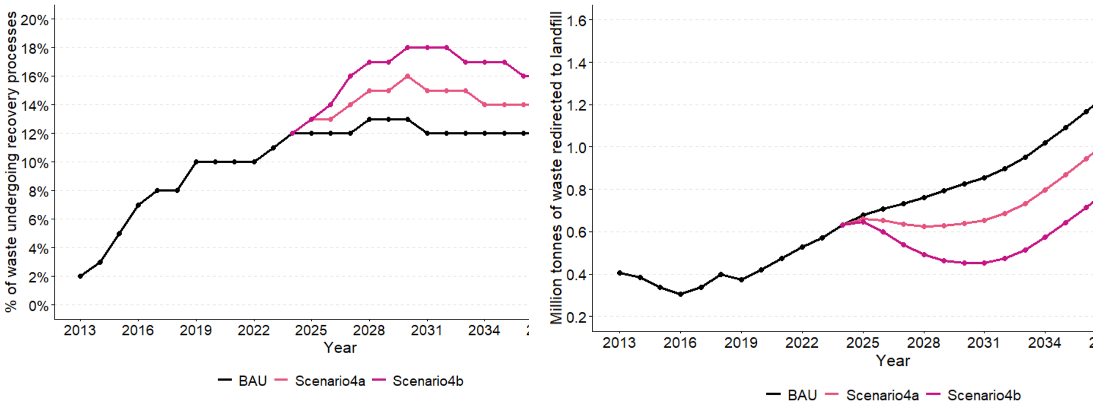


Figure 13. Comparison of results in business as usual (BAU) vs. Scenario 4

a. % of waste undergoing recovery processes (left panel), b. Waste returning to landfill per year (right panel)

Finally, the Circular City (scenario 5) integrates all the interventions from the previous scenarios. As expected, this scenario leads to the best overall results. The total volume of waste dumped or sent to landfills is significantly reduced and reaches the lowest levels across all scenarios (Figure 4a). This metric is particularly important as it captures all waste, whether collected or not, that is ultimately disposed of through linear processes such as landfilling or dumping. When focusing solely on waste redirected to landfills from recovery centres, Scenario 4 outperforms Scenario, which, however, captures part of the system's picture (Figure 14b). These results highlight the integrative strength of the Circular City approach to drive system-wide improvements by addressing upstream, midstream, and downstream processes simultaneously.

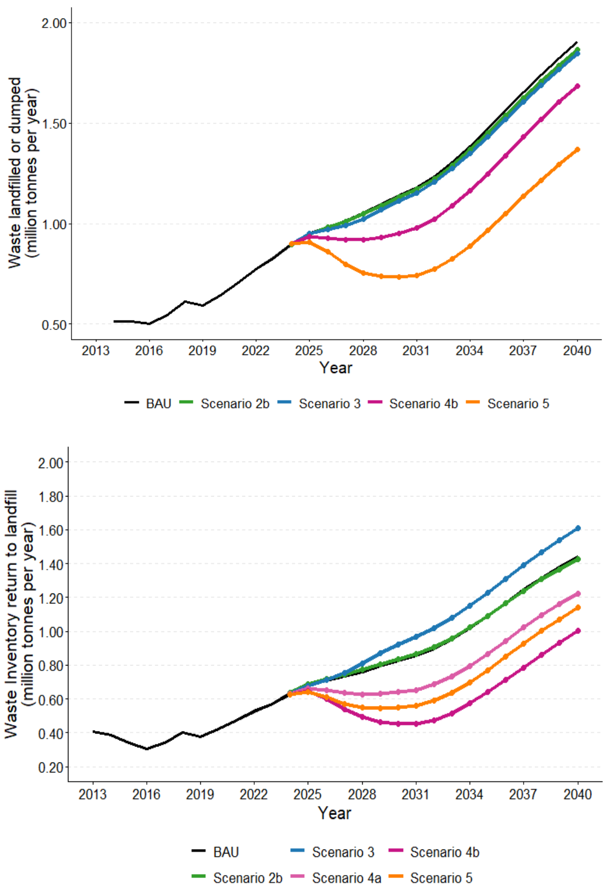


Figure 14. Comparison of results of all scenarios

a. Waste landfilled or dumped per year (left panel), b. Waste redirected to landfill from recovery facilities (right panel)

5.2. Sensitivity analysis

A sensitivity analysis was conducted to identify the key influencing parameters in the SD model. The constant variables within the SD model, which represent exogenous factors that can be adjusted, were identified for this purpose. The most critical parameters selected for testing include the Constant effect of environmental campaigns, the Percentage of people with environmental knowledge who separate waste, and the Percentage of value recovered for CE investments.

The sensitivity analysis was performed under Scenario 5 – Circular City, as this scenario demonstrates the greatest potential for facilitating a transition to a CE in GAMA. Each parameter was varied by ±50% and the average, as well as the lower and upper bounds, were calculated to represent the credible interval of the projections. These results are detailed in the Appendix, Table A.6.

The analysis revealed that using reasonable ranges for these parameters did not alter the identification of the most effective intervention points or their combinations. In other words, the model is robust to uncertainty in these state parameters, reaffirming the reliability of the proposed approach.

6. Discussion

The application of the SD model for managing CE transitions in GAMA's SWM system allows for experimentation of the system's behaviour under different scenarios and with the introduction of different leverage points.

The simulations show a relatively low impact of the interventions in terms of increasing the source separation rates. Efforts to improve the environmental knowledge of the population alone are not sufficient in engaging households in a new behaviour, as could be expected. Universal collection coverage in the region and full elimination of dumpsites were not achieved in any of the scenarios. However, the Increase Capacity (Scenario 4) and Circular City (Scenario 5) manage the greatest reduction in linearly managed waste ending up in landfills or dumpsites. A summary of each scenario's effectiveness is provided in Table 3.

Table 3. Scenario Effectiveness Summary

	Upstream waste separation at the source	**Midstream waste collection efficiency**	**Downstream waste treatment and diversion to landfill**
Scenario 1 (BAU)	Low	Low	Low
Scenario 2	Moderate	No significant change	Moderate
Scenario 3	No significant change	High	Moderate
Scenario 4	No significant change	Moderate	High
Scenario 5	High	High	Very High

This study derived some important policy implications for GAMA. First, efforts to increase environmental awareness among the population should be accelerated and persist over time. Environmental literacy goes beyond knowledge of waste management practices to encompass a broader understanding of how human behaviours impact the environment and public health. Alarmingly, the average climate change literacy rate in Africa is just 37%, significantly lower than rates in Europe and North America, where they exceed 80% (Simpson et al., 2021). In Ghana, this rate is even lower at 21% (Selormey et al., 2019).

Research suggests several strategies to improve environmental awareness. For instance, campaigns that link littering to practical consequences, such as drain blockages, flooding, and disease outbreaks, can help foster better attitudes toward litter prevention. Providing waste bins in public spaces and using persuasive messaging have been shown to enhance personal anti-littering intentions (Oduro-Appiah et al., 2024). Emphasising the broader benefits of waste management could also be impactful. For example, if Ghana eliminates open burning by 2030, an estimated 120 premature deaths could be prevented annually (Mudu et al., 2021).

The Ghanaian government has demonstrated its commitment to improve environmental literacy through policies such as the Ghana National Climate Change Policy and the Ghana Education Strategic Plan, which emphasise the integration of environmental education into the curriculum (Lawson, 2016). Collaborations with local and international civil society organizations and NGOs[5] can further strengthen these efforts by providing resources and capacity-building support.

Second, there is an urgent need to improve and strengthen the integration of the informal sector into the SWM system and improve its efficiency. While the total waste recycling rate in GAMA is about 8.4% in BAU, the informal sector accounts for 74% of this recycling activity, significantly outperforming the formal sector (Oduro-Appiah et al., 2021). Recognising and formalising the contributions of informal workers through strategies that offer better working conditions, training, and incentives is essential. Additionally, integrating indigenous knowledge held by informal workers provides an opportunity to create long-term, environmentally friendly

[5] https://www.friend-in-need.org/wash-innovations/

waste management practices (Anokye & Mohammed, 2024). The results of this modelling exercise demonstrate that increased responsiveness of the informal sector in addressing collection gaps not only enhances overall waste collection coverage but also drives improvements in recovery and treatment facilities. This, in turn, reduces the volume of waste destined for landfills or illegal dumping.

Third, increases in waste recycling and recovery require coordinated changes across the entire SWM value chain. The current reliance on landfill and dumpsite expansions is unsustainable and raises serious concerns about land use, ecological preservation, and sustainability in GAMA (Akubia et al., 2020). The scenario analysis showed that the government's plans to expand upon the recovery and treatment facilities in GAMA will indeed result in a significant reduction of the waste landfilled or dumped. This effect, however, will not last long due to higher increases in waste generation expected to occur over the next years, which will confine the impact of these interventions (see Figure 15).

Addressing these challenges demands a whole system shift toward a CE, where resources are recovered and reused more efficiently. Efforts should focus on strengthening recycling and recovery infrastructure while improving access to recovery facilities and incentivizing waste separation at the source. Additionally, the government should continue promoting public-private partnerships and investments in waste recovery technologies, for the adoption of the most suitable solutions for the specific waste streams produced in GAMA.

Overall, the simulation results highlight critical bottlenecks in the SWM system, emphasising the need for coordinated interventions across multiple stages of the value chain to achieve optimal system-wide outcomes. The scenario analysis agrees with earlier studies in the field of CE transition, which highlight the need for holistic policy interventions that can fuel change to occur in the whole system. Moreover, the findings reveal the synergies between household action and infrastructure upgrades, demonstrating how their combined implementation can yield better results. They also underline the varying effectiveness of different intervention combinations depending on the specific performance indicators being targeted. The findings clearly imply that to make the transition towards sustainable SWM systems, policymakers should take a proactive role in shaping the system's future trajectory and invest in interventions that will enable GAMA to transition toward a more sustainable and circular SWM system. Lastly, the study underscores the value of SD modelling as a practical tool for analysing complex systems with multiple interactions and interdependencies. This approach is not only applicable to SWM systems but also extends to broader contexts in management, policymaking, and sustainability transitions. Moreover, while the SD model was designed in conjunction with experts in the GAMA region, it was implemented in a generic manner, which makes it transferable to other cities and metropolitan regions aiming to develop sustainable and circular waste management systems.

The paper comes with some limitations. In this study, we assume that the growth in the total amount of SWM generated each year is driven solely by population dynamics. However, numerous other factors influence SWM generation, including shifts in consumption patterns, GDP growth, and globalisation trends, among others (Chakori et al., 2021). Moreover, the system involves multiple waste streams (e.g., paper, plastics, aluminium), each with varying processing values and, in some cases, distinct collection methods. Due to data limitations, this study did not account for the varying proportions of these waste streams within GAMA's value chain. Another limitation pertains to the socioeconomic diversity within the region. Waste collection methods, frequencies, and even the quality of waste differ across income groups and neighbourhoods in GAMA. For simplicity and feasibility, the parameters and results of the model are presented at an aggregated level, without distinguishing between these variations.

7. Conclusions

Addressing the global challenge of SWM systems is critical, given the significant volumes of waste produced and the environmental risks associated with poor management practices. This research used modelling and simulation to support the CE transition of GAMA's SWM system. The SD model quantified the key path dependence mechanisms which define the system's transition toward a more circular and sustainable model. The study then developed five "what-if" scenarios, based on stakeholders proposed strategies and leverage points, to test their effect on the system's long-term sustainability goals.

The findings reveal that continued population growth will exacerbate pressure on the SWM systems, highlighting the urgent need for integrated strategies that address the entire value chain. Scenarios focusing solely on upstream interventions (e.g., source separation) midstream improvements (e.g. higher collection coverage), or downstream measures (e.g., increased recovery capacity) demonstrate limited overall impact on the system's performance. Instead, the findings underscore the importance of adopting a holistic, whole-systems approach that enables multiple, coordinated interventions at various points in the system.

This proposed model offers a valuable foundation for other cities in Africa and beyond to explore the complex dynamics of their SWM systems. By leveraging such models, cities can develop targeted strategies to advance circular economy transitions and promote sustainable waste management solutions.

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Appendix 1. Interviews

Table A.1. *Background of the Interviewees*

ID	Position	Years of relevant experience	Minutes of Interview
I1	Formal service provider – lead consultant	50	120
I2	Formal service provider - general manager	5	43
I3	Formal service provider - director of operations	5	39
I4	Researcher	10	75
I5	Civil society - entrepreneur	7	40
I6	Formal service provider - business development manager	15	54
I7	Formal service provider - factory manager	6	20
I8	Social entrepreneur – recycling operations	6	40
I9	Researcher	23	32
I10	Government official – municipal assembly	15	75
I11	Government official - agency	12	71
I12	Formal service provider - Director of Monitoring and Service Quality	16	65
I13	Environmental Consultant & Researcher	12	73
I14	Environmental Consultant	16	40
I15	Government official - ministry	14	42
I16	Social entrepreneur – research institute	7	104
I17	Government official - ministry	11	47
I18	Government official - assembly	20	50
I19	Formal service provider – senior manager	3	51
I20	Government official – municipal assembly	8	49
I21	Formal service provider - director	19	120
I22	Environmental Consultant	4	115
I23	Civil society - advocacy	3	69
I24	Researcher	5	64
I25	Government official – municipal assembly	20	57

I26	Social entrepreneur	3	42
I27	Government official - ministry	12	25
I28	Government official– municipal assembly	11	67
I29	Civil society	15	45
I30	Government official - ministry	9	31
I31	Researcher - technical advisor to the government	13	56
I32	Government official - regional ministry	8	54
I33	Civil society - consultant	7	61

Appendix 2. Model parameters

Table A.2. Secondary data sources

Sub-model	Parameters	Year	Level	Data points & Justification	Sources
Population	Population estimates	2019	GAMA	The population is projected to more than double to 10.5 million by 2040	(Addae & Oppelt, 2019; Ghana Statistical Service, 2021)
		2020	GAMA	GAMA is home to an estimated 4.6 – 4.7 million residents	(Oduro-Appiah et al., 2021; World Bank, 2020a)
		Starting state value: 3.600.000 people			(Owusu, 2015; World Bank, 2020a)
	Annual population growth rate	2000-2020	Accra	2000 – 2016: 2%, 2016 – 2030: 2.4%	(Musah et al., 2020)
	Urbanisation rates	2015	GAMA	Urban population increased by more than 50% between 1985- 2000	(World Bank, 2015)
		2014	Greater Accra	Urban population: (1960,72.6), (1970, 85.3), (1984,83.0), (2000,87.7), (2010, 90.5)	(Ghana Statistical Service, 2014)
		2015	GAMA	Urbanisation rate: 3.6%	(Cities Alliance, 2016)
		2020	Ghana	Annual urbanisation growth rate is estimated to be about 3.2%.	(World Bank, 2020b)
	Age Distribution	2021	Greater Accra	(80+ years_35,599); (70-79 years_80,046); (60-69 years_192,063); (50-59 years_332,608); (40-49 years_610,158); (30-39	Ghana Statistical Service (web[1])

[1] https://www.citypopulation.de/en/ghana/admin/03__greater_accra/

				years_994,776); (20-29 years_1,090,213); (10-19 years_1,004,053); (0-9 years_1,116,176)	
	Death rates	2010	Ghana	Age specific death rates (ASDR) per 1000 mid-year population by residence	(Ghana Statistical Service, 2014)
	Environmental knowledge / literacy	2023	Ghana	Of student population = 62%	(Amengor et al., 2023)
		2020	Accra	Population awareness toward waste-related health risks around 20-30%	(Kanhai et al., 2021)
			Accra	Knowledge on waste segregation among traders =23.7%	(Agbefe et al., 2019)
		Starting state value: cohort 1=30%, cohort 2=30%, cohort 3 =30%, cohort 4=20%			(Estimates based on experts judgment)
Upstream waste separation at the source	Waste generation rates per capita	2005-2015	Accra	0.4kg/person/day in 2005 to 0.7kg/person/day in 2015	(Miezah et al., 2015)
		2005-2020	Accra	(2005, 1500), (2010, 1800), (2013, 2500), (2020,2800) tonnes per day	(GSS/EPA, 2020)
		1999-2017	Ghana	Time series data - Waste Generated by households	(GSS/EPA, 2020)
		2020	Ghana	8% increase in the national average of SWM generation (kg/cap/day) from 2018 to 2030 Expected increase by 2040: + 10%	(GPAP, 2020)
		2020	GAMA	Daily average per capita SWM generation: Accra and Tema: 0.71 kg, rest: 0.50 kg	(Oduro-Appiah et al., 2021)
		2018	GAMA	Daily waste generation: 2,476 metric tons	(World Bank, 2018)
		Starting state value: 657.000 tonnes			(GSS/EPA, 2020)
	Waste composition	2005-2015	Accra	Organic: 60.7, Plastics and rubber: 18, Paper: 8.3, Metal: 4.3, Glass: 2.7. Others: 6.0	(GSS/EPA, 2020; World Bank, 2018)
	Waste separation on-site	2011	Ghana	Absence of source separation of solid waste	(Oduro-Appiah & Aggrey, 2013)
		2020	Ghana	the actual fraction of waste that is source-separated is minimal	(Alhassan et al., 2020)
	Mode of household solid waste disposal	2020	Accra	Informal waste collector: 37.71%, Communal containers: 29.71%, House-to-house: 16.37%, Illegal disposal: 20%	(Alhassan et al., 2020)
		2019	GAMA	32.3% of solid waste generated is dumped into drainages or open spaces	(Ghana Statistical Service, 2021)

	Pro-Environmental Behaviour	2020	Ghana	Citizens overall willingness to participate in recycling activities	(Odonkor & Adom, 2020)
		2014/15	Ghana	Mean score for the level of environmental literacy of business students = 3.01 with standard deviation of 0.89	(Owusu et al., 2017)
		2020	Ghana	"all else held constant", if environmental knowledge increases from zero to one, the probability of engaging in good environmental practices will increase by 7.19%.	(Amoah & Addoah, 2021)
Midstream collection efficiency	Waste collection rates	2021	Accra	Around 80% of waste generated is collected and sent to a transfer station or material recovery facilities	(Amankwaa & Boafo, 2021)
		2018	GAMA	76% collected / 24% improperly disposed of either through burning, burial, open and indiscriminate dumping	(World Bank, 2018)
		2014	GAMA	67.7% of solid waste generated in the region is collected	(GLSS 6, 2014; World Bank, 2017)
		2014	GAMA	59.4 % collected / 31.2% public dump (container) / 4.7 % public dump (open space) / 2.7% burned by household	(Zhou et al., 2021)
	Informal waste collection rates	2020	GAMA	1618 informal service providers and 646 informal recycling entrepreneurs are collecting 1370 tonnes per day, which is equivalent to 46% of municipal solid waste	(GPAP, 2020; Oduro-Appiah et al., 2021)
		2013	Accra	Collection rate of about 70-80% waste generated	(Oteng-Ababio et al., 2013)
	Formal waste collection rates	2020	Ghana	56% national average collection coverage	(GPAP, 2020)
Downstream treatment and diversion to landfill	Recovery rates	2020	GAMA	The annual quantity (102,033 tonnes) of materials recovered for recycling amounts to 8.5% of the total SWM generated (1,198,652 tonnes) within the GAMA	(Oduro-Appiah et al., 2021)
		2020	GAMA	Total waste recovered by all is 68,053 tonnes/1,065,194.25 tonnes (6.4%) per annum in GAMA	(GPAP, 2020)
	Kpone – Landfill capacity	2013, 2015, 2020	Accra	Constructed to accept 700 tons per day, currently receives more than 1400 tons per day	(GSS/EPA, 2020) GSS 2010, GLSS 6 and 7
		2019	GAMA	Landfill commissioned in 2013; waste placement in 2018=1,771,493 tonnes. Time series data for design and actual waste placement (2013-2037)	(Salifu, 2019b)
		2022	Ghana	Average decomposition rates	(Gyabaah et al., 2023)

	Treatment capacity of ACARP & IRECOP (material recovery facilities)	2020	GAMA	ACARP = 500 tons of municipal solid waste per day (organic and non-organic)	(GSS/EPA, 2020)
		2018	GAMA	ACARP design capacity for mixed waste: 300 metric tons per every 8-hour shift. Plans have commenced to expand the facility to about 1200-1500 metric tons per day.	(World Bank, 2018)
		2023	GAMA	IRECOP = 200 tons/day, ACARP = 300 tons/day	(Sarquah et al., 2023)
	Informal recovery rates	2020	GAMA	Informal recyclers recover 85,653 tonnes of recyclables annually, achieving a 6.4% recycling rate. They contribute to 84% of recycling compared to the formal sector.	(Oduro-Appiah et al., 2021)
		2020	GAMA	Informal Service Providers recover 37 tonnes of metals and plastics daily	(GPAP, 2020)

Table A.3. Calibration inputs and assumptions

Note: Complete list of inputs and outputs used in partial- and full model calibration. The first column indicates the sub-system, the second column contains the payoff variables used in the calibration. The third one contains names of the calibrated parameters, column four shows the calibration range explored for each parameter, and column five provides the estimated parameter value. The sixth column provides references to the source of the applied calibration range, and additional comments with regards to the estimated parameter values.

Sub-system	Payoff variables	Calibrated parameters	Calibration range	Average Estimate	References and assumptions
Population	Total Population	Urbanisation rate cohort 20-39	0.032-0.036 1/Years	0.033	Given that GAMA has reached a 90.5% urbanization level (World Bank, 2017), the region is at a saturation phase (Ghana Statistical Service, 2021), I therefore adopt a more conservative estimate.
Upstream waste separation at the source	Total waste (tonnes) generated per year	Waste generated per person per day	0.5 - 0.83 kg	0.6 kg	The literature points to average generation rates of 0.57 kg and 0.83 kg per capita for households (Oduro-Appiah & Afful, 2020), with the amount being lower in 2013 and variant between municipalities and districts (Miezah et al., 2015). I adopt a lower rate of 0.5 kg in 2023, which goes up to 0,71kg in 2023.
	On-site separation rate	Sensitivity to Waste Ubiquity	0-1 dmnl	0.3	Estimated by the modelers, based on studies on peer effect dynamics (Agustina et al., 2023)
Midstream collection efficiency	Collection rate - formal	Reference collection rates formal	0.1-0.5 Per Year	0.39	These estimates are calculated based on the average collection coverage within the GAMA, which is between 60% - 70% (GARID, 2021a) and the formal sector contribution estimates. It also accounts for a projected annual growth rate in quantity of waste collected of 2% (Mudu et al., 2021).
	Collection rate - informal	Informal collectors sensitivity to collection gap	0-1 dmnl	0.65	Informal actors alone contribute to an average SWM collection rate of 46% within the GAMA (Oduro-Appiah et al., 2021). In 2016, were found to be providing as much as 28% of waste collection in the city (Oduro-Appiah et al., 2017). The estimate responds to the relatively high responsiveness of the informal workers in the collection gap.
Downstream treatment and diversion to landfill	Recovery rate	Waste recovery rate of informal sector	0-0.2 Per Year	0.05	Based on Oduro-Appiah et al. (2021), the total SWM recycling rate is estimated at 8.4%, and the informal sector is known to contribute to 74% compared to the formal waste sector. Estimate is based on experts inputs
	Mixed Material recovering - formal	Sensitivity to waste overflow	0-0.2 dmnl	0.02	This is the capital intense and often high-risk investment. The system is described to be quite inelastic with regards to recovery capacity expansion, as described by the experts.

Table A.4. Summary statistics from model calibration results.

MAE = mean absolute error, MSE = mean square error, RMSE = root-mean square error

						Error decomposition		
Payoff variable	MAE	MSE	RMSE	Correlation	R2	Bias (U^M)	Variation (U^S)	Covariation (U^C)
Population (million people)	3.90 $*10^{+4}$	2.21 $*10^{+9}$	4.70 $*10^{+4}$	0.996	0.998	0.571	0.063	0.365
Collection coverage (rate)	6.55 $*10^{-3}$	6.00 $*10^{-5}$	7.75 $*10^{-3}$	0.972	0.945	0.161	0.199	0.818
Landfill receiving waste (tonnes)	5.37 $*10+^{4}$	4.42 $*10^{+9}$	6.65 $*10^{+4}$	0.995	0.990	0.180	0.288	0.531

Note: U^m, U^S, and U^C reflect the fraction of MSE due to bias, unequal variance, and unequal covariance, respectively, where $U^m + U^S + U^C = 1$.

Appendix 3. Structural validation tests

a) Boundary adequacy

Boundary adequacy aims to test whether the important concepts and structures are endogenous to the model. The endogenous and exogenous variables of the model are summarized in Table A.. The model boundary is reasonable because it clearly defines the system's internal structure and external environment.

Table A.5. Summary of the model boundary

Exogenous variables	**Endogenous variables**
Socioeconomic factors • Population growth • Urbanisation rate • Initial environmental attribute (per cohort) • Effect of environmental knowledge on individuals' behaviour SWM system factors • Waste generated per capita • Contracted service quota for private collectors • Initial processing capacity of recovery facilities • Landfills capacities	Waste segregation sub-system • Peer-effect dynamics for CE • On-site separation changes driven by environmental attributes Waste collection sub-system • Informal waste collection rate • Formal collection rate adjustments due to resources availability Waste treatment sub-system • Recovery capacity adjustments due to pressure from lack of landfill space • Quality of waste material recovered • Value creation from waste material recovered

Policy • Initial value re-investment for CE operations	

b) Dimensional consistency

Dimensional consistency requires that the measurement units of variables and constants in each mathematical equation are dimensionally consistent. I have checked all the mathematical equations to ensure that there are no unit errors.

c) Parameter verification

Parameter verification examines whether the parameters and their values are consistent with the description of the real system. In the model, all the constant parameters can be identified in the real system. Their values are obtained from reliable sources such as existing relevant studies and government documents, as outlined in Table A.1.

d) Extreme condition

The extreme-condition test involves assigning extreme values to exogenous parameters and comparing the model-generated behaviour to the observed or anticipated behaviour of the real system under the same extreme condition. Regarding our proposed model, I set the amount of waste generated per person to extreme conditions, including zero and very high values, such as 10kg per person per day. This anticipated behaviour is consistent with that of the real system.

Appendix 4. Sensitivity tests

Sensitivity analysis is performed for each KPI to observe how a change in the most important parameters could affect the outcomes of interest. This allows us to test which scenarios are more robust and will remain impactful despite potential external to the model shocks. The tests were executed under Sobol Sequence sampling in STELLA software with 10 runs.

Table A.6. Uncertainty ranges used in extended sensitivity testing

Parameters	**Units**	**Sensitivity test range**
Constant effect of environmental campaigns	dmnl	0.1 – 0.3

People with environmental knowledge that separate waste	% of people	0.359– 1.078
Value recovered for CE investments	1/(Tonnes)	0.1 – 0.3

Notes: See Table A.1 for default values and their justifications.

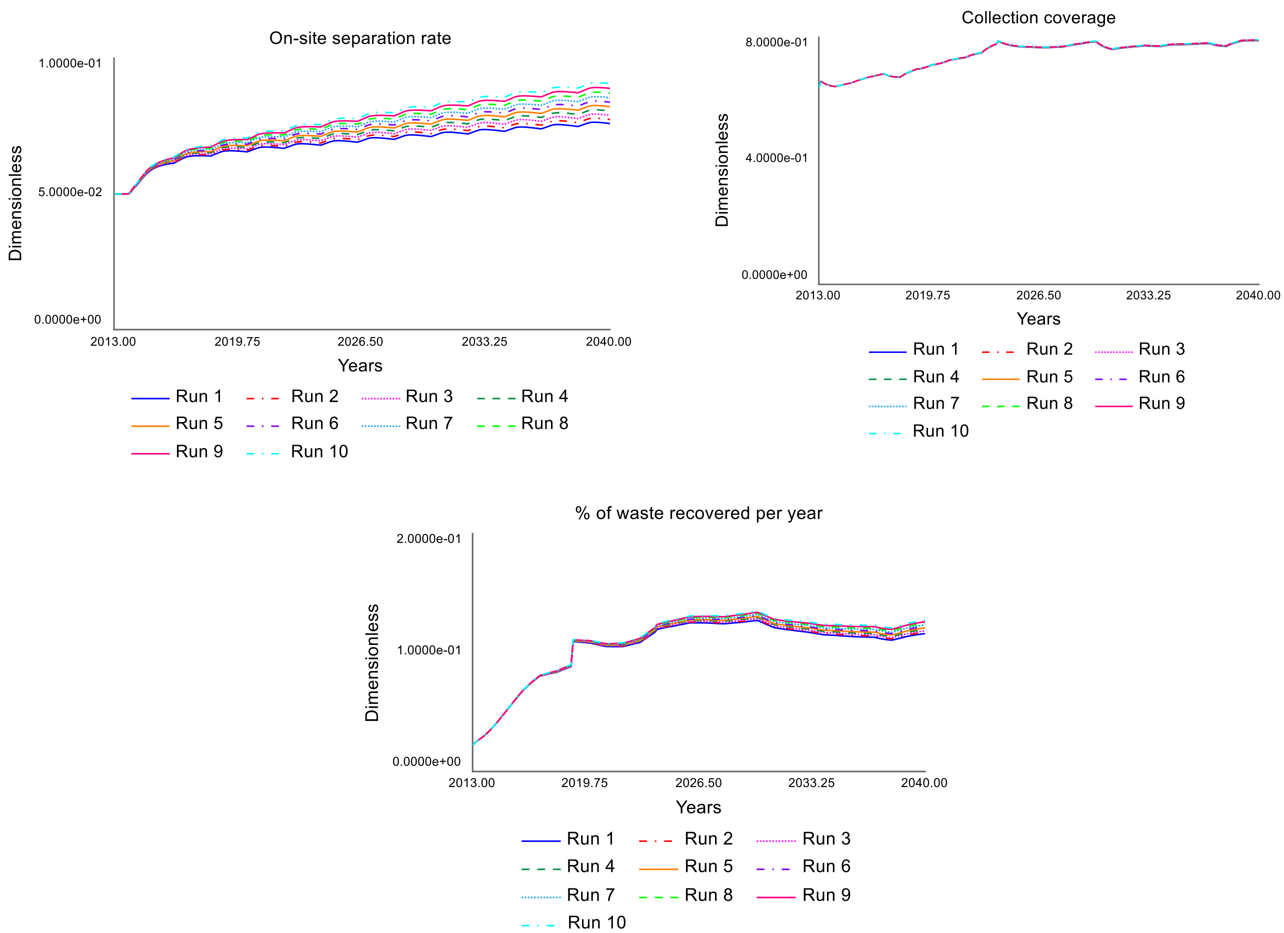


Fig A.1. Test results to changes in ‘Constant effect of environmental campaigns’

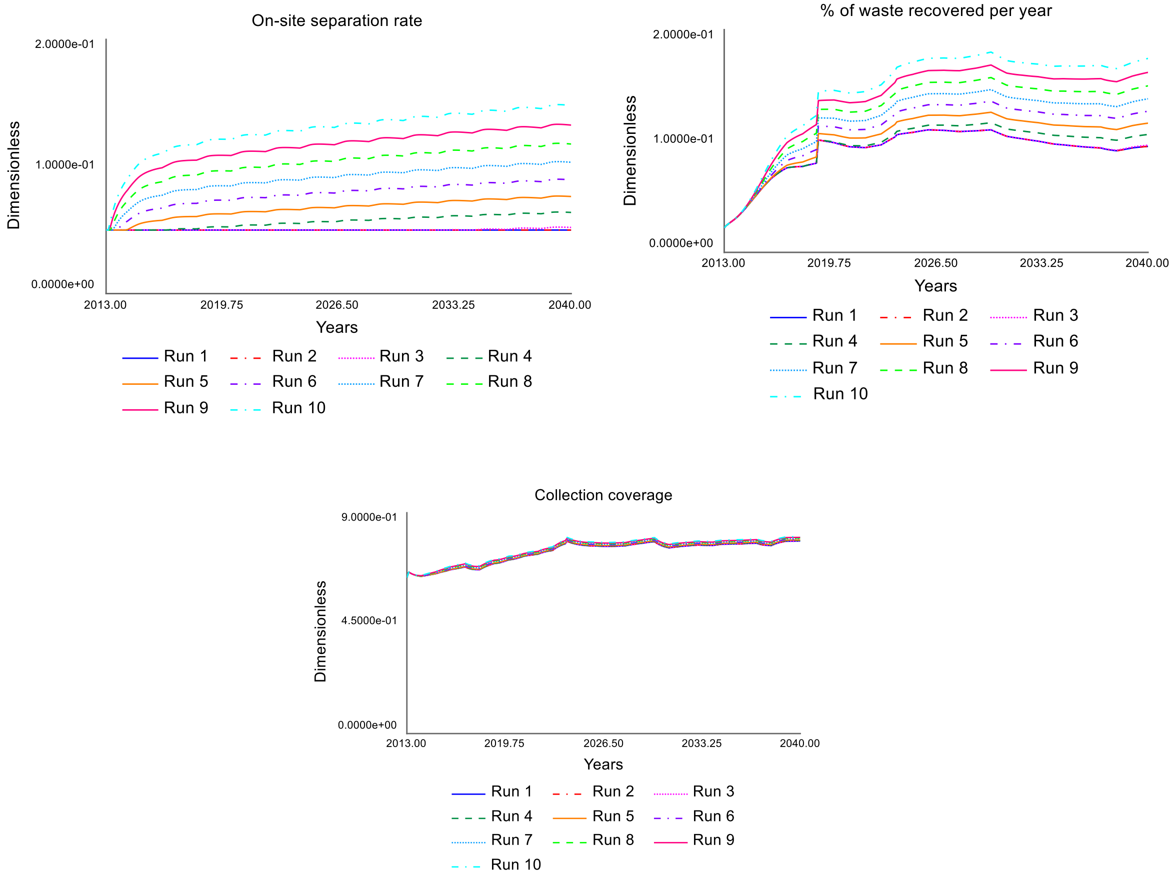
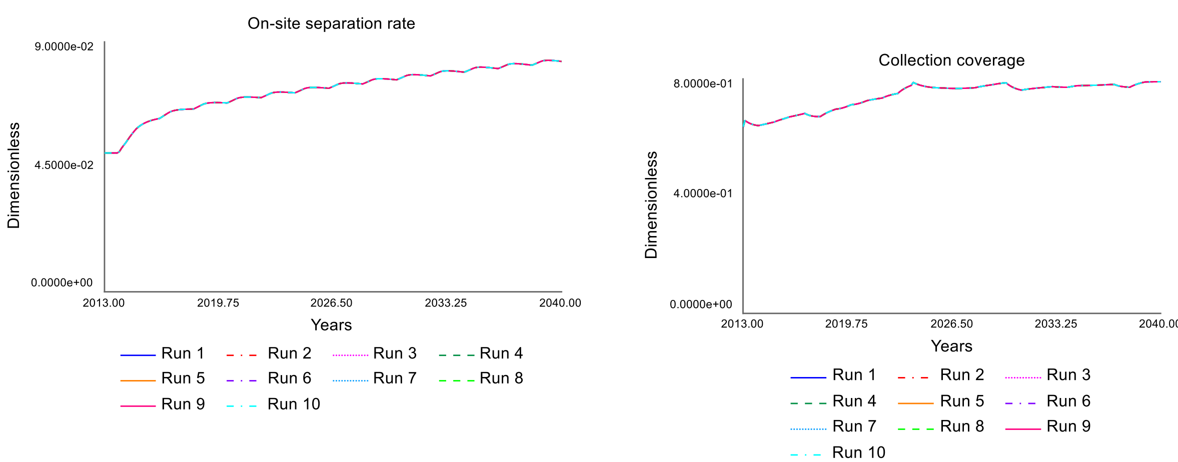


Fig A.2. Test results to changes in People with environmental knowledge that separate waste



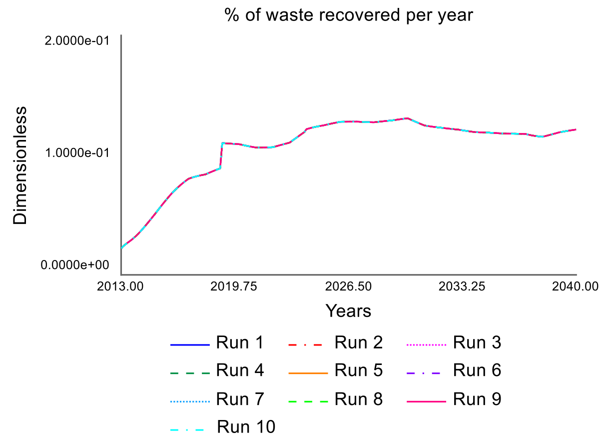


Fig A.3. Test results to % of value recovered for CE investments

Appendix 5. Model Documentation

The SD model and its full documentation are available at the following link:

https://surfdrive.surf.nl/files/index.php/s/EvIsBvnmvv5Ljhi