IJIE

INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

Vol. 18 No. 3 (2026) 227-242
https://publisher.uthm.edu.my/ojs/index.php/ijie

Sustainable Urban Waste Management Strategies Based on System Dynamics in Manado City, North Sulawesi, Indonesia

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DOI: https://doi.org/10.30880/ijie.2026.18.03.015

Article Info

Received: 20 June 2025
Accepted: 18 November 2025
Available online: 30 April 2026

Keywords

Urban waste management, environmental risk index, landfill, sustainable development

Abstract

Urban waste management poses significant challenges amid increasing urbanization and limited infrastructure capacity. This study investigates sustainable waste management strategies at the Sumompo Landfill in Manado using the Environmental Risk Index (ERI) and System Dynamics (SD) modeling approaches. The ERI results yielded a total score of 605.9, categorizing the site as high risk, with strong recommendations for landfill closure and environmental remediation. A community survey revealed that 100% of respondents supported the closure, and 45% reported health issues over the past three years attributed to the landfill. SD simulations were developed under three scenarios: pessimistic, moderate, and optimistic. In the optimistic scenario, household waste sorting through waste banks and composting increased to 50%, and daily waste collection was optimized to twice per day. Under this scenario, the total waste volume entering the landfill in 2030 is projected at 986.198 m^3, significantly lower than the 1.775.157 m^3 projected under the Business As Usual (BAU). For comparison, the 2025 baseline volume is 292.841 m^3. The study proposes six integrated strategies, including source level waste reduction, community engagement, institutional reform, and alternative financing. The findings highlight the critical importance of systemic and participatory approaches in achieving resilient and sustainable urban waste management.

1. Introduction

Urban waste management is one of the major challenges faced by big cities around the world, including in Indonesia. As the population grows and urbanization increases, urban waste production continues to rise significantly. Global waste production is projected to increase by 70% by 2050 [1]. Meanwhile, the primary challenges in waste management for developing countries include inadequate infrastructure, inefficient systems, and low community engagement [2]. This condition contributes to environmental degradation through soil contamination, water pollution, and airborne emissions, while posing public health hazards to adjacent communities near landfill.

In many cities, landfills remain the predominant waste management method, yet inadequate landfill operations consistently generate multifaceted environmental impacts, including greenhouse gas emissions (particularly methane), leachate induced groundwater contamination, and public health risks for adjacent communities. Poor urban waste management in low income countries often characterized by indiscriminate waste disposal exacerbates public health crises through the proliferation of disease vectors. It also degrades urban environments through air and water pollution, aesthetic deterioration, and increased flood risks caused by drainage obstruction and accumulated debris that weaken municipal resilience [3]–[6]. Urban residents living near landfill sites face particularly high risks of exposure to associated health consequences, including malaria, chest pain, diarrhea, cholera, mental health effects, and increased mortality rates. Marginalized social groups bear the greatest burden, as waste disposal facilities are frequently located disproportionately closer to their neighborhoods, exacerbating their vulnerability to these adverse health outcomes [3], [7]–[10].

This underscores the necessity for a 'zero waste city' approach, where the integration of recycling technologies, composting systems, and community education could potentially reduce waste by up to 80% when effectively implemented. Such an integrated waste management strategy not only addresses environmental concerns but also demonstrates the feasibility of sustainable urban waste solutions through technological and behavioral interventions [11], an integrated waste management system employing the waste hierarchy approach (reduce, reuse, recycle) can enhance management efficiency by up to 30%. This strategy not only optimizes resource recovery but also demonstrates the effectiveness of implementing circular economy principles in urban waste systems, particularly when supported by proper infrastructure and community participation [1], this implies that strategic, sustainable waste management systems must be implemented to effectively minimize ecological hazards and guarantee operational sustainability, necessitating integrated solutions that address the entire waste value chain from generation to final disposal while considering local environmental carrying capacities.

In this context, system dynamics approaches have proven effective for analyzing the complex interactions among variables in urban waste management systems, particularly for evaluating waste management policies in European countries. Concurrently, advanced waste processing technologies play a pivotal role in mitigating environmental impacts, offering complementary solutions when integrated with policy analysis frameworks. This dual approach enables comprehensive assessment of both systemic relationships and technological applications in sustainable waste management [12]. This approach enables policy scenario simulations including waste reduction, recycling initiatives, and landfill optimization thereby facilitating data driven decision making in strategy development. By employing system dynamics modeling, causal relationships among social, economic, and environmental factors in waste management can be systematically mapped, yielding more integrated and sustainable solutions. The methodology provides a robust framework for analyzing feedback loops and time delayed effects that are characteristic of complex urban waste systems [13].

The objective of this research is to examine sustainable urban waste management strategies that demonstrate greater effectiveness in reducing adverse environmental consequences.

2. Literature Review

2.1 System Dynamics Approaches in Urban Waste Management Studies

System Dynamics (SD) serves as a computational modeling framework for simulating the nonlinear behavior of complex systems, emphasizing feedback mechanisms between constituent elements. When applied to municipal solid waste management, it facilitates the evaluation of dynamic variables including demographic expansion, waste accumulation rates, infrastructure limitations, and ecological consequences to support policy optimization. Dyson & Chang [14] system dynamics modeling enables the projection of waste generation trends in fast growing urban zones, providing a computational basis for optimizing waste management strategies.

Within a system dynamic based conceptual framework for urban waste management, critical steps include delineating core system elements, analysing their causal linkages, and mapping reinforcing/balancing feedback loops to simulate system behavior. Kollikkathara *et al.* [15] developed a system dynamics model to evaluate waste generation, landfill capacity, and cost related issues, providing support for strategic decision making in sustainable waste management. The analytical approach involves applying system dynamics modeling to simulate and evaluate various waste management scenarios while assessing their environmental impacts [16]. Giannis *et al.* [17] applied system dynamics modeling to evaluate recycling scenarios in Singapore, providing insights into optimal strategies for reducing the environmental impact of waste management.

Previous studies have predominantly focused on technical factors such as waste generation projections, processing capacity, and environmental impacts. However, social dynamics including consumption patterns, recycling awareness, and behavioral incentives in waste management have often been neglected. This study integrates socio behavioral factors into a system dynamics model to examine their influence on waste management strategy effectiveness. Existing research has tended to prioritize short term risk mitigation, such as landfill capacity reduction or plastic waste management, while paying insufficient attention to long term risks like ecosystem degradation, groundwater contamination, and landfill greenhouse gas emissions. Our research develops a model that projects the long term environmental impacts of various waste management scenarios.

Most SD models in waste management are either generic or applied to major cities in developed countries. There remains a paucity of research in developing regions, particularly studies incorporating local contexts such as distinct regulations, cultural factors, and infrastructure. This study develops a context specific model accounting for local factors including policy compliance rates, waste management infrastructure conditions, and available technological capacity.

Previous research has frequently examined the waste management sector in isolation, overlooking its interconnections with other sectors like energy, economy, and public health despite these linkages being crucial for sustainability. This study adopts an interdisciplinary approach by modeling the relationships between waste management, renewable energy, and environmental health sectors.

3. Material and Methodology

This study employs a quantitative research method incorporating environmental quality evaluation through the Environmental Risk Index assessment, also known as the Integrated Risk Based Approach (IRBA). Furthermore, policy scenarios and sustainability strategies are analyzed using SD modeling.

3.1 Study Area

The location of the study is in coordinates 1°31'15.08"N and 124°51'51.30"E, precisely focus in Sumompo Landfill. The location map is presented in Fig. 1.

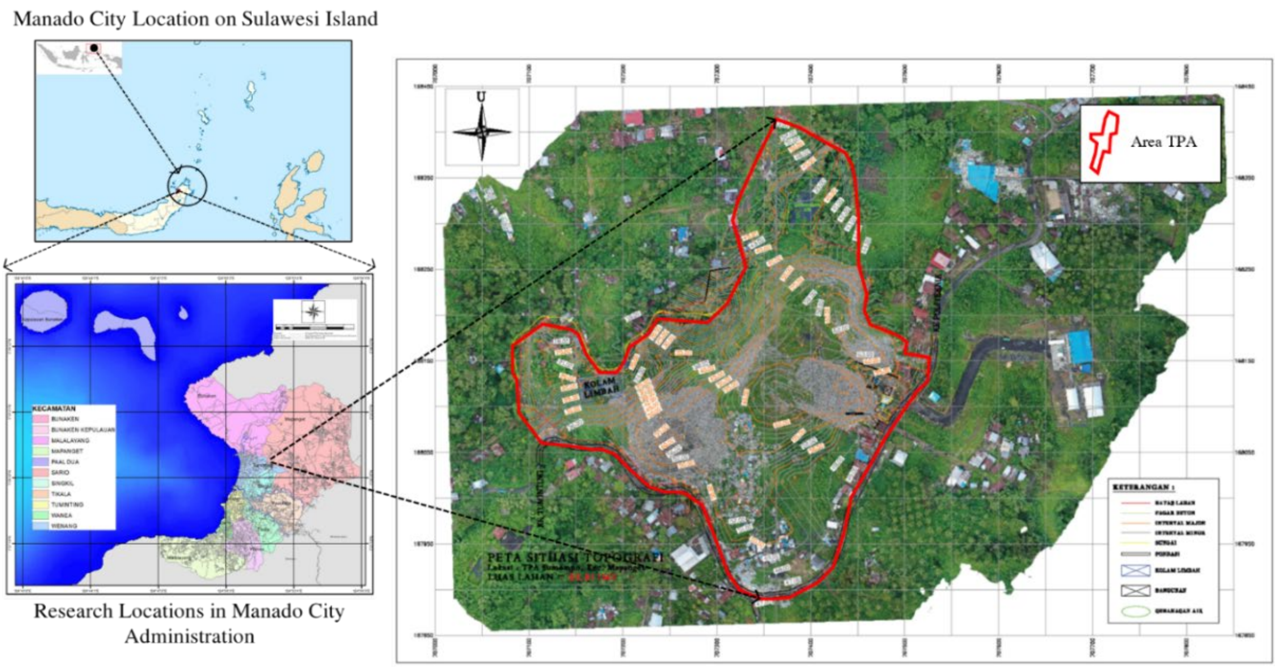

Fig. 1 *Location of the study area*

3.2 Method of Collecting Data

3.2.1 Survey, Observation, and Measurement

This study utilized surveys, field observations, and measurements to collect the data presented in Table 1. The instruments employed included Manado city maps, base maps of the landfill site, field notes, documentation equipment, and a Phantom 4 Pro drone.

Table 1 *Environmental Risk Index (ERI) assessment parameters*

No	Parameters	Data Source
I	Location Criteria	
1	Distance to the nearest water source	Field observation
2	Waste fill depth (m)	Field measurement/data from management/reports
3	Landfill area (Ha)	Field measurement/data from management/reports
4	Groundwater depth (m)	Field measurement/observation
5	Soil permeability (1 x 10^{-6} cm/second)	Permeability testing
6	Groundwater quality	Laboratory testing of groundwater quality
7	Distance to habitat (wetland/conservation forest) (km)	Measurement/map/data from management
8	Distance to the nearest airport (km)	Measurement/map/data from management
9	Distance to surface water (m)	Measurement
10	Type of base soil layer (% clay)	Laboratory testing of landfill base soil quality
11	Site lifespan for future use (years)	Landfill capacity calculation/data from management
12	Waste type (municipal/residential waste)	Waste composition sampling/data from management
13	Total waste disposed (tons)	Calculation/weighing/data from management
14	Daily waste disposal (tons/day)	Calculation/weighing/data from management
15	Distance to the nearest village in the dominant wind direction (m)	Field measurement
16	Flood return period (years)	Climatological data
17	Annual rainfall (cm/year)	Climatological data
18	Distance to nearest city (km)	Measurement/mapping data
19	Community acceptance	Survey/interview data
20	Ambient air quality - CH_4 (%)	Air quality measurements
II	Landfill waste characteristics	Data Source
21	B3 waste content	Hazardous waste (B3) sampling
22	Biodegradable waste fraction (%)	Waste composition sampling
23	Waste filling period (years) (or "Landfill operational lifespan")	Landfill operational data
24	Landfill waste moisture content (%)	Laboratory test results
III	Leachate characteristics	Data Source
25	Leachate BOD (mg/L) (Biochemical Oxygen Demand)	Laboratory test results
26	Leachate COD (mg/L) (Chemical Oxygen Demand)	Laboratory test results
27	Leachate TDS (mg/L) (Total Dissolved Solids)	Laboratory test results

Source: Kurian *et al.* [18]

3.2.2 Questionnaire Distribution and Sampling

A closed ended questionnaire was distributed to 110 respondents using simple random sampling technique within a 50 to 500 meter radius from the landfill site.

3.3 Data Analysis Method

The questionnaire results were analyzed using qualitative descriptive methods based on compiled response data. Before deciding whether to rehabilitate the landfill or implement permanent closure, an environmental quality evaluation must be conducted through either an Environmental Risk Index assessment or IRBA. IRBA a standardized decision making method for open dump closure/rehabilitation assesses environmental risks and is specifically applicable to Indonesian contexts [19]. The IRBA assessment examines three key aspects: technical factors, environmental impacts, and social considerations particularly effects on local communities. The IRBA analysis parameters are categorized into three groups: (1) site criteria (20 parameters), (2) waste characteristics (4 parameters), and (3) leachate characteristics (3 parameters). Each parameter is assigned a weighting factor and sensitivity index relevant to the landfill's specific conditions. The risk index values according to Kurian *et al.* [18] can be seen in Table 2.

Table 2 *Environmental risk index values*

No	Risk Index values	Hazard Evaluation	Recommended Actions
1	750 to 1000	Very high	Permanently cease open dump operations, prohibit future waste disposal use, and implement corrective measures to mitigate impacts
2	600 to 749	Tall	Cease operations of the open dump site and prohibit its future use for waste disposal, with corrective measures for impact mitigation implemented as optional actions
3	450 to 599	Currently	Immediately rehabilitate into a sanitary landfill
4	300 to 449	Low	Rehabilitate into a sanitary landfill in phased stages
5	<300	Very low	Potential for future designation as a controlled landfill

Source: Kurian *et al.* [18]

The method for analyzing policy scenarios and sustainability strategies was developed using a SD approach. SD is an approach to understanding the behavior of complex systems over time. This methodology incorporates feedback loops and time delays to simulate system behavior, enabling analysis of dynamic relationships and prediction of system performance. In SD, a system is represented as a set of interconnected elements that evolve over time through inflows and outflows [20]. A key feature of SD is the use of simulation models to represent complex system behavior. These models enable the exploration of various scenarios and testing of different policies and interventions to understand their potential impacts on the system [21].

This analysis begins by defining the system's objectives. Subsequently, the system requirements necessary to achieve these objectives are identified, and the problem is formulated based on the Business as Usual (BAU) conditions. The issues identified within the system act as barriers to its effectiveness [22]. The next step involves delineating the system by creating input and output diagrams. To facilitate an understanding of the relationships between variables both inputs and outputs a causal loop diagram is employed. This diagram also serves to illustrate the boundaries of the system under study [23]. The technical analysis phase involves constructing a Stock Flow Diagram (SFD) to conduct simulations. Data grouping and inputs are organized within this model structure, which is based on different scenarios. This structured approach enables the generation of comprehensive systemic policy analysis [13], [24], [25].

The SD model is used to simulate the relationships between key variables, including the increased utilization of waste banks for household waste sorting, the increased adoption of composting for household waste sorting, the improved service coverage of waste carts (bentor), the enhanced service coverage of waste trucks, and the optimization of daily waste transport routes derived from Focus Group Discussions (FGD) through a Causal Loop Diagram (CLD). The resulting urban waste management strategies are formulated into three distinct scenarios: (1) BAU or Pessimistic Scenario, which reflects current practices without additional interventions; (2) Moderate Scenario, which assumes a certain level of improvement in key parameters; and (3) Optimistic Scenario, which assumes optimal enhancement of the relevant key parameters.

The SD model simulates the relationships between key variables including increased utilization of waste banks and composting for household waste sorting, improved service coverage of waste carts (garbage motor vehicle) and trucks, and optimized daily waste transport rotations as identified through FGD and modeled via a CLD. Based on this analysis, urban waste management strategies were developed into three scenarios: (1) the BAU or pessimistic scenario, reflecting current practices without intervention; (2) the moderate scenario, incorporating partial improvements in key parameters; and (3) the optimistic scenario, assuming optimal enhancements in critical waste management factors.

4. Result

4.1 Urban Community Perceptions of Waste Management and Landfill

The survey results in Fig. 2, revealed several key findings about urban waste management infrastructure and household practices: The majority of households (70%) have bore wells, with 93% reporting their water is drinkable compared to 86% for dug wells, demonstrating bore wells' superior contamination risk mitigation. Regarding waste management, only 65% of respondents have waste bins at home and a mere 10% practice waste segregation before disposal, reflecting either low public awareness or insufficient infrastructure for proper household waste management.

The survey findings regarding temporary Waste Storage Facilities (WSF) and collection services revealed that only 10% of locations had WSF available, while merely 20% of respondents reported having waste collection officers in their area. These findings clearly demonstrate the inadequate waste management infrastructure and poor service delivery in the region. The study revealed significant environmental impacts from the landfill on residents within a 0 - 100 m radius, with all respondents (100%) reporting foul odors from the landfill clear evidence of suboptimal waste management at the site. These conditions directly affected community health, as 45% of respondents or their family members reported illnesses within the last three years, with half attributing their health issues to the landfill's persistent foul smells. These findings strongly suggest a potential correlation between inadequate waste management practices and public health risks in surrounding communities.

The survey revealed particularly interesting findings regarding environmental awareness and initiatives, specifically concerning organic waste and biogas knowledge: 55% of respondents demonstrated understanding of organic waste and biogas concepts, while a higher proportion (75%) expressed willingness to adopt biogas systems in their households. These results indicate significant potential for enhancing waste management practices through targeted education programs and incentive based initiatives.

Finally, the questionnaire results regarding the planned closure of the landfill indicate that all respondents (100%) agree that the landfill should be closed. This demonstrates an extremely high level of dissatisfaction with the current operation of the landfill.

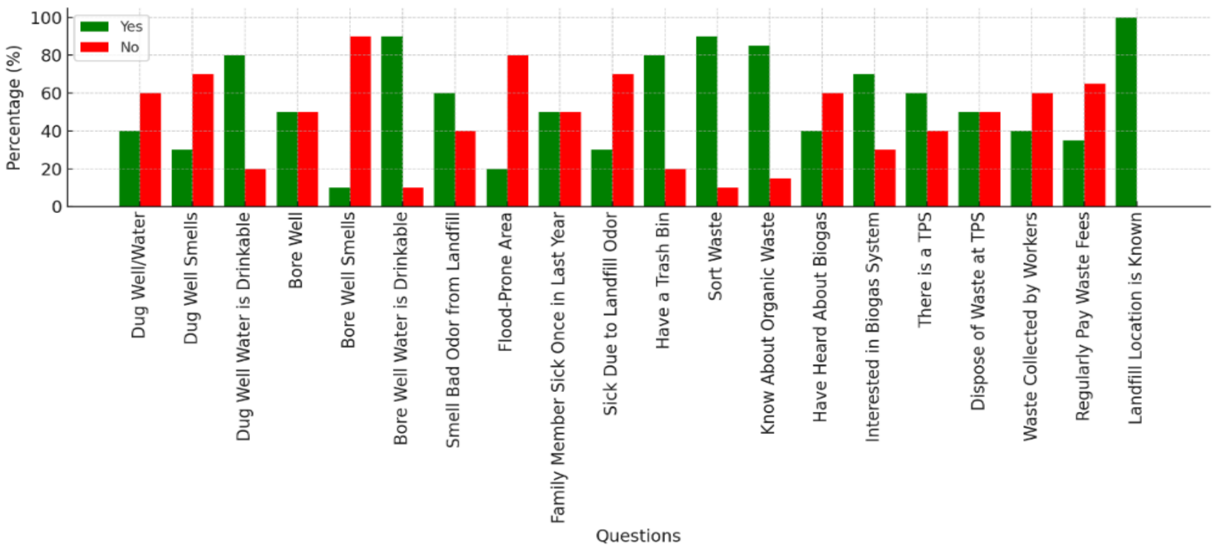

Fig. 2 *Questionnaire results from residents*

4.2 Environmental Risk Index Assessment

Based on the quantitative analysis of the IRBA assessment for the landfill site location, the evaluation of location criteria parameters reveals the following: (1) the most significant parameter is the distance to the nearest water source, scoring 69, indicating a primary concern over potential water source contamination; and (2) other critical parameters include soil permeability (40.5), groundwater quality (37.5), and landfill fill depth (38.4). These values demonstrate the site's impact on soil and water quality.

Subsequently, in the landfill waste characteristics parameters, the analysis results show: (1) the presence of hazardous and toxic materials (B3) in the waste carries the highest weight, with a quantitative value of 17.75, indicating the need for careful attention to toxic waste management; and (2) other parameters such as landfill fill age (43.5) and waste moisture content (19.5) demonstrate the potential for long term waste management. Similarly, for the leachate characteristics parameters, the analysis results indicate: (1) the leachate BOD parameter recorded a value of 27, serving as a key indicator of organic pollution load in groundwater and surface water; and (2) the leachate COD showed a value of 14.25, while the leachate TDS measured 6.5. These parameters demonstrate the potential level of chemical contamination that may occur.

The total score of 605.9 reflects the complexity and challenges involved in managing this landfill. High scoring parameters such as distance to water sources, soil permeability, and groundwater quality indicate that this site requires robust environmental mitigation strategies, particularly to prevent water and soil contamination. Furthermore, according to the Environmental Risk Index in Table 3, when the score exceeds 600, the recommended actions include: ceasing open waste dumping operations, discontinuing future use of the site for waste disposal, and implementing remedial measures to mitigate environmental impacts.

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Overall, this landfill site demonstrates a significantly high environmental risk potential, particularly concerning wastewater management and hazardous materials. Mitigation measures through more effective leachate treatment systems and strict management of hazardous substances (B3) must be prioritized to reduce negative environmental impacts. Should these impacts escalate, landfill closure would become the most viable solution.

Table 3 *IRBA assessment*

No	Parameters	Weight	Measurement Results	Sensitivity Index	Value
I	Location Criteria				
1	Distance to nearest water source (m)	69	50 to 100	1	69
2	Waste fill depth (m)	64	15	0.6	38.4
3	Landfill area (hectares)	61	13.6 Ha	0.6	36.6
4	Groundwater depth (m)	54	5 to 10	0.6	32.4
5	Soil permeability (1×10^{-6} cm/sec)	54	34.93	0.75	40.5
6	Groundwater quality	50	Not drinkable	0.75	37.5
7	Distance to protected habitats (wetlands/conservation forests) (km)	46	6	0.5	23
8	Distance to nearest airport (km)	46	8	0.6	27.6
9	Distance to surface water bodies (m)	41	50 to 100	0.75	30.75
10	Base soil layer composition (% clay content)	41	30 to 50	0.25	10.25
11	Projected site lifespan (years)	36	<5	0.25	9
12	Waste type (municipal/residential)	36	>50%	0.75	27
13	Total waste disposal capacity (metric tons)	30	292,841	0.5	15
14	Daily waste disposal rate (metric tons/day)	24	400	0.4	9.6
15	Distance to nearest village in dominant wind direction (m)	21	246	1	21
16	Flood recurrence interval (years)	16	3 to 5	0.75	12
17	Annual precipitation (cm/year)	11	103 - 448	0.75	8.25
18	Distance to nearest urban center (km)	7	3.48	0.75	5.25
19	Community acceptance level	7	Closing with Remediation	1	7
20	Ambient air methane concentration (CH_4 %)	3	<0.01	0.25	0.75
II	Characteristics of landfill waste				
21	B3 content in waste	71	B3 content 6.98%	0.25	17.75
22	Biodegradable waste fraction (%)	66	21.40%	0.25	16.5
23	Waste filling age (years)	58	3	0.75	43.5
24	Waste moisture in landfill (%)	26	59 to 88%	0.75	19.5
III	Leachate characteristics				
25	Leachate BOD (mg/L)	36	1715	0.75	27
26	Leachate COD (mg/L)	19	2700	0.75	14.25
27	Leachate TDS (mg/L)	13	3053	0.5	6.5
				TOTAL	605.9

Source: Author's analysis

4.3 Urban Waste Modelling and Environmental Risk Mitigation

The initial step involved constructing a CLD to illustrate the cause and effect relationships among parameters obtained from the FGD, as presented in Fig. 3. Subsequently, the SFD model scenario was developed and simulated using controlled inputs and interventions on five leverage factors (see Fig. 4). During this phase, several scenario variations were applied to the leverage points to identify the optimal urban waste management strategy. Three distinct scenarios were formulated: 1) a BAU or pessimistic scenario, 2) a moderate scenario, and 3) an optimistic scenario.

Prior to simulating the SFD model, model validation must be conducted. The validation process employs two testing methods according to Barlas [26]: Absolute Mean Error (AME) with an acceptable threshold of <5% and Absolute Variation Error (AVE) with an acceptable threshold of <30%. The results of which are presented in Table 4, which the primary data used for model validation consists of historical population data from Manado City, shows an AME of 1.03% and an AVE of 2.03%

Table 4 *SFD model data validation*

No	Year	Population History	Population Simulation	AME (%)	AVE (%)
1	2015	423.257	425.634	0.56%	1.13%
2	2016	425.634	425.634	0.00%	0.00%
3	2017	427.906	427.166	0.17%	0.35%
4	2018	430.133	427.807	0.54%	1.08%
5	2019	431.880	429.475	0.56%	1.11%
6	2020	433.635	429.690	0.91%	1.81%
7	2021	451.916	431.065	4.61%	9.01%
8	2022	453.182	449.126	0.90%	1.78%
			Average	1.03%	2.03%

Source: Author's analysis

4.4 Model Scenarios

Before the model simulation is carried out, the variables affecting system performance are first described and outlined in a CLD developed using the Vensim 9.0 program, as shown in Fig. 3.

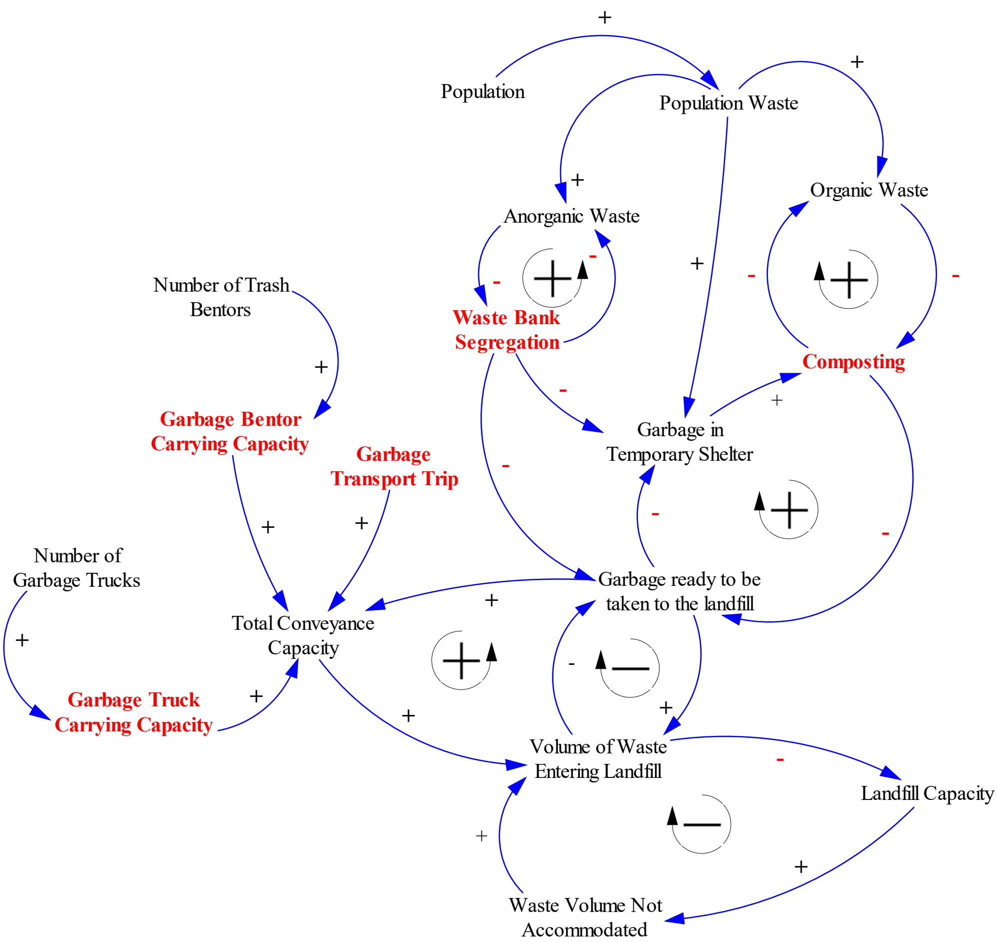

Fig. 3 *CLD urban waste management sustainability*

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Fig. 3 CLD illustrates the causal relationships within an urban solid waste management system, where an increase in population leads to a higher garbage generation rate and greater garbage generated, subsequently increasing both garbage collected and garbage under collection capacity. As the volume of uncollected waste grows, the system responds by enhancing garbage collection capacity and promoting alternative strategies such as composting and trash bank segregation to reduce unmanaged waste. Composting and waste segregation help decrease the collection burden, forming two main feedback loops: a balancing loop that maintains equilibrium between waste generation and collection, and a reinforcing loop that strengthens waste reduction through community participation.

The SFD model scenario as shown in Fig. 4, is simulated from controlled inputs and interventions on five leverage point factors. The scenarios compiled are: 1) BAU, 2) moderate scenarios, and 3) optimistic scenarios.

The SD simulation reveals that under the BAU scenario, the population increases annually from 451.916 in 2024 to 463.147 by the end of 2030. Correspondingly, the daily waste volume entering the landfill rises from 292.841,57 m^3 in 2024 to 300.119,72 m^3 in 2030, demonstrating a direct correlation between population growth and waste generation.

Subsequently, the SFD model was simulated by increasing percentages across five key parameters: (1) enhanced utilization of waste banks for household waste sorting, (2) increased adoption of composting for household waste separation, (3) improved service coverage of waste tricycles (bentor), (4) expanded service coverage of waste trucks, and (5) optimization of daily transportation rounds, as presented in Table 5.

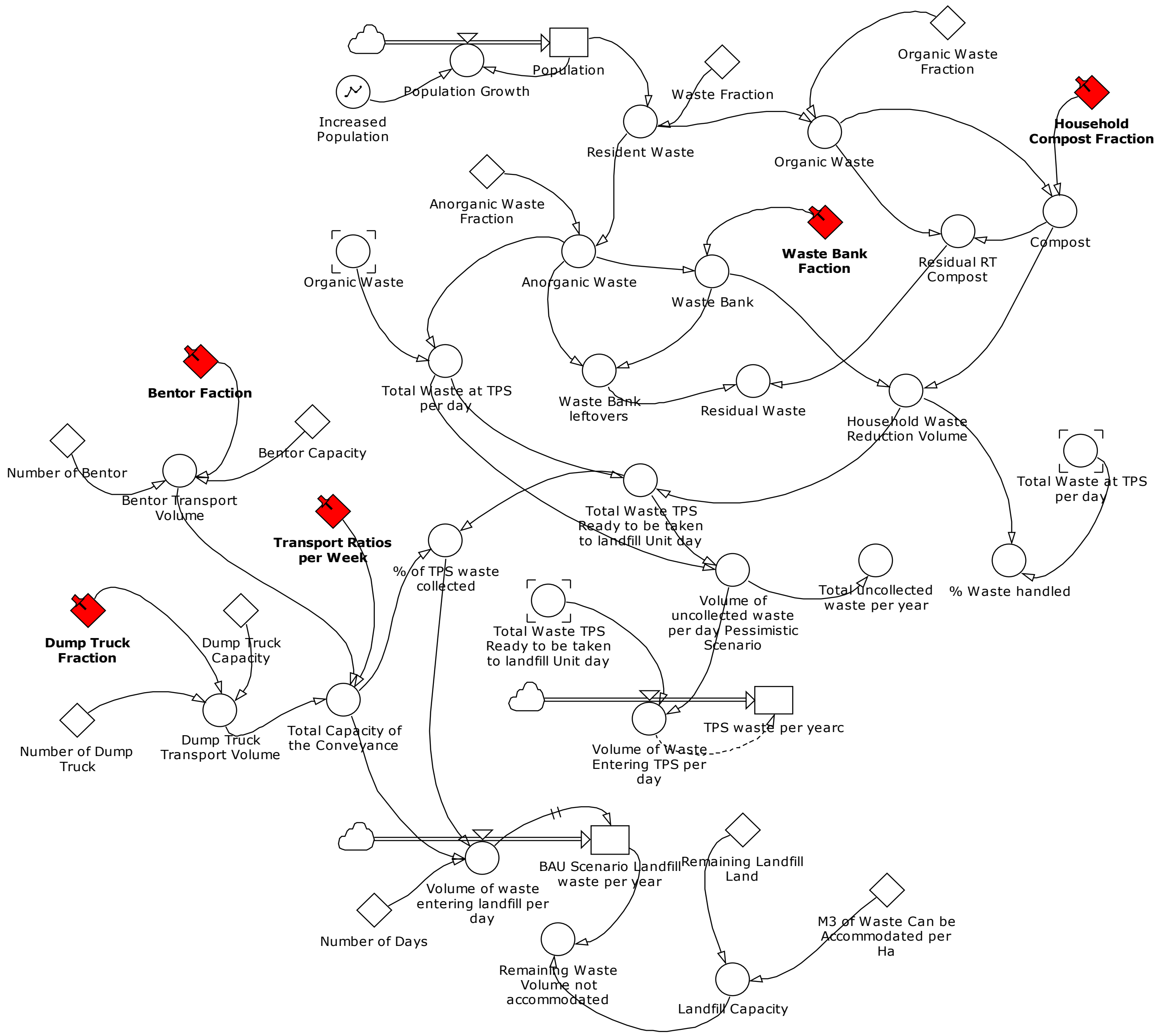

Fig. 4 *SFD urban waste management sustainability*

Table 5 *Scenarios for urban waste management sustainability*

No	Parameters	Sustainability in the future	
		Moderate	Optimistic
1	Increasing the utilization of waste banks for household sorting	The waste bank utilization rate for household waste sorting will be increased from the current 10% to 30%, resulting in an increase of processed waste volume from 63.73 m^3/day to 191.23 m^3/day through waste bank channels.	The waste bank utilization rate for household waste sorting will be increased from the current 10% to 50%, resulting in an increase of processed waste volume from 63.73 m^3/day to 318.69 m^3/day through waste bank channels.
2	Increasing the utilization of composting for household sorting	Utilization of waste banks for household waste sorting will be increased from the current 10% to 30%, thereby raising the composting volume from 51.11 m^3/day to 153.32 m^3/day.	Utilization of waste banks for household waste sorting will be increased from the current 10% to 50%, thereby raising the composting volume from 51.11 m^3/day to 255.53 m^3/day.

No	Parameters	Sustainability in the future	
		Moderate	Optimistic
3	Increasing the fraction of bentor services	The service coverage of bentor will be increased from the current 60% (760 m^3) to 70% (892.50 m^3).	The service coverage of bentor will be increased from the current 60% (760 m^3) to 70% (892.50 m^3).
4	Increasing the fraction of waste truck services	Waste truck service coverage will be increased from the current 60% (270 m^3) to 70% (315 m^3).	Waste truck service coverage will be increased from the current 60% (270 m^3) to 70% (315 m^3).
5	Optimizing daily transportation trips.	Transport operations will be optimized by adding one additional collection round per day.	Transport operations will be optimized by increasing the collection frequency to two rounds per day.

Source: Author's analysis

The waste management scenario analysis reveals three distinct projections: (1) The Pessimistic Scenario (BAU) indicates a significant annual waste volume increase from 292.841,57 m^3 in 2025 to 1.775.157,92 m^3 by 2030, which would lead to extreme landfill overcapacity requiring urgent intervention; (2) The Moderate Scenario shows more controlled waste growth from 227.765,66 m^3 in 2025 to 1.380.678,38 m^3 in 2030, though still necessitating measures to handle excess waste; and (3) The Optimistic Scenario presents the most favorable outcome with annual waste volumes rising from 162.689,76 m^3 to 986.198,85 m^3 during the same period, yet still requiring efficient management strategies to alleviate landfill burdens.

These three scenarios highlight the urgent need to either expand landfill capacity or develop more effective waste management strategies including recycling programs, waste reduction initiatives, and technology-based solutions to mitigate environmental impacts. The comparative progression of the pessimistic, moderate, and optimistic scenarios is illustrated in Fig. 5 and the urban waste management policies and strategies can be seen in Table 6.

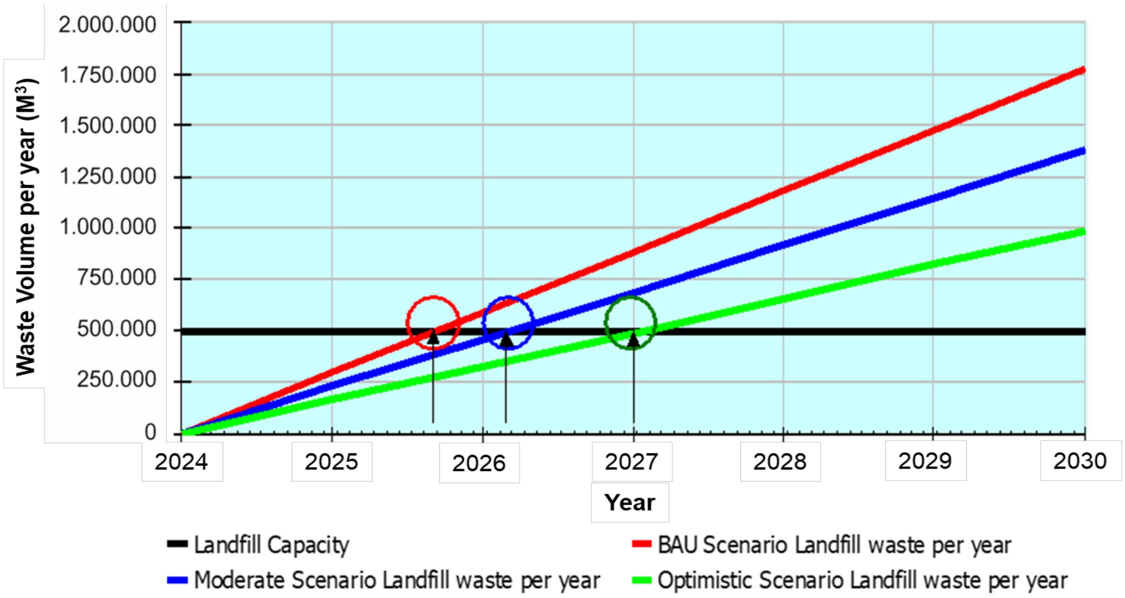

Fig. 5 *BAU, moderate, and optimistic scenario graph sustainability*

Overall, Fig. 5 illustrates that the growth of waste generation has significantly exceeded the landfill capacity (black line) of 493.200 m^3. In the no intervention scenario (red line), the volume of incoming waste reaches 586.883 m^3, surpassing the capacity by mid-2025. Under the moderate scenario (blue line), overcapacity occurs in early 2026 with a total of 686.102 m^3, while in the optimistic scenario (green line), a similar condition arises in 2027 with 654.772 m^3 of waste. These findings highlight the urgent need for concrete interventions, such as waste reduction at the source and enhancement of recycling facilities, to prevent landfill overcapacity.

Table 6 *Urban waste management policies and strategies*

No	Policies	Strategies
1	Handling and reducing waste as much as possible starts from the source.	• Waste reduction as much as possible starts from the source/Upstream. • Increase public understanding of the 3R (reduce-reuse-recycle) efforts and the security of household B3 (hazardous waste materials). • Develop and implement an incentive and disincentive system in the implementation of 3R towards 4R. • Encourage cross sector coordination, especially industry and trade.
2	Reducing waste as much as possible downstream to minimize environmental pollution around the landfill	• Increasing the intensity and performance of handling garbage hills in landfills, by making garbage truck roads and safety embankments that will make it easier to dispose of garbage towards ravines/remaining land that can be utilized. • Carrying out rehabilitation of landfill that pollute the environment • Improving the quality of landfill management towards integrated waste management.
3	Increasing the active role of the community and the business/private sector as management partners	• Increase understanding of waste management from an early age through education for school age children • Disseminate understanding of waste management to the general public • Increase community development, especially for women, in waste management • Encourage community based waste management • Develop an incentive system and a conducive climate for the business/private sector
4	Improving service coverage and quality of management systems	• Optimization of waste infrastructure and facilities utilization • Increasing service coverage in a planned and equitable manner • Increasing waste facility capacity according to service targets • Improving Sumompo landfill management (integration with regional landfill) • Research, development, and application of appropriate and environmentally friendly waste management technology
5	Institutional development, regulations and legislation (Law Enforcement)	• Improve the status and capacity of management institutions • Improve the performance of waste management institutions • Separate the functions/units of regulators and operators • Improve cooperation and coordination with other stakeholders • Improve the quality of human resources • Encourage collective management of regional scale waste management • Improve the completeness of legal products as a basis and reference for the implementation of waste management • Encourage the implementation of a monitoring system and the application of legal sanctions consistently in order to foster officials, the community and other stakeholders
6	Development of alternative sources of financing	• Encourage increased waste cost recovery by the government • Encourage participation in waste financing by the private sector with the concept of philanthropy

Source: Author’s analysis

5. Discussion

Urban waste management has become a critical issue in efforts to create a healthy and sustainable environment. Based on assessments of the landfill, current facilities face serious challenges regarding both capacity and environmental impacts. The assessment results indicate that this landfill must be immediately closed due to their significant negative environmental effects, including groundwater contamination, methane emissions, and damage to surrounding ecosystems. This conclusion is further supported by questionnaire results showing that most respondents agree inadequate landfill management poses major risks to public health and the environment. If the landfill continues operating without an integrated waste management strategy, its capacity will likely be exhausted by mid-2025. This will lead to critical issues including a waste disposal capacity crisis, heightened environmental contamination, and deteriorating living conditions for nearby residents.

However, the landfill's operational lifespan could potentially be extended to 2027 through targeted interventions. Six key strategies are proposed: (1) source level waste minimization, (2) downstream waste reduction to curb landfill pollution, (3) strengthened community private sector partnerships, (4) enhanced service coverage using renewable waste technologies, (5) institutional and regulatory framework development, and (6) alternative financing mechanisms for urban waste systems. These measures would optimize waste operations, reduce ecological damage, and maintain landfill functionality until 2027. Simultaneously, they would establish the necessary foundation for transitioning to sustainable urban waste management models in the long term.

The waste management policies and strategies identified in this study align with the integrated and sustainable waste management approach promoted by the Ministry of National Development Planning [27]. This approach emphasizes improving waste management efficiency and inclusivity through innovative funding mechanisms and financing exploration to support systemic improvements. Previous research findings by Waluyo & Kharisma [28] on ideal waste management policies highlight stringent regulations to advance national circular economy implementation and enhance overall waste systems. While this study doesn't focus specifically on circular economy, key policy variables formulated for urban waste reduction including expanded household waste bank utilization, increased household composting adoption, improved waste tricycle and truck service coverage, and optimized daily transport routes – represent critical findings that could ultimately contribute to circular economy objectives.

Previous research findings align with and reinforce the results of this study, particularly Sankoh *et al.* [29] who found that both households living within fifty meters of waste disposal sites and those farther away suffered from landfill related diseases like malaria, chest pain, diarrhea, and cholera, especially when waste sites were located near residential areas. Similarly, Ardiansyah *et al.* [30] found that poorly managed plastic waste damages coastal environments, disrupts marine ecosystems, and endangers public health. These issues stem from ineffective regulations and limited institutional capacity, exacerbating regional waste crises. Policy reforms are urgently needed to facilitate landfill resource recovery, implement fiscal incentives, streamline permitting processes, and engage local communities through education, training, and economic incentives [31], [32].

The findings of this study are consistent with those of other studies, which indicate that a high Environmental Risk Index value signifies the need for rehabilitation or closure of high risk landfill sites [33]–[35]. Kollikkathara *et al.* [15] use SD approach has proven effective in modeling the relationships among waste generation, landfill capacity, and management policies to predict long term impacts. Overall, these studies underscore the importance of implementing risk based sustainable waste management strategies through waste reduction at the source, recycling initiatives, and the strengthening of environmental policies and monitoring systems to minimize landfill burdens and mitigate ecological impacts. Ultimately, sustainable waste management requires government private sector community synergy [36]. Thus, the current findings both validate existing research through new parameters and offer original contributions that extend beyond previous studies.

6. Conclusion

This study highlights the need for six integrated, effective, and sustainable waste management strategies to minimize negative environmental impacts through: (1) maximizing waste handling and reduction at source, (2) maximizing downstream waste reduction to minimize pollution around landfills, (3) enhancing active community and private sector participation as management partners, (4) improving service coverage and system quality through renewable waste management technologies, (5) developing institutional frameworks, regulations, and policy alignment for sustainable urban development and environmental risk mitigation, and (6) exploring alternative urban waste management funding sources. This finding emphasizes that environmental quality, such as urban waste management, is an integral part of urban design [13], [37], [38].

The study concludes that under the pessimistic scenario, landfill capacity will be exceeded by mid-2025 with a total waste volume of 586.883 m^3. However, the optimistic scenario involving 50% increased utilization of waste banks, composting, and two daily collection cycles extends capacity early 2027 with 654.772 m^3 of waste.

A limitation of this study is that respondents were only sampled from residents within 0-500 meters of the landfill. Future research should expand coverage to include a broader sample of Manado City residents. Follow up studies could also determine priority waste management policy strategies and which related programs should be prioritized according to the six integrated waste management strategies above.

Acknowledgement

We are grateful for the participation of stakeholders in contributing their ideas in carrying out this research. The authors thank the Manado City Government and all respondents for their support. Thanks to Klabat University, Sam Ratulangi University and special for Institute of Green Products, Feng Chia University Taiwan for their contributions.

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Suriandjo, Sinsuw, Sangkertadi and Chu;* ***data collection:*** *Waani and Lahamendu;* ***analysis and interpretation of results:*** *Suriandjo, Sinsuw, Sangkertadi and Chu;* ***draft manuscript preparation:*** *Suriandjo and Sinsuw. All authors reviewed the results and approved the final version of the manuscript.*

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