

Dynamic Integrated Model for Sustainable Solid Waste Management in Bengkulu City

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ARTICLE INFO

Received: 25 Feb 2025

Received in revised: 12 Jul 2025

Accepted: 16 Jul 2025

Published online: 18 Aug 2025

DOI: 10.32526/ennrj/23/20250048

Keywords:

Municipal waste management/
Waste reduction/ Management
costs/ Landfill space/ Dynamic
systems

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ABSTRACT

Rapid urbanization and increased consumption patterns have intensified municipal solid waste (MSW) challenges in developing cities. This study applies a system dynamics model to project waste generation, management costs, and landfill requirements in Bengkulu City, Indonesia, over a 20-year period. Four scenarios were simulated: business-as-usual, minimum (25%), moderate (50%), and optimistic (65%) waste reduction. The model integrates critical parameters including population growth, waste generation rates, recycling capacity, and community participation. Results indicate that without intervention, cumulative waste volume will overwhelm landfill capacity and escalate operational costs. Conversely, implementing waste reduction strategies—such as strengthening source separation, expanding composting and waste banks, adopting advanced technologies, and enforcing supportive policies—substantially reduces landfill dependency and operational expenses. The optimistic scenario demonstrates the highest efficiency, reducing required landfill land by over 85% and significantly lowering management costs. This study highlights the importance of multi-stakeholder collaboration, digital monitoring integration, and circular economy principles in urban waste governance. The model offers a practical decision-support framework for policymakers aiming to develop resilient, inclusive, and sustainable waste management systems in similar urban contexts.

HIGHLIGHTS

This study highlights a dynamic system model in solid waste management (SWM) that integrates waste reduction, landfill needs, management costs, and emphasizes the contribution of costs as environmental services to reduce dependence on regional budgets through the “Waste Independence-Waste Independence” strategy, which focuses on community awareness, infrastructure, and cross-sector collaboration.

1. INTRODUCTION

Solid waste management (SWM) has become an increasingly critical global issue due to the rapid urbanization and rising consumption patterns that contribute to escalating waste volumes. By 2050, global municipal solid waste is projected to reach 3.4 billion tons annually, with the steepest growth observed in developing countries. Currently,

approximately 40% of waste is landfilled, 33% is openly dumped, 19% is recycled, and 11% is incinerated, with the remainder managed through other conventional methods (Govani et al., 2021). In many developing countries, SWM still relies on the basic “collect-transport-dispose” model. Improperly managed waste especially when uncollected or untreated leads to environmental degradation,

Citation: Ermayendri D, Simarmata M, Arianto W, Reflis, Riwandi, Sukiyono K. Dynamic integrated model for sustainable solid waste management in Bengkulu City. Environ. Nat. Resour. J. 2025;23(6):494-515. (<https://doi.org/10.32526/ennrj/23/20250048>)

including clogged waterways, contaminated water bodies, and increased disease vectors such as mosquitoes and rodents (Guerrero et al., 2013). This solid waste consists not only of organic and inorganic materials but also includes agricultural residues, hazardous substances, and microplastics, which have detrimental effects on aquatic life and, ultimately, pose broader risks to human health and the environment (Ferronato and Torretta, 2019; Rahman et al., 2023). In addition, the uncontrolled decomposition of organic waste in landfills produces methane, a potent greenhouse gas that significantly contributes to climate change (Lee et al., 2017).

Recent research has emphasized the importance of integrated, sustainable approaches to waste management that go beyond conventional practices. Biotechnological innovations, for instance, are being employed to detect and mitigate microplastic pollution through the use of biosensors, enzymatic degradation, and specialized microorganisms, while the development of biodegradable alternatives to single-use plastics offers promising long-term solutions (Mai et al., 2018; Rahman et al., 2023). Parallely, the paradigm of urban wastewater management is shifting toward decentralized systems, resource recovery, and water reuse, which align closely with solid waste reduction and environmental protection goals. Additionally, the valorization of agricultural waste biomass for bioenergy production—such as biogas, bioethanol, and biochar—can simultaneously reduce landfill loads and support renewable energy transitions (Pfister et al., 2005). These strategies are essential for mitigating methane emissions from landfills, a major contributor to climate change (do Carmo Precci Lopes et al., 2022; Sołowski et al., 2020).

Furthermore, the transition toward a sustainable environment must be underpinned by the integration of green energy technologies (Hla and Roberts, 2015). While renewable energy sources such as solar, wind, and bioenergy present both advantages and limitations, their incorporation into waste and water management systems fosters resilience and lowers carbon footprints (Bruno et al., 2021; Zhang et al., 2024). Innovations in agricultural production, such as speed breeding, indirectly influence waste generation by increasing crop outputs, and consequently, agricultural residues (Meena et al., 2023). When properly harnessed, these residues serve as valuable feedstocks for energy production. In this context, sustainable solid waste management is no longer solely a matter of disposal but must be viewed as a

complex, interdisciplinary challenge—requiring biotechnological, agricultural, and infrastructural innovations to ensure long-term ecological and human well-being (Moya et al., 2017).

Effective waste management is a multidimensional process that encompasses various interrelated aspects, each critical to ensuring environmental sustainability and public health. Effective management begins with understanding waste composition and implementing proper collection and source separation to enhance recycling and resource recovery. Treatment technologies such as composting, anaerobic digestion, and incineration help reduce landfill dependence and recover energy. Equally important are robust policy frameworks and active community participation, which are essential for sustainable and inclusive waste system (Kumar and Samadder, 2017; Wilson et al., 2006).

As a potential solution, the system dynamics approach provides a comprehensive framework for integrated waste management by capturing the complex interrelationships among waste reduction efforts, cost efficiency, landfill performance, and active community involvement. This methodology facilitates the simulation and assessment of diverse policy scenarios, such as economic incentives and public awareness campaigns, supporting the development of sustainable and adaptive waste management strategies. By incorporating dynamic feedback mechanisms and temporal variations, system dynamics provides policymakers with tools to identify critical leverage points for effective intervention. Ultimately, it enables the alignment of environmental objectives with the social and economic conditions of rapidly evolving urban environments (Bornstein, 2018; Radosavljevic et al., 2023; Sondh et al., 2024; Thatcher et al., 2024).

Dynamic systems modeling has been used by numerous researchers to analyze complex (Li et al., 2024), and the circular economy of waste (Ibarra Vega and Bautista-Rodriguez, 2024). This method has been applied in various fields such as the social sciences (Blakeslee et al., 2017; Smith and Thelen, 2003), fisheries (Free et al., 2023), mining (Friederich et al., 2022), wastewater management (Fragkoulis et al., 2011), agriculture (Pfister et al., 2005), food waste (Lam et al., 2018), and many other areas. The dynamic modeling approach allows policymakers and urban planners to simulate and evaluate the long-term impacts of various waste management strategies, integrating

socioeconomic and environmental dimensions (Dyson and Chang, 2005; Forrester, 1961).

This study introduces a waste management model designed to guide the development of effective waste reduction strategies. The model outlines four main scenarios: the first assumes no waste reduction efforts; the second, the Minimal Reduction scenario, targets a 25% reduction through basic recycling and composting; the third, the Moderate Reduction scenario, aims for a 50% reduction by expanding community-based programs and implementing green technologies; and the fourth, the Optimistic Reduction scenario, seeks a 65% reduction through a combination of stringent policy enforcement, technological innovation, and widespread public participation. The simulation of these four scenarios dynamically influences waste generation sent to landfills, waste management costs, fees, and the required landfill area over the next 20 years. Population projections, which reflect waste generation patterns, are based on historical demographic data and economic growth, measured by the Gross Regional Domestic Product (GRDP), in Kota Bengkulu from 2013 to 2022.

The novelty of this study lies in the application of a dynamic systems modeling approach specifically tailored to municipal solid waste management in Bengkulu City, integrating waste generation dynamics, financial management, landfill land requirements, and community participation into a single, interrelated framework. Unlike previous studies that typically focus on isolated aspects of waste management, this research offers a comprehensive, scenario-based simulation over a 20-year projection period, evaluating the long-term impacts of varying levels of waste reduction interventions. The study also provides a decision-support tool that enables policymakers to assess the trade-offs between operational costs, landfill capacity, and environmental impacts under different policy scenarios, thus bridging the gap between theoretical modeling and practical, locally adaptable waste management planning.

2. METHODOLOGY

2.1 Study site

Bengkulu City is the capital of Bengkulu Province, located on the western coast of Sumatra Island, directly facing the Indian Ocean. Geographically, it lies between 3°45'-3°59' South Latitude and 102°14'-102°22' East Longitude. The city covers a total area of 539.3 km², consisting of

151.7 km² of land and 387.6 km² of sea. Due to its coastal location, Bengkulu City is exposed to strong ocean waves, making the area vulnerable to natural coastal erosion or abrasion. Topographically, Bengkulu City is relatively flat. The majority of the land—approximately 142.24 km², or 98.42% of the total area—has a slope of 0-15%. Only a small portion, about 2.28 km² or 1.58%, has steeper slopes ranging from 15-40%. The flattest areas are located along the coastline, with elevations ranging from 0 to 10 meters above sea level. In contrast, the eastern part of the city rises slightly higher, with altitudes ranging from 25 to 50 meters above sea level.

2.2 Solid waste management in Bengkulu

Waste management in Bengkulu City is carried out by the local government through the Environmental Agency (Dinas Lingkungan Hidup, DLH). The institutional framework for waste management is outlined in the Bengkulu City Mayor Regulation No. 08 of 2018 concerning the establishment of a Technical Implementation Unit for Waste Management within the Environmental Agency of Bengkulu City. The institutional aspects of waste management in Bengkulu City are also detailed in the Strategic Plan of the Environmental Agency for the years 2019-2023, which designates the Environmental Agency as the authority responsible for waste management in the city. Within the agency, one of the departments with a primary responsibility for waste management is the Cleanliness Division. Additionally, the Environmental Services include the Waste and Hazardous Waste Management Division, which oversees the Waste Reduction Section, Waste Handling Section, and Hazardous Waste Section.

The actual waste management service in Bengkulu City begins with waste collection at the source and continues with transportation to the final processing site, following the “collect-transport-dispose” approach. Waste generation comes from household waste as well as similar waste from residential areas, commercial establishments, restaurants, hotels, offices, educational institutions, public facilities, and street sweeping activities, with organic waste dominating the composition. The majority of waste is transported directly to the landfill without any sorting efforts, except by scavengers who separate and collect waste at the landfill (Environmental Services of Bengkulu City, 2022).

2.3 Dynamic system

System dynamics, introduced by Jay Forrester in the 1960s at MIT, is a quantitative method for analyzing complex systems and long-term decision-making (Stermann, 2001). The analysis begins with identifying key problems, critical variables, and system boundaries using causal loop diagrams. This initial understanding forms the foundation for developing formal models that are applied across various fields, such as business, environment, and politics (Dyson and Chang, 2005; Zulkipli et al., 2018). The next stage involves developing hypotheses and stock-flow models to illustrate variable interactions. Model validation is conducted through structural and behavioral testing to ensure alignment with real-world patterns. Various policy scenarios are then tested to assess their effectiveness, providing a data-driven foundation for more accurate decision-making.

This study used PowerSim Studio 10 as a simulation tool to model the dynamic and interrelated nature of the waste management system. The software integrates key subsystems, such as waste production, reduction, landfill land requirements, management costs, and service charges. This enables scenario-based analysis to support long-term planning. PowerSim's causality and stock flow modeling features provide valuable insights into system

behavior, helping stakeholders evaluate the impact of different strategies and make informed decisions for more sustainable and adaptive waste management. The stages of dynamic system analysis in this study are presented in Figure 1.

The dynamic system method is a structured framework commonly employed in the analysis of complex systems and policy design. It combines both qualitative and quantitative approaches to model dynamic behaviors over time. This methodology begins with system analysis, where researchers identify the key problems, variables, system boundaries, and time horizon relevant to the study. Establishing these fundamental components ensures that the scope and focus of the analysis are clear and aligned with the objectives of the research.

Following system analysis, the next stage is hypothesis development, where assumptions about causal relationships between variables are formulated. These hypotheses provide the theoretical basis for constructing the system dynamics model. In the subsequent stage, model development, the identified variables and hypothesized relationships are visualized through causal loop diagrams and stock-and-flow diagrams. This visual modeling enables a deeper understanding of the interactions within the system and allows researchers to simulate the system's behavior under various conditions.

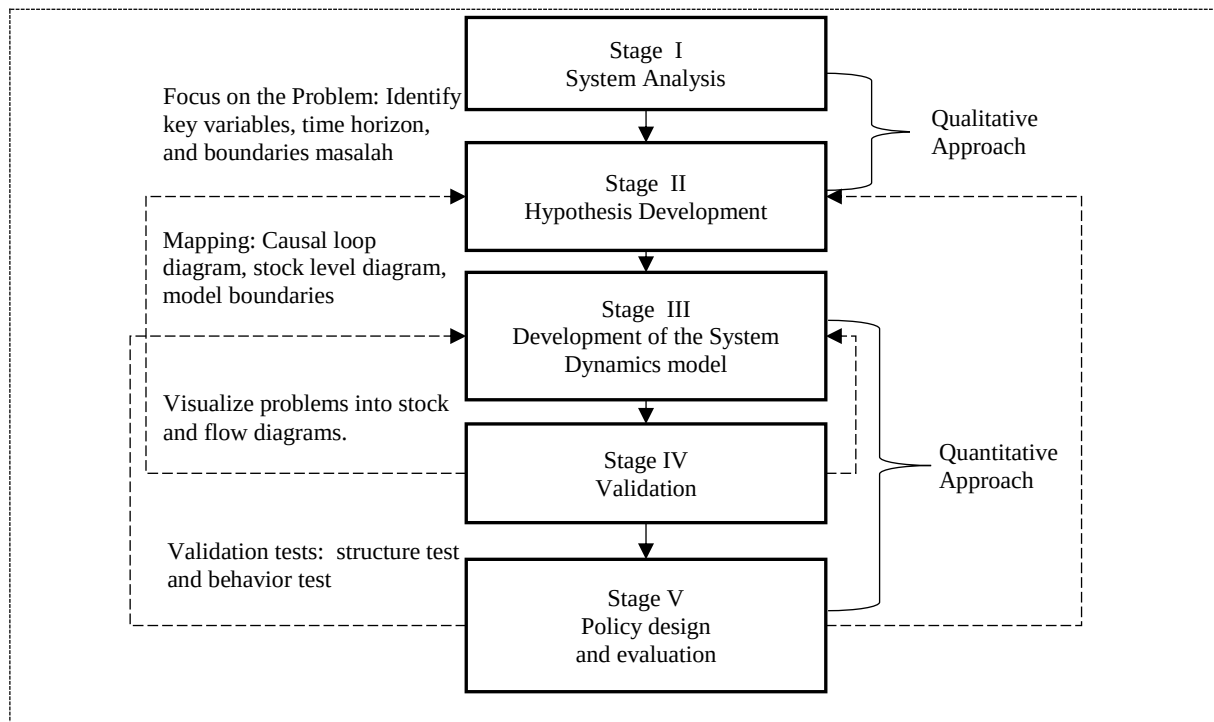


Figure 1. Stages of dynamic system methods

The fourth stage is validation, where the model undergoes structure and behavior tests to ensure its accuracy and reliability. Structure tests verify the internal consistency of the model, while behavior tests compare the simulated outputs against historical data. Once validated, the final stage, policy design and evaluation, involves using the model to simulate alternative scenarios and assess their potential impacts. This enables decision-makers to select the most effective policy options based on evidence derived from model simulations. Through this systematic process, dynamic system methods offer a robust tool for analyzing complex problems and supporting strategic policy formulation.

2.3.1 System identification: Key parameters for effective waste reduction

This study proposes a dynamic system model for sustainable municipal solid waste management in Bengkulu City, focusing on the issues of increasing waste generation, limited landfill capacity, and financial challenges faced by the local government. The system integrates key subsystems, including waste generation, waste reduction at source, waste collection and transportation, landfill land requirements, and financial management through government budgets and household waste fees. Critical variables modeled include the waste generation rate, percentage of waste reduction, volume of waste transported to the landfill, required landfill area, operational costs, and revenues from waste fees. These variables interact dynamically over time, influenced by population growth, economic activities, and community participation. The system boundaries are set within Bengkulu City's administrative area, covering household and similar domestic waste types over a 20-year planning period (2025-2045).

Four simulation scenarios are developed to assess policy effectiveness: Business as usual (0% reduction), minimum (25%), moderate (50%), and optimistic (65%) waste reduction by 2045. Each scenario will be analyzed for its impact on total waste generation, landfill land demand, operational costs, and financial sustainability, including government budget allocations and public waste collection fees. The dynamic model aims to produce evidence-based projections to guide strategic decisions, offering insights into how varying levels of waste reduction influence infrastructure needs, environmental outcomes, and municipal financial performance. This approach is expected to support the formulation of

integrated, realistic, and sustainable waste management policies for Bengkulu City over the long term. Effective waste reduction is underpinned by several critical parameters that must be addressed systematically. Foremost among these is the strengthening of waste segregation at the source, which serves as the foundational step in minimizing overall waste volume. In parallel, implementing composting initiatives at both community and city scales can substantially decrease the amount of organic waste destined for landfills. The expansion of waste bank networks is equally essential, as it broadens public access to recycling opportunities and encourages community participation.

The reduction scenarios simulated in this dynamic model aim to generate evidence-based projections to guide strategic decisions, offering insights into how different levels of waste reduction affect the infrastructure needs, environmental outcomes and financial performance of the city. This approach is expected to support the formulation of integrated, realistic, and sustainable waste management policies for Bengkulu City in the long term. Furthermore, the adoption of advanced waste management technologies enhances operational efficiency, while the consistent enforcement of related policies ensures regulatory compliance and accountability. Collaboration with the private sector also plays a pivotal role by fostering innovation and resource mobilization. Lastly, the establishment of regular monitoring mechanisms is crucial for evaluating progress and informing policy adjustments. Collectively, these integrated measures contribute to the development of a more sustainable and responsible waste management system. The system identification in this study is shown in [Figure 2](#).

2.3.2 Causal loop diagram

The black box description of the system performance variables is explained through the Causal Loop Diagram presented in [Figure 3](#), illustrating the relationships between variables within the system. Causal Loop Diagram illustrates the dynamic interactions within the urban waste management system, emphasizing the relationship between population growth, waste generation, and municipal handling capacity. As the population increases, driven by the population growth rate, the number of households rises, leading to higher waste generation levels. This increase in waste generation directly affects the volume of both organic and inorganic

waste, placing greater demands on the city's waste management infrastructure. The escalation in waste volume subsequently leads to higher handling costs

for waste management services, creating a feedback loop that influences municipal financial planning and operational efficiency.

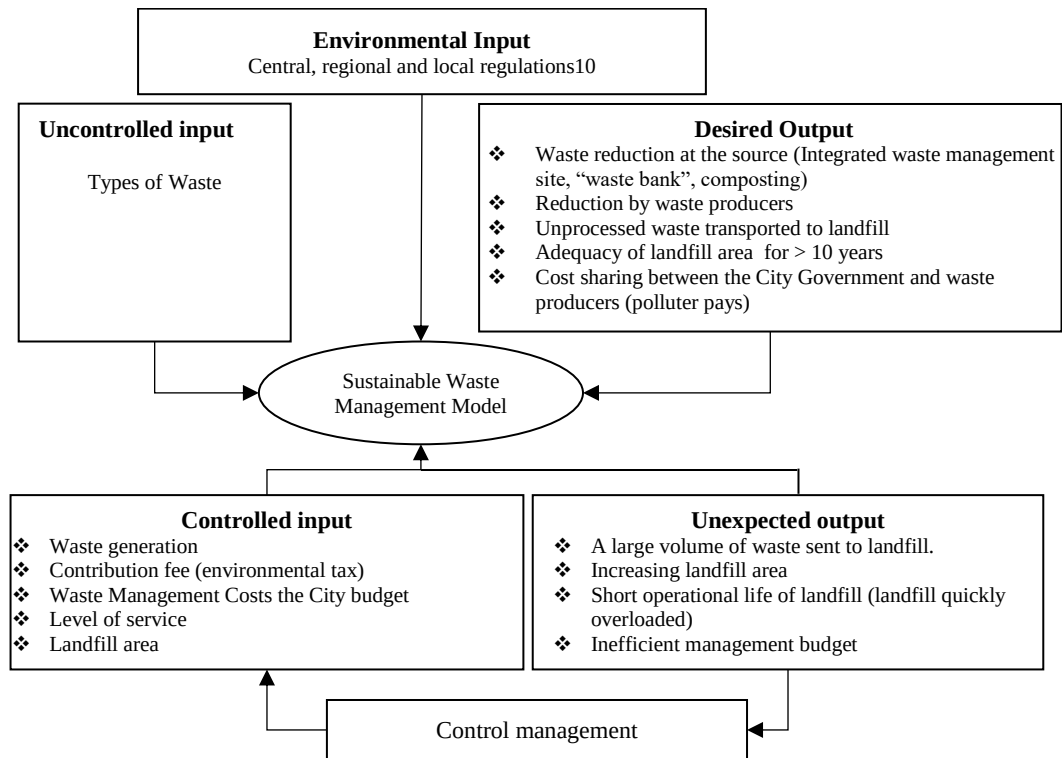


Figure 2. Variables affecting system performance (black box)

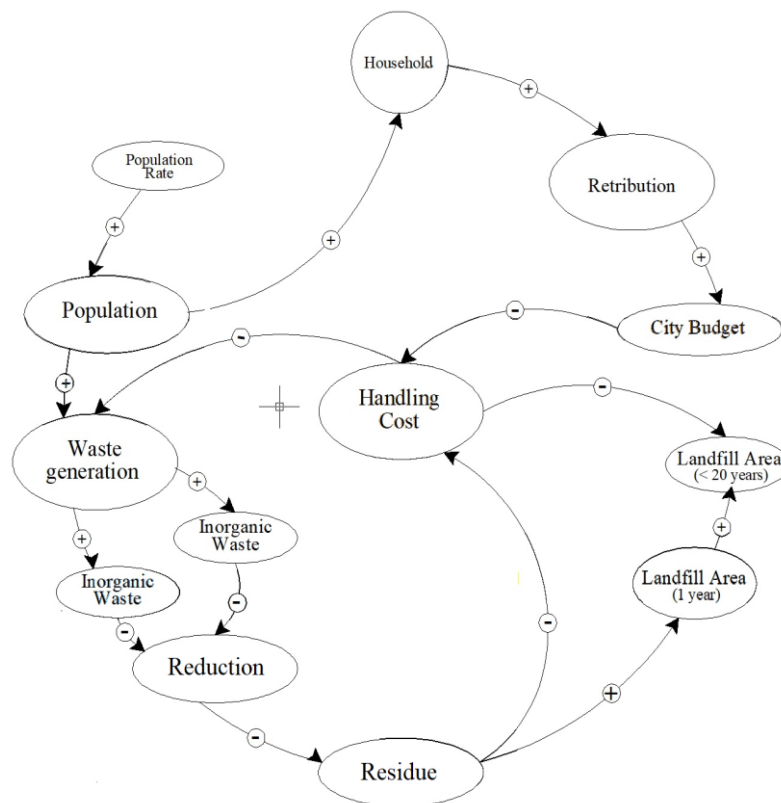


Figure 3. Causal loop diagram (CLD)

An essential component of the system is the waste reduction process, primarily through waste sorting activities. The reduction process helps decrease the volume of inorganic waste that becomes residual waste requiring landfill disposal. This reduction lowers the overall burden on the landfill, thereby moderating the rate of landfill area utilization. The feedback loop indicates that effective waste reduction strategies can reduce residual waste, leading to decreased handling costs and extended landfill lifespan. However, if reduction efforts are inadequate, residual waste will continue to accumulate, intensifying the pressure on landfill space and operational costs.

Additionally, the diagram captures the financial feedback loop between waste handling costs and the city budget, which is influenced by household waste service retributions. Increased retributions from a growing number of households contribute positively to the city budget, supporting waste management services. Conversely, higher handling costs, resulting from increased waste generation and residual accumulation, can strain the city budget if not matched by adequate financial inflows. The interplay between these factors highlights the importance of integrated waste management strategies and policy interventions, particularly in promoting waste sorting and reduction programs to achieve sustainable urban waste management outcomes.

In addition, the diagram captures the feedback cycle of five main components, namely: waste generation, waste reduction, landfill land requirement, management cost, and retribution. These five elements do not stand alone, but interact with each other to form an overall waste management system. The impact of the inter-subsystem linkages is very significant in achieving sustainable waste management. The volume of waste generation determines the initial burden of the management system, while the effectiveness of reduction efforts affects the amount of volume that must be treated or disposed of. The increase in waste volume drives the need for more landfill space, posing spatial and ecological challenges, especially in dense urban areas. On the other hand, an increase in management burden results in an increase in operational costs, which demands sustainability in terms of financing. In this case, retribution becomes an important instrument to cover the cost, but its effectiveness is highly dependent on an efficient collection mechanism and the level of community

participation. The five subsystems thus form a dynamic system structure, which requires an integrated approach, intersectoral coordination and long-term planning to ensure a balance between environmental sustainability, economic viability and social acceptability.

2.3.3 Stock flow diagram (SFD)

Based on the CLD above, the SFD was made and is presented in [Figure 4](#) along with the details of Variable Definitions in [Table 1](#). In the SFD model, it can be explained that the number of residents affected by the population growth rate per year can be seen from the waste produced by each person per year, which is 915.5 liters/person/year. The assumption made for waste management planning in this study is the amount of waste produced in 2025, so that the graphs start in 2025, assuming that in 2025 waste management activities have been carried out in an integrated manner, and efforts to reduce the total waste are mentioned.

The Stock Flow Diagram (SFD) presented illustrates a dynamic systems model for sustainable waste management in Bengkulu City, incorporating the interconnected relationships between population growth, waste generation, financial resources, and landfill land use requirements. The model begins with the population stock, which increases over time based on a predetermined growth rate. This increase in population directly influences the number of households, subsequently determining the total waste generation volume. Cumulative waste generation is calculated by multiplying the waste generation rate per capita by the total population, establishing the primary inflow to the waste management system.

Waste generated in the city is handled through a waste management process at a specific handling rate, which determines the cumulative waste managed over time. The model recognizes that not all waste can be processed or diverted, and the residual waste—the portion that remains after handling and reduction efforts—flows into the landfill system. The reduction rate, which is influenced by implemented waste reduction scenarios (ranging from 0%, minimum 25%, moderate 50%, to optimistic 65%), determines the effectiveness of waste sorting, recycling, or other diversion programs. Higher reduction rates result in a lower volume of residual waste, reducing the cumulative waste sent to landfills and consequently limiting the need for landfill land expansion.

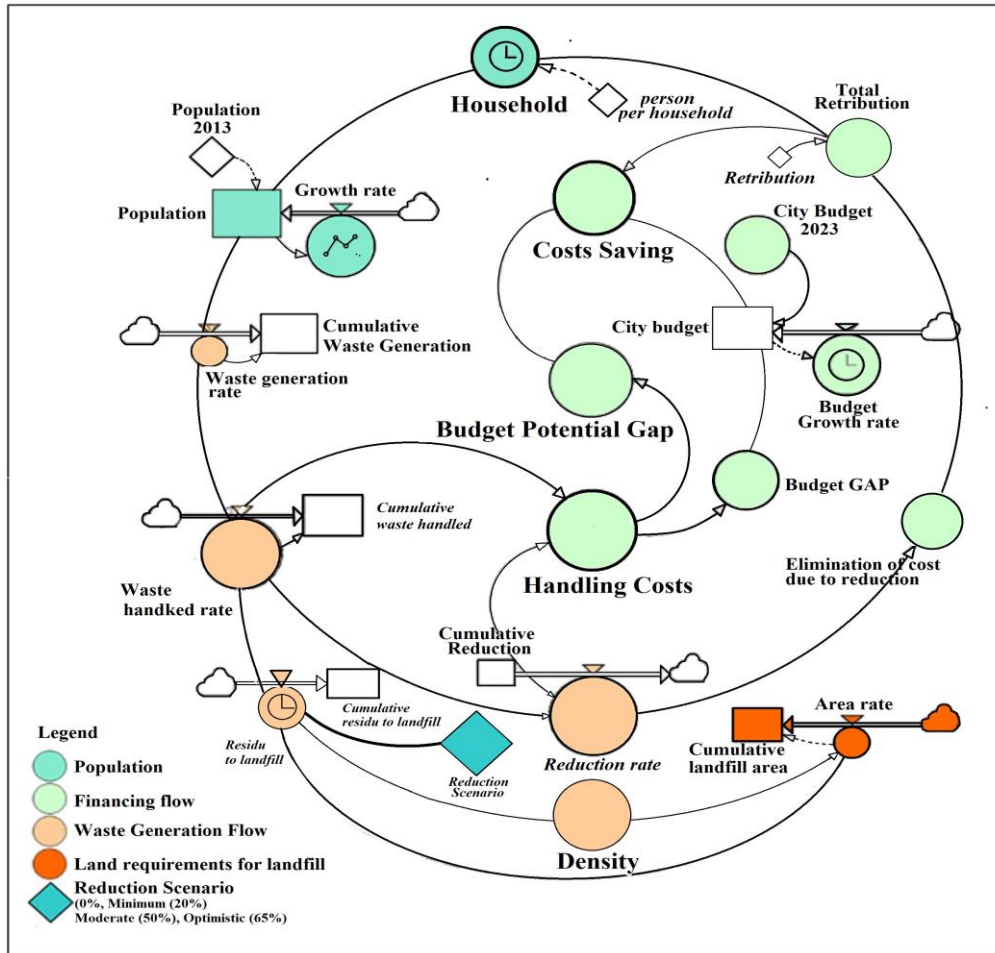


Figure 4. Stock flow diagram the proposed integrated waste management in Bengkulu City

An essential element of the model is the financing mechanism for waste management operations. Households contribute to municipal waste services through a retribution fee, which collectively forms the city's budget for waste management. This budget grows annually based on a predetermined growth rate. However, the model highlights a potential budget gap when handling costs increase at a rate faster than budget growth, particularly when waste generation surpasses the city's management capacity. To address this, cost savings from waste reduction programs are factored into the model as a feedback mechanism, reducing the overall handling cost burden and helping to stabilize the budget.

The diagram also integrates a spatial component by linking residual waste volumes to land requirements for landfill areas. Cumulative residual waste is translated into required landfill land based on landfill density and area rate factors. As residual waste accumulates, the model tracks the cumulative landfill area used over time. This aspect underscores the long-term land use implications of waste management

decisions and highlights the importance of reducing residual waste volumes to prevent excessive land conversion for landfill purposes, particularly in urban areas with limited land availability such as Bengkulu City.

Overall, the Stock Flow Diagram serves as a strategic decision-support tool for evaluating the long-term impacts of various waste management scenarios. By simulating changes in population, waste generation rates, reduction strategies, and financial capacities, stakeholders can forecast potential budget gaps, identify operational bottlenecks, and estimate future landfill land needs. This system dynamics approach enables policymakers to design adaptive, data-driven waste management interventions that align with sustainability goals, resource constraints, and urban development priorities in Bengkulu City through 2045.

To offset these costs, the model factors in revenue streams from household and commercial waste retribution fees, simulating various compliance and collection efficiency rates. Furthermore, the residual waste volume—after reduction efforts—is

used to estimate the required landfill area, based on waste compaction rates and landfill design life. By linking population dynamics, technological interventions, financial viability, and spatial planning,

this system dynamics model offers a comprehensive framework for evaluating long-term waste management strategies in Bengkulu City.

Table 1. Details of variable definitions in SFD

Description	Definition
Population 2013-2022	2013: 334.500 2014: 342.900 2015: 351.300 2016: 359.500 2017: 366.435 2018: 368.784 2019: 370.135 2020: 373.600 2021: 378.600 2022: 384.800 2023: 391.045
Growth rate	Population*(GRAPH (TIME,2013,1,{0.025112, 0.024497,0.023342,0.019291,0.00641,0.003663, 0.009361,0.013383,0.016376//Min:0,003663, Max:0,025//})//Min:0, Max:1//)
Household constants	3,41
Household	IF(TIME>2025, Population/'Constant household',0)
Waste generation	0.9125 tons/person/year
Waste generation rate	Population*2.5*365
Waste handled rate	100%
Reduction rate	'Waste handled rate'-'Residue to Landfill'
Sampah ke TPA	IF(TIME>2024,'Waste handled rate'-('Waste handled rate'*'Reduction Scenario'))
Density	'Residue to Landfill '* 0.6
landfill area rate (hectare)	((('Residue to Landfill'-Density)/30)/10000
Handling cost/cubic meter	\$ 0.88,-
Elimination of costs due to reduction	('Reduction rate'/Cubic)*Dollar
Retribution	\$ 23.35 per year/household
Total Retribution	(Household*Retribution)-'Elimination of costs due to reduction'
Handling Cost	((('Waste handled rate'-'Reduction rate')/Cubic)*Dollar
Budget Growth Rate	IF(TIME>2025,'City Budget'*'Budget Constant')
Reduction Scenario	Current (0%), 25% (minimal), 50% (moderate), 65% (optimistic)

The system dynamics model developed in this study incorporates several interrelated variables to project the long-term implications of municipal solid waste management in Bengkulu City. Population data from 2013 to 2023 indicate steady growth from 334,500 to 391,045 inhabitants, with an average annual increase ranging from 0.37% to 2.51%. Waste generation is estimated at 0.9125 tons per person per year, equivalent to 2.5 liters per capita daily. Waste management simulations assume 100% collection efficiency, with varying reduction rates based on four scenarios: 0%, 25%, 50%, and 65%. The model calculates landfill area requirements using a waste density of 0.6 tons/m³ and a maximum landfill depth of 30 meters. Financial variables include a waste handling cost of \$0.88 per cubic meter and a household retribution fee of \$23.35 per year. The model also integrates budget growth projections and

cost savings associated with waste reduction, enabling comprehensive scenario-based analysis of waste generation, operational expenses, and revenue from retributions over a 20-year period.

2.3.4 Validation

The value of “0” is between the range of μ_1 and μ_2 or between $(-18.724) - (+12.378)$; $(P[(x_1 - x_2) - hw \leq \mu_1 - \mu_2] \leq (x_1 - x_2) + hw]$, so h_0 is accepted or the simulation is valid (Table 2). There is no significant difference between real data and simulation results using Powersim software. This model is parameterized using historical data and relevant variables, allowing for the simulation of waste reduction across different scenarios. The waste reduction scenarios include a minimal scenario, which represents the lowest level of waste reduction; a moderate scenario, reflecting an intermediate level of

reduction; and an optimistic scenario, which achieves the highest level of waste reduction.

Model validation was conducted using a t-test comparison between real population data and simulation results for the period 2013-2022. The results show a very close alignment between observed and simulated values, with the average real population recorded at 363,055 and the simulated value at 366,228. The standard deviations were also nearly identical, at 15,959.99 and 15,959.85, respectively. Statistical testing using a two-tailed t-test with 18 degrees of freedom produced a t-count of 2.1788,

which falls within the acceptance range of the T-table value of 2.179 at a 95% confidence level. This indicates no significant difference between real and simulated data. The absolute error remained within acceptable limits, with the mean error ranging from -3,172 to 12,378.56. These results confirm the validity and reliability of the dynamic system model in accurately representing demographic trends in Bengkulu City, providing a strong foundation for subsequent waste generation and management scenario simulations.

Table 2. T-test model validation

Year	Real data	Simulation data		
2013	334,500.00	334,500.00		
2014	342,900.00	342,899.96	25.472.127	25.471.673
2015	351,300.00	351,299.98	2.595.270.735.524.450	
2016	359,500.00	359,500.03	72.092.138.341.532	72.089.569.199.048
2017	366,435.00	366,435.14	144.181.707.540.581	
2018	368,784.00	368,783.99	Df 18	
2019	370,135.00	370,134.85	T Table 2.179	
2020	373,600.00	373,599.68	Hw 2.1788	25.472.127
2021	378,600.00	378,599.57	2.1788	7.137
2022	384,800.00	384,799.51	15.551	
Average	363,055.40	366,228.08	-3,172.68	(18.724)
Standard Deviation	15,959.99	15,959.85	-3,172.68	12,378.56

3. RESULTS AND DISCUSSION

3.1 Current waste management process flow in Bengkulu City

The process begins with the source of waste, which primarily originates from residential areas and public places such as markets, streets, and commercial zones. Following waste generation, the next step is waste collection, which is carried out by both the private sector and the city authority, ensuring that waste is gathered efficiently from different locations. After collection, waste is transported through the

transportation system, which is also managed by both private operators and the city authority, delivering the waste to designated disposal sites. The final stage of the process is the landfill, where waste is disposed of through open dumping. This traditional method poses environmental concerns, emphasizing the need for improved waste management practices, such as sustainable disposal techniques and waste reduction strategies. The flow of the solid waste management process in Bengkulu City is presented in [Figure 5](#).

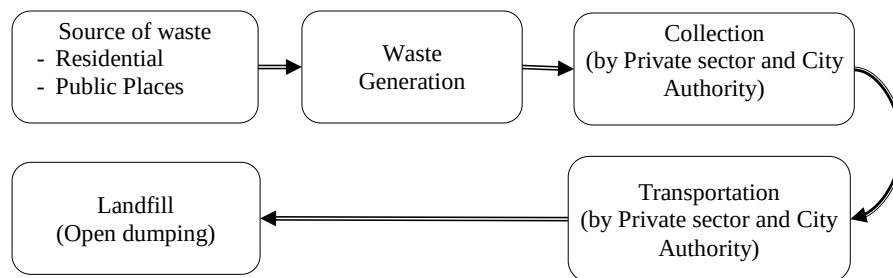


Figure 5. Process flow of solid waste management in Bengkulu City

3.2 Population projections

The population growth of Bengkulu City has demonstrated a consistent upward trend over the past decade. Based on historical data, the population increased from 334,500 persons in 2013 to 384,800 persons in 2022. In the period between 2013 and 2017, the city experienced a relatively steady annual growth rate, with the population rising from 334,500 to 366,435 persons, driven by natural population growth and rural-to-urban migration (Figure 6).

However, starting in 2018, the growth rate began to decelerate slightly. This slowing trend

became more apparent during the onset of the COVID-19 pandemic in 2020. The pandemic, which caused significant social and economic disruption globally, also impacted population dynamics in Bengkulu City. Although the city's population continued to grow during 2020-2022, the rate of increase was moderated due to several factors, including restrictions on population movement, increased mortality rates, and delays in internal migration. In 2020, the population reached 373,600 persons, increasing modestly to 378,600 in 2021 and 384,800 in 2022.

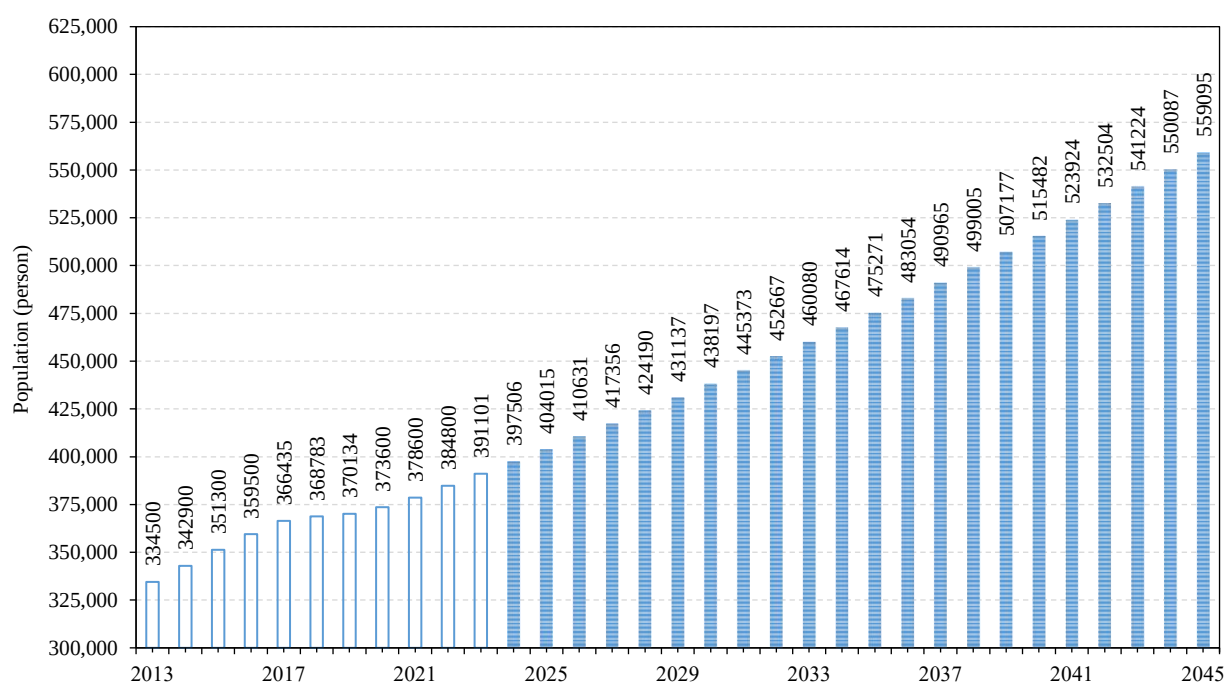


Figure 6. Population projections until 2045

Post-pandemic recovery, beginning in 2023, is projected to restore the city's population growth trajectory. With improvements in public health conditions, economic activities, and mobility, Bengkulu City's population is expected to continue increasing, reaching 559,095 persons by 2045. The projection suggests that, while the pandemic temporarily affected the growth rate, its long-term impact on the overall population trend remains limited, as growth is anticipated to steadily resume in the years following the pandemic. This population forecast provides critical input for urban planning, infrastructure development, and public service provision in Bengkulu City, ensuring that future

growth is accommodated in a sustainable and well-managed manner.

3.3 Waste generation

Based on Figure 7, the volume of waste generation in Bengkulu City is projected to increase steadily from 368,664 cubic meters in 2025 to 510,174 cubic meters by 2045. This growth is closely linked to the city's rising population, driven by natural growth and ongoing internal migration from rural areas to the urban center. The movement of people seeking better economic opportunities, education, and services contributes to a higher concentration of waste production, particularly in residential, commercial, and public areas.

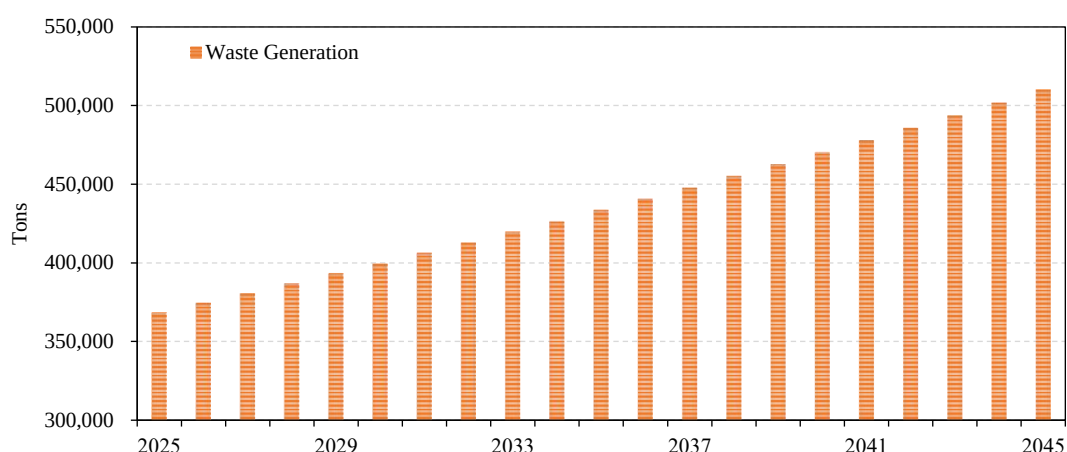


Figure 7. Graph of total waste increase in Bengkulu City from 2025 to 2045

In addition, Bengkulu's improving economic conditions following the COVID-19 pandemic are expected to influence waste generation patterns. As household incomes rise and consumption habits shift towards packaged and processed goods, the volume of waste produced per capita will gradually increase. This projection underscores the urgent need for the city to strengthen its waste management infrastructure, expand waste reduction programs, and promote sustainable lifestyle practices to ensure environmental sustainability in line with future urban and economic development.

Without intervention, the surge in waste could overburden landfills, increase pollution, and escalate management costs. Sustainable strategies such as source reduction, recycling, composting, and advanced waste processing technologies are crucial. The Integrated Solid Waste Management (ISWM) approach, based on the 3R (Reduce, Reuse, Recycle) concept, offers a systematic solution tailored to local conditions (Behera and Samal, 2022; Devi et al., 2023; Pinha and Sagawa, 2020).

3.4 The challenges involved in solid waste reduction

In the years ahead, Bengkulu City is expected to encounter serious challenges in managing and reducing its solid waste. The combination of rapid population growth, internal migration, and increasing economic activities will contribute to a steady rise in waste generation. A significant portion of this waste consists of organic materials such as food waste, leaves, and market waste, while the rest is dominated by plastics and other non-organic materials. Limited public awareness, weak waste segregation practices, and overdependence on the already overloaded Air

Sebakul landfill are major obstacles in reducing the volume of waste disposed of at final disposal sites.

To address these issues, Bengkulu City must prioritize integrated waste reduction strategies by promoting recycling and composting at the source. Community-based waste banks (bank sampah) and local recycling initiatives should be expanded to encourage residents to sort recyclable materials like plastics, paper, and metals. Meanwhile, composting programs targeting organic waste from households, traditional markets, and public spaces can significantly reduce the amount of biodegradable waste sent to landfills. The introduction of decentralized composting sites and household composting campaigns would help manage organic waste efficiently while producing valuable compost for urban agriculture. These combined efforts, supported by strong policy enforcement, public education, and private sector participation, will be crucial in creating a sustainable and effective solid waste management system for Bengkulu City in the future.

In this study, four levels of waste reduction scenario simulation were conducted. Reduction scenarios were developed to project varying levels of intervention within the waste management system, ranging from a business-as-usual approach to the most ambitious reduction targets. These scenarios reflect not only the expected reduction rates but also the complexity and intensity of the efforts required at each level. The no reduction scenario (0%) represents the existing condition, where the waste management system operates without significant improvements. At this stage, most waste is collected and disposed of in landfills, with minimal sorting, processing, or recycling. The system remains focused on end-of-pipe

solutions such as collection and disposal, with limited upstream intervention or waste minimization strategies. The minimum reduction scenario (25%) reflects early-stage efforts to reduce waste generation. This includes the introduction of basic waste separation at the household level, as well as the promotion of community-scale composting and waste bank initiatives. Public participation begins to emerge, but institutional transformation remains limited. Waste reduction reaches approximately one-fourth of the total waste generated.

The moderate reduction scenario (50%) represents a transitional phase toward a more integrated system. Institutional roles become stronger, with increased involvement from local governments, the private sector, and civil society. Waste processing technologies are introduced more systematically, regulations are enforced more consistently, and cross-sector partnerships are established. At this stage, up to 50% of the waste is successfully diverted through composting, recycling, and source reduction efforts. The optimistic reduction scenario (60-65%) reflects an ideal condition in which nearly all organic waste is converted into compost, while inorganic materials such as plastic, paper, and metal are recycled to the fullest extent possible. The waste management system becomes holistic and fully integrated, supported by appropriate technologies, strong policy enforcement, financing mechanisms, and stakeholder collaboration. Waste reduction reaches its highest level,

demonstrating the realization of circular economy principles at the city scale.

3.5 Waste generation with reduction

Based on Figure 8, Bengkulu City is projected to generate a cumulative waste volume of 12,979,047 m³ over the next 20 years, reflecting a significant challenge in waste management amid population growth and lifestyle changes. This increasing waste volume demands more effective management strategies, particularly in reducing waste generation at its source. The Air Sebakul landfill, which has been in operation for 32 years, is now in a critical condition with its capacity exceeded, making it unable to accommodate more waste. This challenge is further complicated by the Regional Spatial Planning Regulation of Bengkulu City 2021-2041, which does not allocate land for a new landfill, accelerating the urgency of waste reduction strategies such as composting, recycling, and reducing plastic use. Programs like Waste Banks, public education, and the development of recycling infrastructure are priority steps to ensure sustainable waste management. Without proper intervention, Bengkulu City risks facing an environmental crisis that could impact public health and overall quality of life. Therefore, collaboration between the government, the community, and the private sector is essential to establish a more sustainable waste management system and ensure Bengkulu City's livability in the future.

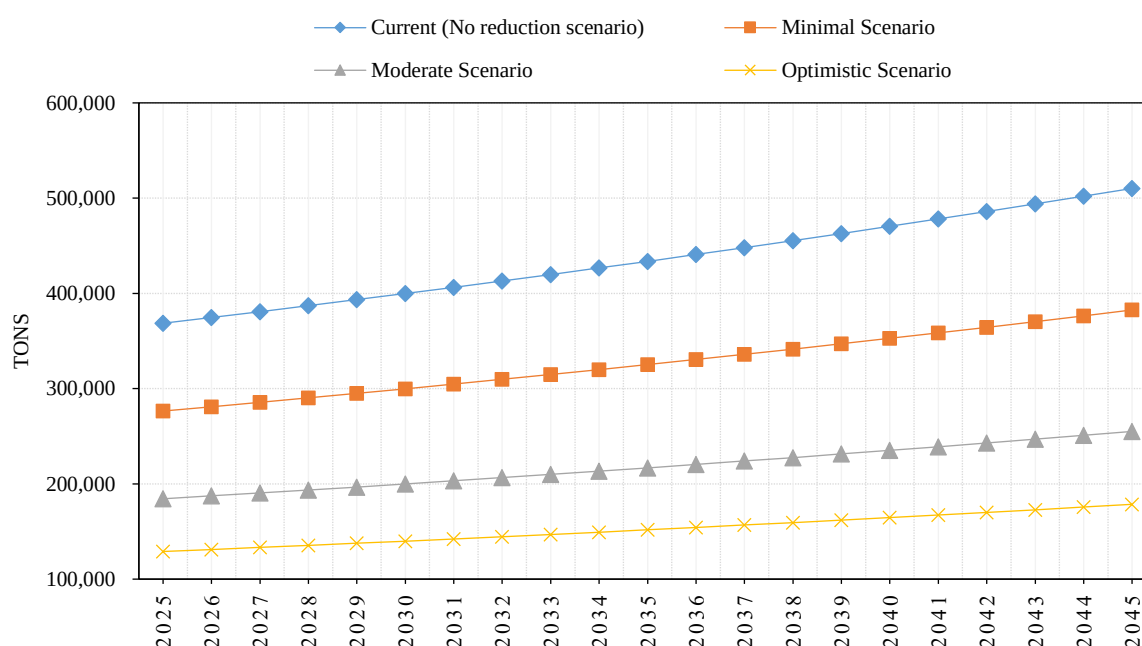


Figure 8. Simulation and projection of residue to landfill with not reduction and reduction scenarios

The simulation and projection results in [Figure 8](#) illustrate the trends of waste residue directed to the landfill under four reduction scenarios in Bengkulu City from 2025 to 2045. In the Existing Reduction scenario, where no substantial waste minimization improvements are applied, the amount of residue increases steadily each year, driven by continuous population growth and rising waste generation rates. The Minimum Reduction scenario, assuming a 20% reduction effort, results in a slightly lower but still increasing trend of landfill residue, indicating that minimal intervention is insufficient to control waste accumulation in the long term. These two scenarios demonstrate how inadequate reduction efforts will sustain high dependency on landfill disposal and threaten the availability of landfill space in the city.

Conversely, the Moderate Reduction scenario, targeting a 50% reduction rate, effectively slows the growth of waste residue sent to the landfill. This projection highlights the positive impact of applying intermediate reduction measures such as waste sorting, recycling programs, and community-based composting initiatives. The Optimistic Reduction scenario, assuming a 65% reduction rate, shows the most promising outcome, maintaining a relatively stable and low volume of landfill residue throughout the projection period. This scenario underscores the

importance of comprehensive and consistent waste reduction efforts to sustainably manage urban waste and minimize environmental and spatial burdens from landfill dependency. The comparison between these scenarios confirms that achieving higher reduction rates is essential for ensuring sustainable waste management in Bengkulu City over the next two decades.

3.6 Projection of landfill land requirements until 2045

To estimate the land area required for landfilling purposes, the volume of waste must be calculated from the mass using a density-based conversion. According to SNI 19-2454-2002, the maximum waste thickness (before final closure) is typically 20-30 meters, depending on site-specific design and geological conditions. For the purpose of this estimation, the final depth is assumed to be 30 meters. The density of household waste varies significantly depending on the level of compaction: uncompacted waste averages 150-250 kg/m³, medium compacted 300-400 kg/m³, and densely compacted (e.g., sanitary landfills) about 500 kg/m³ ([Table 3](#)).

$$\text{Volume (m}^3\text{)} = \frac{\text{Density (}\frac{\text{kg}}{\text{m}^3}\text{)}}{\text{Weight (kg)}} \times \text{Weight (kg)} \quad (\text{m}^3)$$

Table 3. Landfill area by waste weight

Waste compaction level	Density (kg/m ³)	Volume (m ³) per ton	Land area required for landfill (layer depth 30 m)
Uncompacted	200	5,000	167 m ²
Moderately compacted	300	3,300	111 m ²
Densely compacted	500	2,000	67 m ²

The implementation of waste reduction strategies across four distinct reduction scenarios demonstrates substantial potential for land use efficiency. The current scenario requires 29.28 hectares, whereas the Minimum, Moderate, and Optimistic scenarios require only 8.78, 5.86, and 4.10 hectares, respectively. The Optimistic scenario represents the smallest land increase, approximately 0.17-0.24 hectares per year. By implementing waste reduction strategies, the city can save more than 23 hectares, reduce environmental impact, and enhance waste management sustainability ([Figure 9](#)). Without intervention, waste accumulation over 20 years is projected to reach 8,782,842.61 m³, requiring 29.28 hectares of land. Waste reduction by 25%, 50%, and

65% would decrease land requirements to 8.78, 5.86, and 4.10 hectares, respectively. Compaction of waste up to 70% can save land and costs by up to 73% ([Banerjee et al., 2023](#)). Moreover, landfills contribute 15% of global methane emissions, exacerbating climate change ([Guo et al., 2024](#)).

The simulation and projection results in [Figure 9](#) reveal the long-term implications of four waste reduction scenarios on cumulative landfill land requirements in Bengkulu City over a 20-year planning horizon (2025-2045). Under the Existing Reduction scenario, where current waste management practices continue without significant improvement, the projected landfill area requirement reaches 29.28 hectares by 2045. This substantial land demand

highlights the unsustainable nature of the existing system, where the continuous increase in waste

generation and minimal reduction efforts result in accelerated land consumption for landfill purposes.

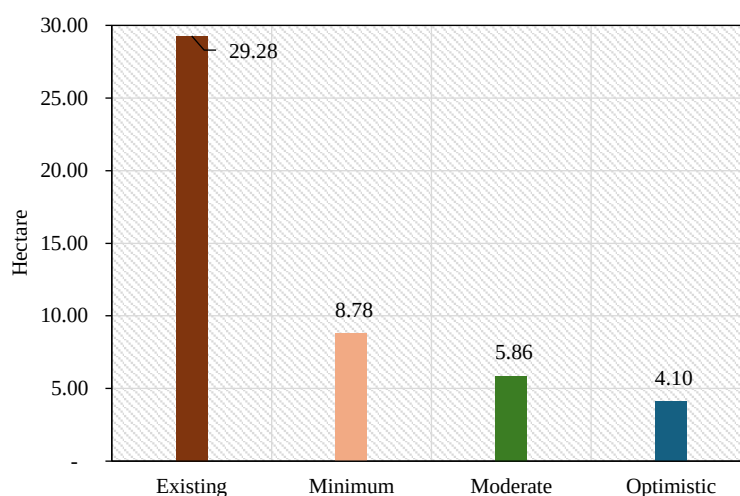


Figure 9. Simulation and projection of cumulative landfill area until 2045 with a reduction scenario

In contrast, implementing higher waste reduction rates considerably reduces the projected landfill area requirements. The Minimum Reduction scenario (21% reduction) lowers the need to 8.78 hectares, while the Moderate Reduction scenario (50% reduction) further decreases land requirements to 5.86 hectares. The most effective outcome is observed in the Optimistic Reduction scenario (65% reduction), which limits the cumulative landfill land requirement to only 4.10 hectares by 2045. These projections emphasize the critical importance of integrating progressive waste reduction strategies into urban waste management policies to ensure sustainable land use, protect environmental quality, and extend the operational lifespan of landfill facilities in Bengkulu City.

3.7 Handling cost, total retribution and saving cost

The simulation results demonstrate distinct financial patterns for waste management in Bengkulu City under four waste reduction scenarios over a 20-year projection. In the Existing Scenario, both handling costs and total retribution steadily increase from 2025 to 2045, with handling costs consistently surpassing revenue from retributions. Although cost savings show gradual growth, they remain insufficient to offset the rising operational expenses. This trend highlights the financial vulnerability of maintaining

the current waste management system without adopting additional reduction measures.

Under the Minimum Reduction Scenario (20% reduction), financial performance improves modestly. Handling costs grow at a slower rate compared to the existing condition, while cost savings increase progressively due to reduced waste volumes requiring treatment and disposal. However, despite this improvement, a noticeable financial gap between handling costs and total retribution persists by 2045, suggesting that limited reduction efforts provide some relief but are inadequate for achieving sustainable financial equilibrium in waste management operations (Figure 10).

The Moderate Reduction Scenario (50%) and Optimistic Reduction Scenario (65%) show considerably better financial outcomes. In the Moderate Scenario, handling costs grow more gradually, while cost savings significantly increase, gradually narrowing the financial gap with retribution revenue. The most favorable outcome appears in the Optimistic Scenario, where waste reduction efforts substantially limit cost increases, and cumulative cost savings almost match the total handling expenses by 2045. This indicates that aggressive and well-integrated waste reduction strategies not only alleviate environmental pressure but also strengthen the city's fiscal capacity to manage waste sustainably in the long term.

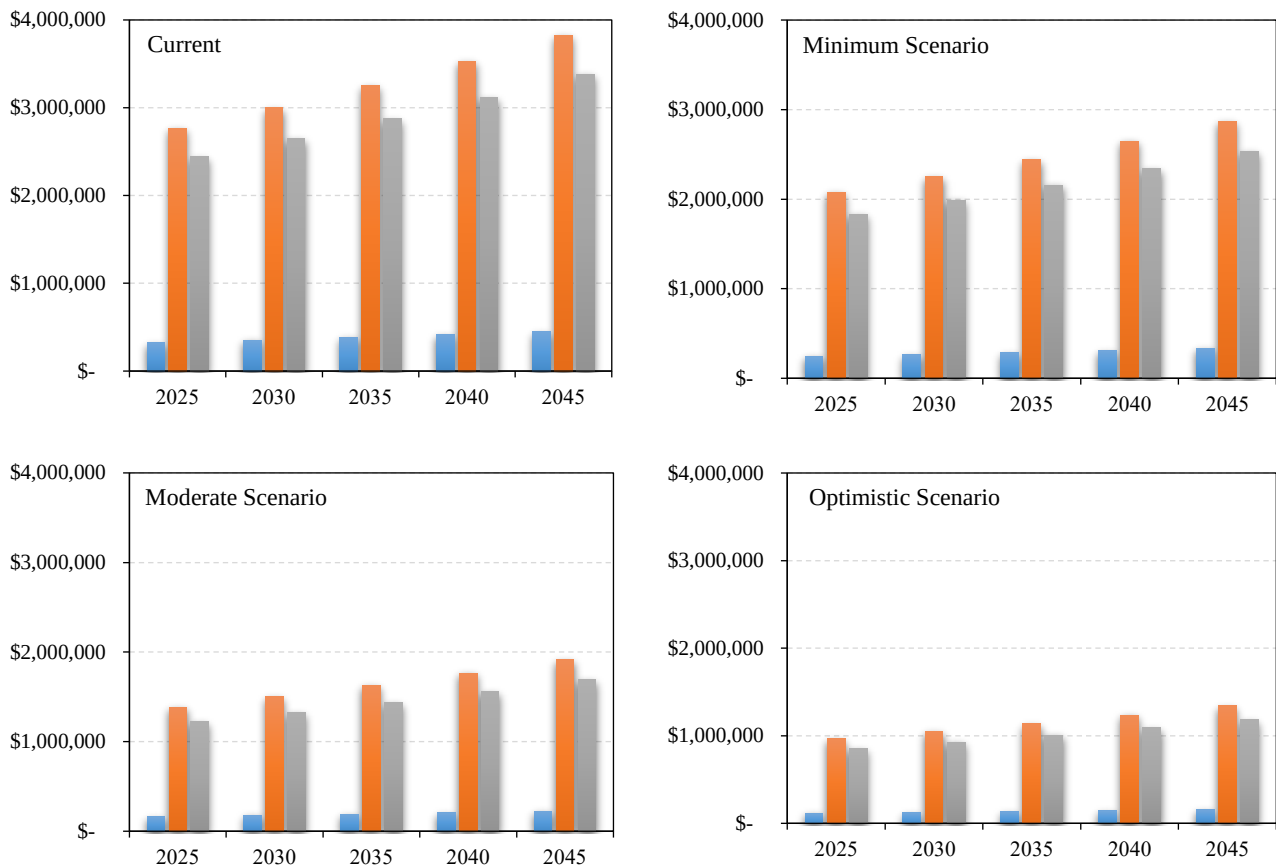


Figure 10. Simulation and projection of handling costs, total retribution and cost savings until 2045 with four reduction scenario

3.8 Scenario model

3.8.1 Without reduction (Existing)

In the absence of a waste reduction scenario, household waste volume will continue to increase, further burdening landfills. As these landfills fill quickly, they lead to soil, water, and air pollution. Methane emissions from decomposing organic waste contribute significantly to global warming, while landfill costs and space limitations will become increasingly problematic.

Therefore, reduction strategies such as reducing, reusing, and recycling are essential for sustainable waste management and budget optimization (Boateng et al., 2023; Del Carmen-Niño et al., 2023; Nepal et al., 2023; Ugwu et al., 2021).

3.8.2 Minimum scenario

The growth of Waste Banks in Bengkulu City since 2022 has shown positive development as part of the government's and community's efforts to enhance the effectiveness and sustainability of waste management. Currently, five active Waste Bank units operate with a primary focus on managing recyclable waste, such as plastic and paper. However, the absence of composting programs within Waste Bank

operations has restricted the overall waste reduction impact. Therefore, there is significant potential to expand waste management initiatives, particularly by integrating composting into the Waste Bank system and Integrated Waste Management Facilities (IWMF). With optimal support from the community, government, and private sector, Bengkulu City has the potential to achieve a waste reduction target of up to 25% (Abubakar et al., 2022). Strategic measures such as developing waste processing infrastructure, educating the public on waste separation, and optimizing recycling and composting systems can enhance the effectiveness of sustainable waste management (Behera and Samal, 2022; Knickmeyer, 2020; Lim et al., 2016).

3.8.3 Moderate scenario

Achieving a 50% waste reduction through programs like "Merdeka Sampah" in Bengkulu City is certainly a significant challenge. However, with the right approach, the chances of success are considerable. The following factors need to be considered: 1) public awareness and participation; 2) development of infrastructure and technology; 3) multi-sector collaboration; 4) regulations and policies;

and 5) community independence and innovation. Achieving a 50% waste reduction through the “Merdeka Sampah” program in Bengkulu City is remains possible, but it requires intensive collaboration between the government, community, and private sector. Public awareness, infrastructure support, enabling policies, and local innovation are key factors that will determine the success of this program remains possible. With the right strategies and effective implementation, the chances of reaching this target are high, but it will require long-term commitment and continuous adaptation to emerging challenges. Recycling capacity can be increased from 39% to 100% by strengthening informal recycling facilities (Kala et al., 2022).

3.8.4 Optimistic scenario

To achieve the 65% waste reduction target in Bengkulu City, an integrated strategy is required, which includes: 1) strengthening waste separation at the source by providing adequate facilities and incentives for residents, 2) developing composting programs at both community and city levels, 3) expanding Waste Banks across all neighborhoods with a specific focus on different waste types and collaboration with the recycling industry, 4) implementing innovative technologies, such as digital applications and waste-to-energy conversion, and 5) enforcing waste separation policies through clear regulations and sanctions.

Waste reduction can be achieved by limiting the use of hard-to-recycle materials, promoting composting, and engaging the private sector. Thus, it is essential to include corporate social responsibility CSR initiatives and strategic partnerships. The government should play a key role by facilitating education and training programs, as well as providing incentives and recognition for successful waste management efforts. Additionally, regular monitoring and evaluation are necessary to assess impact and make policy adjustments. With an integrated strategy that includes source separation, appropriate management technology, supportive policies, and multi-stakeholder collaboration, the target waste reduction target of up to 65% can be achieved. Through strong community involvement, Bengkulu City has the potential to become a model for effective and sustainable waste management.

3.9 Impact of parameters on achieving waste reduction

Effective waste reduction strategies must address critical parameters that enhance the efficiency and sustainability of urban solid waste management systems. First, strengthening the waste sorting system at the source is essential because it improves the effectiveness of downstream processes, such as recycling and composting.

Second, developing community- and municipal-level composting methods can divert large volumes of organic waste from landfills while producing valuable compost. Third, expanding the capacity and outreach of waste banks can incentivize recycling behavior and improve material recovery rates. Fourth, adopting advanced waste management technologies, such as mechanized sorting, anaerobic digestion, and incineration with energy recovery, can increase system-wide efficiency. Additionally, effectively enforcing policies and regulations ensures compliance and promotes accountability among stakeholders. Collaborating with the private sector is also vital for mobilizing investments, innovation, and operational expertise. Lastly, establishing mechanisms for periodic monitoring and evaluation enables data-driven decision-making, continuous improvement, and policy refinement. Together, these parameters form the foundation for a comprehensive, resilient waste reduction framework.

The structured evaluation presented in Table 3 demonstrates a clear progression in the perceived importance of seven key waste management parameters across four waste reduction scenarios: Existing (0%), Minimum (25%), Moderate (50%), and Optimistic (65%). Using a five-point ordinal scale (☆ to ☆☆☆☆☆), each parameter exhibits a steady increase in importance as the reduction targets become more ambitious. Descriptive statistical analysis reveals a strong linear trend, with the average importance score rising from 1.43☆ in the baseline scenario to 5.00☆ in the most ambitious scenario—representing an overall increase of more than 249%. These findings suggest a systemic transition from conventional waste handling practices to more integrated and transformative management approaches.

Table 3. Matrix of the importance level of parameter in each reduction scenario

No	Parameter	Scenario			
		Existing (0%)	Minimum (25%)	Moderate (50%)	Optimist (65%)
1	Strengthen the waste sorting system at the source	☆	☆☆	☆☆☆☆	☆☆☆☆☆
2	Develop composting methods at both community and city scales	☆	☆☆☆	☆☆☆☆☆	☆☆☆☆☆
3	Expand the capacity and reach of the waste bank	☆	☆☆☆	☆☆☆☆	☆☆☆☆☆
4	Implement advanced waste management technologies	☆	☆☆	☆☆☆☆	☆☆☆☆☆
5	Enforce policies and regulations effectively	☆☆	☆☆☆	☆☆☆☆	☆☆☆☆☆
6	Foster collaboration and partnership with the private sector	☆☆	☆☆☆	☆☆☆☆	☆☆☆☆☆
7	Conduct periodic monitoring and evaluation	☆☆	☆☆☆	☆☆☆☆	☆☆☆☆☆
Amount		1.43☆	2.71☆	4.14☆	5.00☆
Description:					
☆	Less important	☆☆☆☆ Very important			
☆☆	Quite Important	☆☆☆☆☆ Very - very important			
☆☆☆	Important				

In the baseline scenario (0%), the waste management system remains predominantly traditional, with most parameters rated as “less important” or “quite important.” Strategies such as composting, waste bank expansion, and the implementation of advanced technologies are not yet considered priorities. However, in the Minimum (25%) scenario, the average score increases significantly to 2.71☆—an 89.5% improvement—indicating an emerging recognition of community-based and decentralized interventions. This upward trajectory continues in the Moderate (50%) scenario, where the average importance score reaches 4.14☆. At this stage, nearly all parameters are rated as “very important,” reflecting a growing institutional commitment to strategies that integrate technological innovation, policy enforcement, and multi-sectoral collaboration.

In the Optimistic (65%) scenario, all parameters achieve the maximum rating of 5.00☆, indicating a consensus on the critical role each component plays in achieving substantial waste reduction. This uniformity underscores the necessity of a comprehensive and synergistic approach, encompassing source-level waste sorting, large-scale composting, expanded waste bank systems, advanced technological adoption, effective regulatory frameworks, private sector engagement, and continuous monitoring and evaluation. The high degree of linear correlation ($R^2 \approx 0.99$) between the level of reduction target and the average importance score further confirms that the prioritization of these parameters intensifies in direct proportion to the system’s performance goals. Accordingly, the realization of ambitious waste

reduction targets necessitates multi-dimensional interventions that extend beyond physical infrastructure and formal regulation, and instead emphasize behavioral change, institutional integration, and stakeholder-driven solutions.

Applying a dynamic system model to waste management in Bengkulu City provides a holistic, strategic approach to responding to the complexity of the waste management system while improving the effectiveness of policies and the efficiency of operations in accordance with the city's capacity and characteristics. Simulations of four waste reduction policy scenarios namely, no intervention, minimum reduction, moderate reduction, and optimistic reduction were conducted by considering important parameters such as population growth rate, waste generation volume, recycling capacity, and community participation.

The simulation results for each scenario provide projections for waste generation, management budget requirements, and estimated landfill area in the short and long term. This information is crucial for decision-makers to select the most rational and sustainable scenario, reducing operational costs and optimizing the use of available resources. Thus, this approach makes the planning process more data-driven and adaptable to environmental and social dynamics. Furthermore, integrating dynamic system models with digital technologies, such as real-time waste volume monitoring, citizen reporting applications, and information management systems, improves accountability and public engagement. Collaboration between stakeholders, including the community, the private sector, and educational institutions, can be

strengthened to create an inclusive, integrated waste management ecosystem. Therefore, Bengkulu City has strong potential to become a pilot medium-sized city for the implementation of smart, participatory, and sustainable environmental governance.

Bengkulu City and the Brazilian case study share similar challenges in waste management, particularly low recycling rates, limited public participation, and inadequate infrastructure. The Brazilian model, which aims to raise dry waste collection from 8.5% to 15% in ten years, highlights the importance of improving sorting efficiency—an equally relevant goal for Bengkulu. However, the financial unsustainability of recycling programs, as shown in Brazil's reliance on subsidies, also reflects conditions in Bengkulu. While Brazil has begun using system dynamics (SD) modeling to influence recycling behavior, Bengkulu is still in the early stages of exploring such tools (Pinha and Sagawa, 2020). Similar issues are evident in Yogyakarta and Depok (Artika and Chaerul, 2020; Habibah et al., 2020), where waste management policies face barriers such as low public awareness, weak institutional coordination, and poor infrastructure. In Yogyakarta, system modeling indicates ineffective implementation due to cultural and structural gaps, while in Depok, future waste projections call for expanded treatment capacity to reduce landfill use. However, this requires significant investment, posing financial challenges for local governments. These cases highlight the urgent need for integrated, participatory, and financially sustainable waste strategies across Indonesian cities, including Bengkulu.

Applying a dynamic systems model to waste management in Bengkulu City offers a comprehensive and strategic framework for addressing the complexity of urban waste systems. This approach aligns policies with the city's unique capacity and characteristics, while also enhancing the effectiveness of interventions and operational efficiency. By simulating four policy scenarios—no intervention, minimum reduction, moderate reduction, and optimistic reduction—the model provides insights into the implications of each strategy, incorporating critical parameters such as population growth, waste generation volume, recycling capacity, and levels of community participation. The results of these simulations yield valuable projections related to future waste generation, budgetary requirements, and the expansion of landfill areas. These outputs are essential for policymakers seeking to identify the most rational and sustainable

options, particularly in balancing operational costs and resource availability. The data-driven nature of the model supports more informed and adaptive planning processes, allowing the city to anticipate environmental and social changes while maintaining effective waste services.

Further value is added when the dynamic model is integrated with emerging digital technologies. Tools such as real-time waste monitoring systems, citizen reporting apps, and centralized information platforms enhance both accountability and public involvement. These technologies facilitate transparent governance and efficient service delivery, while also encouraging citizens to actively participate in managing their waste. In turn, the model enables better responsiveness to public feedback and real-time data, fostering a more agile and effective system. Finally, the adoption of this model serves as a catalyst for multi-stakeholder collaboration involving local communities, the private sector, and academic institutions. Such engagement promotes the development of an inclusive and integrated waste management ecosystem. With these capabilities, Bengkulu City is well-positioned to serve as a model for other medium-sized cities aiming to implement smart, participatory, and sustainable environmental governance. The dynamic systems model not only offers technical improvements but also reinforces the long-term vision of a resilient and future-ready urban management framework.

4. CONCLUSION

This study demonstrates the effectiveness of a system dynamics approach in addressing the complex challenges of municipal solid waste management in Bengkulu City. By simulating four waste reduction scenarios over a 20-year period, the model provides valuable insights into the environmental and financial implications of various intervention levels. The findings reveal that without proactive measures, rapid population growth and increased consumption will severely strain existing landfill capacity and escalate management costs. Conversely, integrated waste reduction strategies—encompassing source separation, composting, waste bank expansion, technological innovation, and policy enforcement—substantially mitigate environmental pressures while optimizing land and financial resources.

The moderate and optimistic reduction scenarios, achieving 50% and 65% waste reduction respectively, offer the most sustainable outcomes by lowering landfill dependency, reducing operational

expenses, and enhancing resource recovery. Furthermore, the incorporation of digital monitoring tools and multi-stakeholder collaboration strengthens waste governance, promotes public participation, and improves service accountability. This study underscores the importance of systemic, data-driven planning to transition towards a circular economy framework. The proposed dynamic model serves as an adaptable decision-support tool for urban policymakers, providing a strategic pathway for medium-sized cities seeking to implement inclusive and sustainable waste management systems.

ACKNOWLEDGEMENTS

The author would like to thank the Department of Environmental Health, Health Polytechnic, Ministry of Health, Bengkulu, Indonesia, for facilitating this research and providing the necessary study permits.

AUTHOR CONTRIBUTIONS

Conceptualization, Formal Analysis, Investigation, Software, Resources and writing, Defi Ermayendri; Methodology, Wahyudi Arianto; Validation, Marulak Simarmata; Writing-Original Draft Preparation; Writing-Review and Editing, Riwardi and Ketut Sukiyono.

DECLARATION OF CONFLICT OF INTEREST

We hereby declare that the manuscript entitled “Dynamic Integrated Model of Sustainable Solid Waste Management in Bengkulu City” is an original scientific work that has never been published before in any form and is not in the process of being reviewed or published in other journals. We ensure that all data, analysis, and interpretation presented in this manuscript are the results of research conducted using valid methods and in accordance with scientific standards. All forms of quotations, references, and contributions from other parties have been given proper credit through appropriate citations. We also declare that there is no form of plagiarism in this manuscript, either directly or indirectly. If in the future there is a violation of publication ethics, I/we are willing to accept the consequences set by the journal. All authors involved in the preparation of this manuscript have made significant contributions, both in research design, data analysis, and preparation of scientific articles. No names are listed as authors without substantial scientific contributions.

We hereby submit the publication rights to the Environment and Natural Resources Journal, in accordance with the provisions applicable in the journal’s publishing policy.

REFERENCES

- Abubakar IR, Maniruzzaman KM, Dano UL, AlShihri FS, AlShammari MS, Ahmed SMS, et al. Environmental sustainability impacts of solid waste management practices in the global south. *International Journal of Environmental Research and Public Health* 2022;19(19):Article No. 12717.
- Artika I, Chaerul M. Dynamic system model for waste management scenario evaluation in Depok City. *Jurnal Wilayah dan Lingkungan* 2020;8(3):261-79 (in Indonesian).
- Banerjee S, Chakraborty S, Banerjee S, Dutta A. Decision making and economical optimization of a city scale solid waste management system: An integrated model simulation on Kolkata, India. *Materials Today: Proceedings* 2023. DOI: 10.1016/j.matpr.2023.07.238.
- Behera S, Samal K. Sustainable approach to manage solid waste through biochar assisted composting. *Energy Nexus* 2022;7:Article No. 100121.
- Blakeslee J, Kothari BH, McBeath B, Sorenson P, Bank L. Network indicators of the social ecology of adolescents in relative and non-relative Foster households. *Children and Youth Services Review* 2017;73:173-81.
- Boateng S, Boakye-Ansah D, Baah A, Aboagye B, Kyeremeh PAG. Solid waste management practices and challenges in rural and urban senior high schools in Ashanti Region, Ghana. *Journal of Environmental and Public Health* 2023; 2023:Article No. 9694467.
- Bornstein MH. *Dynamic Systems Theory*. In: *The SAGE Encyclopedia of Lifespan Human Development*. SAGE Publications, Inc.; 2018.
- Bruno M, Abis M, Kuchta K, Simon FG, Grönholm R, Hoppe M, et al. Material flow, economic and environmental assessment of municipal solid waste incineration bottom ash recycling potential in Europe. *Journal of Cleaner Production* 2021;317:Article No. 128511.
- Del Carmen-Niño V, Herrera-Navarrete R, Juárez-López AL, Sampedro-Rosas ML, Reyes-Umaña M. Municipal solid waste collection: Challenges, strategies and perspectives in the optimization of a municipal route in a Southern Mexican Town. *Sustainability* 2023;15(2):Article No. 1083.
- Devi RU, Gangaraju G, Kumar KS, Balakrishna K. A sustainable approach for an integrated municipal solid waste management. In: *Recent Trends in Solid Waste Management*. Elsevier; 2023. p. 55-74.
- do Carmo Precci Lopes A, Ebner C, Gerke F, Wehner M, Robra S, Hupfauf S, et al. Residual municipal solid waste as co-substrate at wastewater treatment plants: An assessment of methane yield, dewatering potential and microbial diversity. *Science of the Total Environment* 2022;804:Article No. 149936.
- Dyson B, Chang N Bin. Forecasting municipal solid waste generation in a fast-growing urban region with system dynamics modeling. *Waste Management* 2005;25(7):669-79.
- Environmental Services of Bengkulu City. *Basic Information on the Air Sebakul Landfill, Bengkulu City*. Bengkulu City Government; 2022.

- Ferronato N, Torretta V. Waste mismanagement in developing countries: A review of global issues. *International Journal of Environmental Research and Public Health* 2019;16(6):Article No. 1060.
- Forrester JW. *Industrial Dynamics*. MIT Press; 1961.
- Fragkoulis D, Roux G, Dahhou B. Detection, isolation and identification of multiple actuator and sensor faults in nonlinear dynamic systems: Application to a waste water treatment process. *Applied Mathematical Modelling* 2011;35(1):522-43.
- Free CM, Bellquist LF, Forney KA, Humberstone J, Kauer K, Lee Q, et al. Static management presents a simple solution to a dynamic fishery and conservation challenge. *Biological Conservation* 2023;285:Article No. 110249.
- Friederich J, Lugaresi G, Lazarova-Molnar S, Matta A. Process mining for dynamic modeling of smart manufacturing systems: Data requirements. *Procedia CIRP* 2022;107:546-51.
- Govani J, Singh E, Kumar A, Zacharia M, Rena, Kumar S. New generation technologies for solid waste management. In: *Current Developments in Biotechnology and Bioengineering*. Elsevier; 2021. p. 77-106.
- Guerrero LA, Maas G, Hogland W. Solid waste management challenges for cities in developing countries. *Waste Management* 2013;33(1):220-32.
- Guo D, Zhang S, Hou H, Zhang Y, Xu H. Synergistic evaluation methodology for pollution and carbon reduction in the field of solid waste resource utilization. *Environmental Impact Assessment Review* 2024;108:Article No. 107604.
- Habibah E, Novianti F, Saputra H. Analysis of Factors Influencing the Implementation of Waste Management Policies in Yogyakarta Using Dynamic System Modeling. *Jurnal Analisa Sociology* 2020;9:124-36 (in Indonesia).
- Hla SS, Roberts D. Characterisation of chemical composition and energy content of green waste and municipal solid waste from Greater Brisbane, Australia. *Waste Management* 2015;41:12-9.
- Ibarra Vega D, Bautista-Rodriguez S. The impact of circular economy strategies on municipal waste management: A system dynamics approach. *Cleaner Engineering and Technology* 2024;21:Article No. 100761.
- Kala K, Bolia NB, Sushil. Analysis of informal waste management using system dynamic modelling. *Heliyon* 2022;8(8):e09993.
- Knickmeyer D. Social factors influencing household waste separation: A literature review on good practices to improve the recycling performance of urban areas. *Journal of Cleaner Production* 2020;245:Article No. 118605.
- Kumar A, Samadder SR. A review on technological options of waste to energy for effective management of municipal solid waste. *Waste Management* 2017;69:407-22.
- Lam CM, Yu IKM, Medel F, Tsang DCW, Hsu SC, Poon CS. Life-cycle cost-benefit analysis on sustainable food waste management: The case of Hong Kong International Airport. *Journal of Cleaner Production* 2018;187:751-62.
- Lee U, Han J, Wang M. Evaluation of landfill gas emissions from municipal solid waste landfills for the life-cycle analysis of waste-to-energy pathways. *Journal of Cleaner Production* 2017;166:335-42.
- Li G, Wang W-Jing, You X-Yi. Social-economic assessment of integrated waste pickers in municipal solid waste management system: A case of Tianjin in China. *Journal of Cleaner Production* 2024;434:Article No. 140302.
- Lim SL, Lee LH, Wu TY. Sustainability of using composting and vermicomposting technologies for organic solid waste biotransformation: Recent overview, greenhouse gases emissions and economic analysis. *Journal of Cleaner Production* 2016;111:262-78.
- Mai L, Bao LJ, Wong CS, Zeng EY. Microplastics in the terrestrial environment. In: *Microplastic Contamination in Aquatic Environments*. Elsevier; 2018. p. 365-78.
- Meena MD, Dotaniya ML, Meena BL, Rai PK, Antil RS, Meena HS, et al. Municipal solid waste: Opportunities, challenges and management policies in India: A review. *Waste Management Bulletin* 2023;1(1):4-18.
- Moya D, Aldás C, López G, Kaparaju P. Municipal solid waste as a valuable renewable energy resource: A worldwide opportunity of energy recovery by using waste-to-energy technologies. *Energy Procedia* 2017;134:286-95.
- Nepal M, Karki Nepal A, Khadayat MS, Rai RK, Shyamsundar P, Somanathan E. Low-cost strategies to improve municipal solid waste management in developing countries: Experimental evidence from Nepal. *Environmental and Resource Economics* 2023;84(3):729-52.
- Pfister F, Bader HP, Scheidegger R, Baccini P. Dynamic modelling of resource management for farming systems. *Agricultural Systems* 2005;86(1):1-28.
- Pinha ACH, Sagawa JK. A system dynamics modelling approach for municipal solid waste management and financial analysis. *Journal of Cleaner Production* 2020;269:Article No. 122350.
- Radosavljevic S, Banitz T, Grimm V, Johansson LG, Lindkvist E, Schlüter M, et al. Dynamical systems modeling for structural understanding of social-ecological systems: A primer. *Ecological Complexity* 2023;56:Article No. 101052.
- Rahman MN, Shozib SH, Akter MY, Islam ARMT, Islam MS, Sohel MS, et al. Microplastic as an invisible threat to the coral reefs: Sources, toxicity mechanisms, policy intervention, and the way forward. *Journal of Hazardous Materials* 2023;454:Article No. 131522.
- Smith LB, Thelen E. Development as a dynamic system. *Trends in Cognitive Sciences* 2003;7(8):343-8.
- Sołowski G, Konkol I, Cenian A. Production of hydrogen and methane from lignocellulose waste by fermentation: A review of chemical pretreatment for enhancing the efficiency of the digestion process. *Journal of Cleaner Production* 2020;267:Article No. 121721.
- Sondh S, Upadhyay DS, Patel S, Patel RN. Strategic approach towards sustainability by promoting circular economy-based municipal solid waste management system: A review. *Sustainable Chemistry and Pharmacy* 2024;37:Article No. 101337.
- Sterman JD. Systems dynamics modeling: Tools for learning in a complex world. *IEEE Engineering Management Review* 2002;30(1):8-25.
- Thatcher A, Biyela P, Field TL, Hildebrandt D, Kidd M, Nadan S, et al. Contextualising urban sanitation solutions through complex systems thinking: A case study of the South African sanitation system. *Journal of Cleaner Production* 2024;451:Article No. 142084.
- Ugwu CO, Ozoegwu CG, Ozor PA, Agwu N, Mbohwa C. Waste reduction and utilization strategies to improve municipal solid waste management on Nigerian Campuses. *Fuel Communications* 2021;9:Article No. 100025.
- Wilson DC, Velis C, Cheeseman C. Role of informal sector recycling in waste management in developing countries. *Habitat International* 2006;30(4):797-808.

Zhang X, Feng D, Wang J, Sui A. Integrating renewable energy systems: Assessing financial innovation, renewable energy generation intensity, energy transition and environmental regulation with renewable energy sources. *Energy Strategy Reviews* 2024;56:Article No. 101567.

Zulkipli F, Nopiah ZM, Basri NEA, Kie CJ, Zulkepli J, Khalid KI. Integrated dynamical model for Malaysian solid waste management using system dynamics. *International Journal of Engineering and Technology* 2018;7(3):131-5.