Industrial and Domestic Waste Management

Research Article
Volume 6(2), 2026, 608−623
https://doi.org/10.53623/idwm.v6i2.1352

Spatial-System Dynamics Modeling for Municipal Solid Waste Landfill Capacity Projection: A Case Study in Pekanbaru, Indonesia

Agus Mulyadi*, St Nova Meirizha, Hanan Sururi

Industrial Engineering Department, Faculty of Engineering, Universitas Muhammadiyah Riau, Jl. Tuanku Tambusai, Pekanbaru Postcode 28294, Indonesia

*Correspondence: agusmulyadi@umri.ac.id

SUBMITTED: 14 August 2026; REVISED: 9 November 2026; ACCEPTED: 12 November 2026

ABSTRACT: The rapid population growth in Pekanbaru has resulted in a significant increase in waste generation. The imbalance between the limited capacity of the Final Disposal Site and the continuously increasing volume of waste has become an urgent environmental issue that needs to be addressed. This study aims to project the remaining capacity of Muara Fajar 2 landfill and evaluate policy scenarios to extend its operational lifespan. A spatial-system dynamics (SSD) model was developed by integrating system dynamics (SD) and Geographic Information Systems (GIS) to simulate population growth, waste generation, waste management, landfill filling, and land availability. GIS data were used to define spatial constraints, while simulation results were mapped to show annual changes in landfill area. The model was developed using causal loop and stock-flow diagrams, verified through dimensional and structural checks, and validated against 2019–2024 data using MAPE. The baseline simulation results show that Muara Fajar 2 landfill is projected to reach full capacity by 2027 if no policy intervention is made. The MAPE values for the population variable, waste volume, and landfill capacity are 9.09%, 9.93%, and 5.47%, respectively, which indicates acceptable agreement with historical data within the calibration period (MAPE is used as one indicator of fit, not as proof of model validity). Nine scenarios combining a waste management rate (55-73%), a waste reduction rate (20-40%), and additional landfill area (5-40 ha) were compared. Among the scenarios tested, the combination of 73% waste management, 40% waste reduction, and 5 ha of additional landfill area (Scenario A1) gives the lowest waste volume (1,619,250 tons) and leaves 7.51 ha of landfill area in 2045. Economic and greenhouse-gas indicators were not evaluated, so the scenarios are compared on waste volume and remaining landfill area only. The results provide a quantitative basis for discussing sustainable waste-management and landfill-capacity policies in Pekanbaru.

KEYWORDS: Spatial-system dynamics; landfill; domestic waste; simulation; projection

1. Introduction

Rapid urbanization and population growth have intensified solid waste management challenges, particularly in developing countries [1]. Increasing waste generation, combined

with limited landfill capacity and competition for urban land, has created substantial environmental and public health concerns. The availability of suitable land for final disposal facilities has become increasingly constrained by infrastructure development, urban expansion, and land-use conversion. These challenges are particularly evident in rapidly growing cities where waste management infrastructure has not expanded proportionally to population growth. Pekanbaru, the capital of Riau Province, Indonesia, has a population of approximately 1,143,360 inhabitants, placing increasing pressure on its existing waste management infrastructure [2].

Municipal solid waste management in Pekanbaru remains inadequate, with only approximately 46.72% of generated waste reported as properly managed [3]. According to the Ministry of Environment and Forestry, municipal waste generation reached approximately 1,011.01 metric tonnes per day, equivalent to 369,019.82 metric tonnes annually, in 2023. A substantial proportion of waste remains unmanaged or is disposed of through uncontrolled burning and illegal dumping, contributing to environmental degradation and public health risks [3, 4]. Pekanbaru previously operated two final disposal sites in the Rumbai area. Muara Fajar 1, established in 1997 with an area of 8.6 ha, ceased operations in 2007. Consequently, Muara Fajar 2, covering approximately 5.5 ha, currently serves as the city's only active landfill. Continuous population growth and increasing waste generation have intensified pressure on its limited disposal capacity, raising concerns about its remaining operational lifespan [4]. Figure 1 illustrates the relationship between municipal waste generation and the quantity of waste delivered to the landfill between 2019 and 2023.

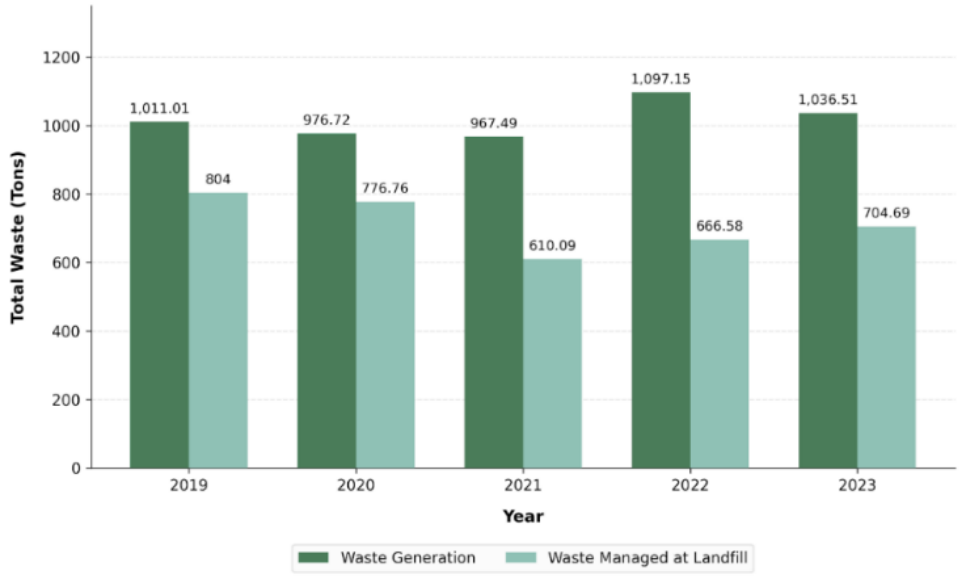


Figure 1. Municipal solid waste generation and waste delivered to the landfill in Pekanbaru from 2019 to 2023.

As shown in Figure 1, the quantity of waste delivered to the landfill remained consistently lower than total municipal waste generation throughout the study period. The proportion of generated waste delivered to the landfill was approximately 79.5% in 2019 and 2020, declining to 63.1% in 2021 and 60.8% in 2022 before increasing to 68.0% in 2023. The average proportion over the five-year period was approximately 70%. Meanwhile, the difference between generated and delivered waste increased from approximately 207 tonnes in 2019 to 431 tonnes in 2022, before declining to 332 tonnes in 2023, based on the values presented in Figure 1. These trends indicate persistent limitations in waste collection and disposal services.

Waste that does not reach the landfill may be subjected to uncontrolled disposal practices, including open burning and illegal dumping [4]. Consequently, landfill capacity planning must consider not only increasing waste generation but also variations in waste collection, treatment, and disposal rates.

Municipal solid waste management involves complex interactions among population growth, waste generation, collection efficiency, treatment capacity, landfill availability, and land-use changes [5, 6]. These interconnected factors require an integrated modelling approach capable of representing both temporal dynamics and spatial constraints. SSD, which integrates SD with Geographic Information Systems (GIS), provides a potential framework for addressing these challenges [7, 8]. SD represents feedback relationships, accumulation processes, and changes over time, including population growth, waste generation, and landfill filling. In contrast, GIS provides spatial information on land use, available land, and landfill boundaries, allowing spatial constraints to be incorporated into dynamic simulations [9, 10]. The integration can be implemented through loosely or tightly coupled approaches, depending on the frequency and direction of data exchange. In the present study, a loosely coupled approach was adopted, in which GIS-derived spatial parameters informed the SD model, while simulated landfill-area requirements were subsequently transferred to GIS for spatial visualization. Previous SSD applications have demonstrated its usefulness in water resource management, urban planning, urban expansion, and land carrying-capacity assessments [9-12]. These applications suggest that SSD could also support long-term landfill capacity forecasting and sustainable waste management planning.

Previous studies have investigated landfill planning and municipal solid waste management using statistical modelling, GIS, machine learning, and SD approaches [12-18]. GIS-based methods have been widely applied to landfill site suitability assessment, spatial optimization, and the identification of potential disposal locations [13-15, 19]. Machine learning approaches have also been employed to predict waste generation based on demographic, socioeconomic, and environmental variables [18]. However, these approaches do not necessarily represent the feedback mechanisms and accumulation processes that determine long-term landfill capacity. Conversely, SD models have been applied to simulate waste generation, treatment processes, landfill utilization, and management policies over time [16-18]. Although SD can represent complex temporal interactions, conventional implementations may provide limited spatial detail regarding land availability, land-use constraints, and potential landfill expansion. Statistical approaches offer useful projections based on historical trends but generally provide less explicit representation of feedback relationships and spatial constraints [12].

Despite these advances, an important research gap remains in integrating dynamic landfill-capacity forecasting with spatially explicit land-availability constraints within a unified decision-support framework. Existing studies have combined SD and GIS to estimate waste generation and identify suitable locations for waste management facilities [20]. However, the reviewed literature provides limited evidence of applications that systematically connect landfill filling dynamics, changing land requirements, and alternative waste management policies through spatially informed simulations. Furthermore, the implications of waste reduction, waste management performance, and additional landfill area have not been sufficiently examined together for Pekanbaru. Addressing this gap is essential for

understanding how alternative policy interventions may influence the remaining operational lifespan of existing landfill facilities.

The novelty of this study lies in developing and applying a loosely coupled SSD framework that integrates GIS-derived land-availability constraints with dynamic landfill-capacity projections and policy scenario evaluation. Unlike approaches that primarily focus on waste generation forecasting or landfill site suitability, the proposed framework simultaneously considers waste accumulation, management performance, and spatial land requirements. GIS-derived land-use information is incorporated into the SD model, while simulated changes in landfill-area requirements are transferred back to GIS for spatial interpretation. The framework is applied to Muara Fajar 2, providing a case-specific assessment of landfill capacity under alternative waste management and land-expansion scenarios. Although the SD model includes operational, maintenance, and depreciation cost components, economic performance is not evaluated in the present scenario comparisons.

Therefore, this study aimed to develop and apply an SSD model to forecast the remaining capacity of Muara Fajar 2 landfill and evaluate alternative waste management strategies for Pekanbaru. Specifically, the study sought to (i) integrate population growth, waste generation, waste management, landfill filling, and spatial land availability within an SSD framework; (ii) project landfill capacity and operational lifespan under baseline conditions; (iii) evaluate alternative scenarios involving waste management rates, waste reduction rates, and additional landfill areas; and (iv) identify scenarios that improve landfill capacity utilization and support long-term municipal solid waste management planning. The findings are expected to provide quantitative evidence to support landfill management policies and sustainable urban waste management strategies in Pekanbaru.

2. Materials and Methods

This study employed a SSD approach to project landfill capacity and land availability in Pekanbaru, Indonesia. The SD model was developed using Vensim software to simulate population growth, waste generation, waste management, and landfill area utilization from 2019 to 2045. GIS were used to process land-use data, identify spatial constraints, delineate landfill boundaries, and visualize simulation results. Integrating SD modelling with GIS-based spatial analysis enabled the assessment of temporal changes in waste management and their implications for landfill capacity and spatial land requirements. This integrated approach supported the analysis of causal relationships among waste management variables and the evaluation of long-term policy scenarios [21].

2.1. Research Framework.

The research was conducted in seven stages: (1) collection of historical and spatial data; (2) identification of variables influencing landfill land availability; (3) development of a Causal Loop Diagram (CLD); (4) construction and parameterization of a Stock and Flow Diagram (SFD); (5) model verification and validation; (6) GIS-based spatial analysis and mapping; and (7) development and comparison of policy scenarios. The SD model and GIS were integrated through sequential data exchange, as described in 2.5. This framework was designed to represent historical waste management conditions and project future changes in landfill capacity under alternative policy interventions.

2.2. Data Collection.

Primary and secondary data were collected to develop and validate the SSD model. Primary data were obtained through semi-structured interviews with staff members of the Pekanbaru Department of Environment and Sanitation (DLHK). Informants were selected purposively based on their responsibilities and experience in landfill operations and municipal waste management planning. The interviews were conducted in 2025 to verify the causal relationships represented in the CLD and estimate model parameters for which published statistical information was unavailable. Secondary data included population statistics, population growth rates, municipal waste generation, waste management performance, landfill capacity, and geographical land-use information. These data were obtained from the Central Bureau of Statistics (BPS) and DLHK of Pekanbaru. Historical data covering 2019–2024 were used for model validation.

2.3. Causal Loop Diagram (CLD).

A Causal Loop Diagram (CLD) was developed to represent the feedback relationships among variables influencing landfill capacity and waste management dynamics. CLDs provide a graphical representation of causal interactions within complex systems, facilitating the identification of feedback mechanisms and system behavior [22]. The variables included in the CLD were identified through literature reviews, field observations, and expert consultations. Causal relationships were represented by positive (+) or negative (−) polarities. A positive relationship indicates that changes in two connected variables occur in the same direction, whereas a negative relationship indicates that they occur in opposite directions, assuming other factors remain constant. Feedback loops were classified as reinforcing (R) or balancing (B). Reinforcing loops contain an even number of negative causal links and tend to amplify changes, whereas balancing loops contain an odd number of negative links and tend to counteract changes [23]. The CLD was developed by defining system boundaries, identifying relevant variables, establishing causal relationships, and evaluating the consistency of the resulting feedback structure with observed system conditions [24].

2.4. Stock and Flow Diagram (SFD).

The CLD was translated into a Stock and Flow Diagram (SFD) to quantify the relationships among system variables and simulate their changes over time. The SFD consisted of stocks, flows, auxiliary variables, constants, and connectors. Stocks represented accumulated quantities, including population, accumulated waste, and landfill area, while flows represented the rates at which these quantities changed. Auxiliary variables and constants defined the mathematical relationships and parameters governing the system. Connectors represented information dependencies between variables, whereas cloud symbols indicated sources or sinks outside the model boundaries [5]. The SFD provided the quantitative structure for simulating landfill capacity and evaluating alternative waste management scenarios.

2.5. GIS and SD-GIS Coupling

GIS are computer-based tools used to collect, store, manage, analyze, and visualize geographically referenced information for spatial analysis and decision-making [25]. GIS

enables the integration of spatial and non-spatial datasets, making it particularly useful for environmental management, land-use planning, and infrastructure development [26]. The SD and GIS models were integrated using a loosely coupled approach involving sequential data exchange. Initially, GIS-derived land-use classification and landfill boundary data were transferred to the SD model to establish the initial landfill area of 5.5 ha in 2019, land-use proportions (24% built-up land, 66% forest, and 11% vacant land), and spatial constraints associated with the *New Landfill Area* parameter. These spatial inputs provided the basis for defining land availability and potential landfill expansion within the simulation framework. The SD model subsequently simulated annual waste generation, waste management flows, accumulated waste, and landfill area consumption based on the mathematical relationships established in the Stock and Flow Diagram (SFD). The simulated landfill area requirements for selected years were then transferred to GIS for spatial visualization. These outputs were mapped onto the landfill boundaries to illustrate changes in the remaining and exhausted landfill areas over time. The spatial outputs were further used to assess the feasibility of additional landfill areas proposed under the policy scenarios, including expansions of 5, 20, and 40 ha. This assessment considered the availability of land identified through GIS analysis and the spatial constraints associated with existing land-use classifications. The integration therefore supported the comparison of alternative landfill expansion scenarios and their implications for long-term waste management planning. The integration was classified as loosely coupled because data were exchanged sequentially between the SD model and GIS rather than continuously at each simulation time step. Consequently, land-use changes were not updated endogenously during the simulation. Landfill depletion was calculated within the SD model, whereas GIS provided spatial input parameters and visual representations of the simulation results. This approach enabled the combined assessment of temporal landfill capacity dynamics and spatial land availability without requiring fully integrated spatial-dynamic computations.

2.6. Verification and Validation Model

Model verification and validation were performed to evaluate the structural consistency, mathematical correctness, and ability of the developed SD model to reproduce historical system behavior. These procedures were essential for assessing the reliability of the simulation results and identifying potential modelling errors [21].

2.6.1. Model Verification.

Model verification was conducted to ensure that the mathematical formulations and causal relationships were consistent with the conceptual framework. Two verification procedures were applied. First, dimensional consistency was evaluated using the unit-checking function in Vensim. This procedure examined whether the mathematical equations maintained consistent measurement units across stocks, flows, and auxiliary variables. The model was considered dimensionally consistent when no unit-related errors were detected.Second, structural verification was conducted by examining the relationships among model variables and comparing them with theoretical concepts, relevant literature, and expert assessments. This procedure ensured that the model structure adequately represented the principal mechanisms governing population growth, waste generation, waste management, and landfill capacity.

2.6.2. Model Validation.

Model validation was conducted by comparing simulated outputs with historical observations to assess the model's ability to reproduce observed system behavior. Three principal variables were evaluated: population, waste generation, and landfill capacity. Historical data from 2019 to 2024 were used for the comparison. The Mean Absolute Percentage Error (MAPE) was employed to quantify the average percentage deviation between simulated and observed values. MAPE was selected because it provides a scale-independent measure that facilitates comparisons among variables expressed in different units, including population (persons), waste generation (tonnes), and landfill capacity (hectares) [27]. MAPE was calculated using Equation (1):

$$MAPE = \frac{100\%}{n}\sum_{t=1}^{n}\left|\frac{A_t - S_t}{A_t}\right|$$

where A_t is the actual value, S_t is the simulated value in year t, and n is the number of observations (n = 6 for 2019–2024).

The interpretation of MAPE values followed the criteria proposed by Lewis [30]. Values below 10% indicated very good accuracy, values between 10% and 20% indicated good accuracy, values between 20% and 50% indicated reasonable accuracy, and values exceeding 50% indicated poor predictive accuracy. However, MAPE measures only the average percentage deviation between simulated and observed values and does not independently establish structural validity, detect systematic bias, or identify errors in the timing of system behavior. Therefore, MAPE was used as an indicator of historical model fit alongside dimensional consistency and structural verification.

3. Results and Discussion

3.1. Causal Loop Diagram Model

Municipal solid waste is generated through various human activities and consists of materials that are no longer required for their original purposes [28]. The model developed in this study assumed that population growth was a primary driver of increasing waste generation. As the population increased, consumption activities intensified, resulting in greater waste generation and increasing pressure on landfill capacity. The initial stage of model development involved constructing a Causal Loop Diagram (CLD) to represent the relationships among variables within Pekanbaru's municipal solid waste management system. The variables were identified through a literature review, empirical data analysis, and an assessment of local waste management conditions. This process ensured that the conceptual model incorporated the principal factors influencing waste generation, management performance, and landfill availability.

The developed CLD identified eight feedback loops, comprising three reinforcing loops (R1–R3) and five balancing loops (B1–B5), as illustrated in Figure 2. The reinforcing loops R1 and R2 represented population growth driven by births and immigration, respectively. An increasing population contributed to further births and potentially greater immigration, thereby reinforcing population growth. Conversely, the balancing loops B1 and B2 represented

population reductions associated with deaths and emigration [32]. Population growth increased consumption activities and municipal solid waste generation, contributing to waste accumulation through the reinforcing loop R3 [34]. Increasing waste generation placed additional pressure on waste management infrastructure, accelerated landfill depletion, and increased operational, maintenance, investment, and depreciation costs [35]. Although formal waste management activities reduced the quantity of waste requiring disposal, inadequately managed waste could adversely affect environmental quality and public health [36]. The balancing loops B3–B5 represented competition among different land uses. Land allocated to landfill development (B3), residential and commercial development (B4), and agricultural activities (B5) reduced the amount of land available for alternative purposes. Consequently, land-use efficiency policies could influence the allocation and availability of land for waste management infrastructure [33, 37]. Overall, the CLD demonstrated how population growth and increasing waste generation interacted with waste management performance and land-use constraints, providing the conceptual foundation for the quantitative simulation model.

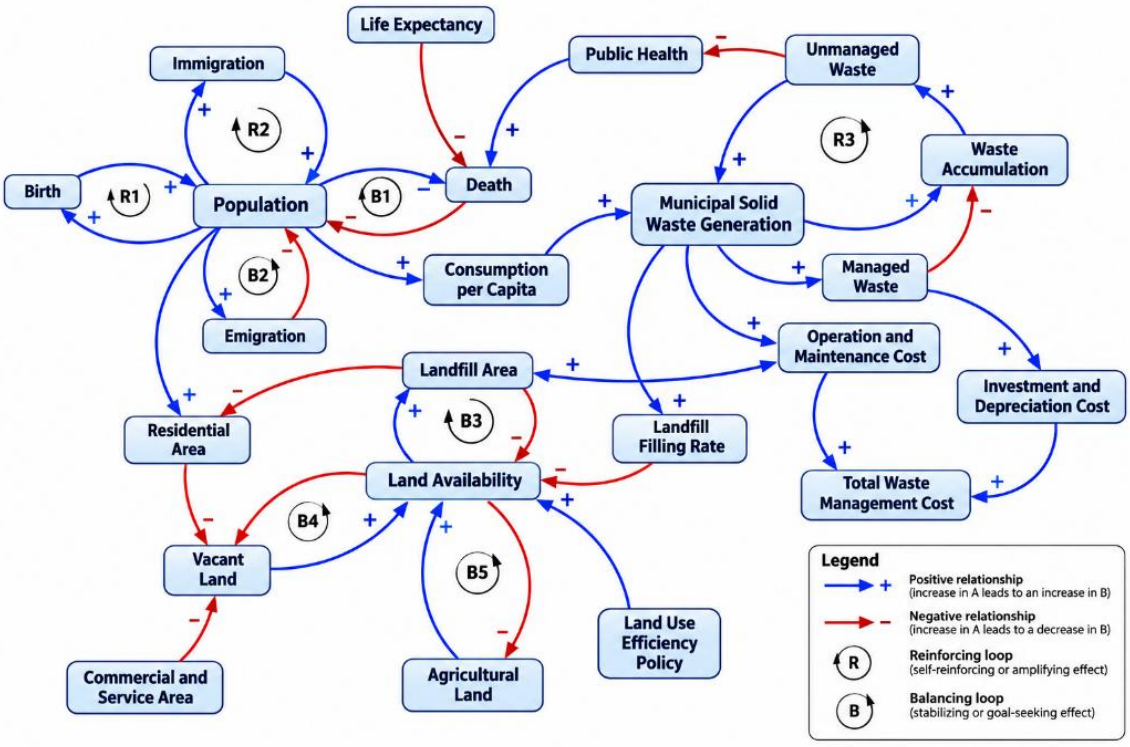


Figure 2. Causal Loop Diagram (CLD) of Municipal Solid Waste Management in Pekanbaru.

3.2. Stock and Flow Diagram.

Based on the CLD, a Stock and Flow Diagram (SFD) was developed to quantify the dynamic relationships among population growth, municipal solid waste generation, waste management, and landfill capacity. The model incorporated an initial population of 1,143,360 inhabitants and a per capita waste generation rate of 0.8 kg/person/day. The baseline waste reduction and waste management rates were set at 10% and 45%, respectively. The simulation covered the period from 2019 to 2045, allowing the assessment of long-term changes in waste accumulation and landfill availability. Figure 3 presents the Stock and Flow Diagram (SFD) of municipal solid waste management in Pekanbaru.

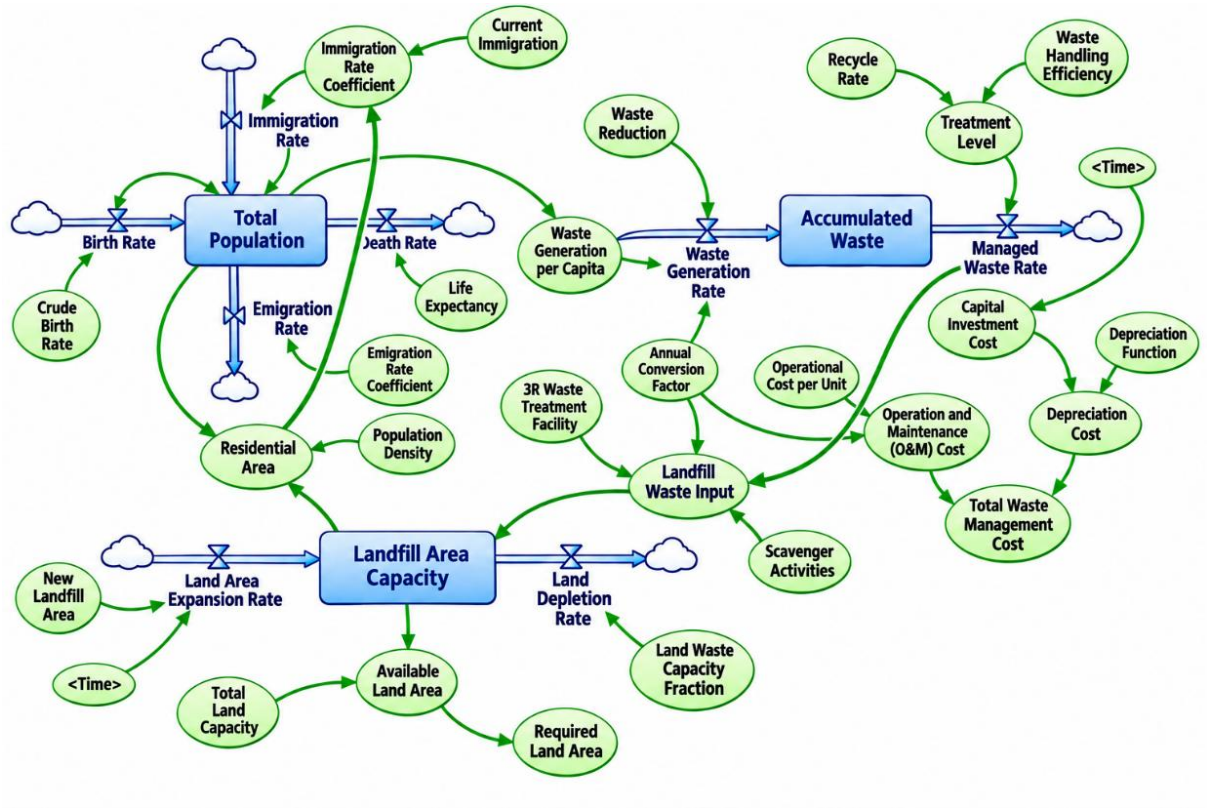


Figure 3. Stock and Flow Diagram (SFD) of Municipal Solid Waste Management in Pekanbaru.

Table 1 presents the mathematical relationships used to simulate waste generation, waste management, and landfill depletion. Annual waste generation was calculated from population size, per capita waste generation, and the waste reduction rate. The generated waste was subsequently allocated among mutually exclusive management pathways, including formal waste treatment or diversion, waste recovery by scavengers, processing at reduce–reuse–recycle (3R) facilities, and direct landfill disposal. This allocation was intended to prevent double counting among waste management activities. Landfill depletion was calculated by dividing the quantity of waste entering the landfill by the assumed waste-holding capacity per hectare. Additional landfill area was introduced through an expansion flow, while operational, maintenance, and depreciation costs were calculated separately. However, economic indicators were not included in the policy scenario evaluation. Under baseline conditions, with a waste management rate of 45%, a waste reduction rate of 10%, and no additional landfill area, the simulation projected a continuous decline in available landfill capacity. The remaining landfill area decreased from 5.00 ha in 2019 to 1.78 ha in 2024, 1.12 ha in 2025, and 0.46 ha in 2026, before reaching zero in 2027. The average annual reduction was approximately 0.65 ha during the later simulation period. This decline was primarily associated with increasing waste generation driven by population growth, while waste management and reduction rates remained unchanged. The results highlighted the potential consequences of maintaining existing waste management practices without additional interventions.

Table 1. Main model variables, equations, initial values, assumptions, and references.

No.	Variable (unit)	Type	Equation / Initial Value / Assumption	Reference
1	Total population, P (persons)	Stock	dP/dt = Immigration + Birth − Emigration − Death; P_0 = 1,143,360 (2019)	[2]

2	Immigration rate (persons/year)	Flow	P × immigration coefficient; dependent on residential area (Figure 3)	[2]
3	Emigration rate (persons/year)	Flow	P × emigration coefficient; coefficient = 0.01/year	[2]
4	Birth rate (persons/year)	Flow	P × crude birth rate; birth rate = 0.015/year	[2]
5	Death rate (persons/year)	Flow	P / life expectancy; life expectancy = 78 years	[32]
6	Waste generation rate, G (kg/year)	Flow	P × g × 365 × (1 − WR); g = 0.8 kg/person/day	—
7	Accumulated waste (kg)	Stock	d(Acc)/dt = G − M; initial value = 376,467,000 kg	—
8	Managed waste rate, M (tonnes/year)	Flow	G × treatment level; baseline = 45%; scenarios = 55–73%	DLHK
9	Treatment level (fraction)	Auxiliary	Waste handling efficiency + recycling rate	DLHK
10	Waste reduction, WR (fraction)	Constant	Baseline = 0.10; scenarios = 0.20–0.40	DLHK
11	Landfill waste input, L (kg/year)	Auxiliary	G − S − R − M; S = scavenger recovery; R = 3R facility processing	DLHK interviews
12	Landfill area capacity, A (ha)	Stock	dA/dt = Expansion − Depletion; A_0 = 5.5 ha (2019)	DLHK/GIS
13	Land depletion rate (ha/year)	Flow	L / c; c = 250,000,000 kg/ha	—
14	Land area expansion rate (ha/year)	Flow	Additional landfill area introduced through a pulse function; baseline = 0; scenarios = 5, 20, or 40 ha	—
15	Total waste management cost (IDR/year)	Auxiliary	Operation and maintenance costs + depreciation costs	[35]

3.3. Verification and Validation.

Model verification was conducted through dimensional consistency testing and structural assessment. Dimensional consistency was examined using the unit-checking function in Vensim to ensure that the mathematical relationships among model variables were expressed in compatible units. Structural verification involved evaluating the causal relationships and model assumptions against theoretical principles, relevant literature, and expert assessments. These procedures were intended to identify formulation errors and ensure that the model structure adequately represented the waste management system [21]. Model validation was performed by comparing simulated results with historical observations for population, waste generation, and landfill capacity from 2019 to 2024. The Mean Absolute Percentage Error (MAPE) values were 9.09%, 9.93%, and 5.47%, respectively. According to the classification proposed by Lewis [30], all three values indicated very good agreement with historical observations because they were below 10%. However, the population and waste generation MAPE values approached this threshold, indicating that some discrepancies remained. Furthermore, Table 2 shows that simulated landfill capacity was consistently lower than observed capacity after 2019, suggesting a systematic tendency to overestimate landfill depletion. Therefore, the projected exhaustion year of 2027 should be interpreted cautiously as a potentially early estimate rather than a definitive prediction. MAPE was used to assess historical model fit and was considered alongside dimensional and structural verification.

Table 2. Comparison of observed and simulated landfill area capacity during 2019–2024.

Year	Observed area (ha)	Simulated area (ha)	Error (%)
2019	5.00	5.00	0.00

2020	4.50	4.37	2.99
2021	3.90	3.73	4.45
2022	3.40	3.08	9.33
2023	2.70	2.43	9.83
2024	1.90	1.78	6.22
MAPE			**5.47**

3.4. Baseline Projection and Spatial Visualization of Landfill Availability.

GIS-based spatial visualization was employed to illustrate changes in landfill availability based on the SD simulation results. Land-cover analysis classified Pekanbaru into built-up and undeveloped areas. Built-up land, predominantly comprising residential areas, accounted for approximately 24% of the city's total area. Undeveloped land consisted primarily of forest areas (approximately 65%) and vacant land (11%). These spatial characteristics provided information on land availability and potential constraints affecting future landfill expansion. Figure 4 illustrates the projected reduction in the remaining landfill area of Muara Fajar 2 under baseline conditions. The simulation indicated that available landfill area decreased from 5.00 ha in 2019 to 1.78 ha in 2024 and was projected to decline further to 0.46 ha by 2026. Without improvements in waste management performance or additional landfill capacity, the remaining area was projected to be exhausted by 2027. This finding highlighted the urgency of implementing alternative waste management strategies, including increased waste reduction, improved recycling and treatment capacity, and the identification of suitable land for future disposal facilities. Integrating SD simulation outputs with GIS visualization provided a spatial representation of landfill depletion and supported the assessment of long-term waste management requirements.

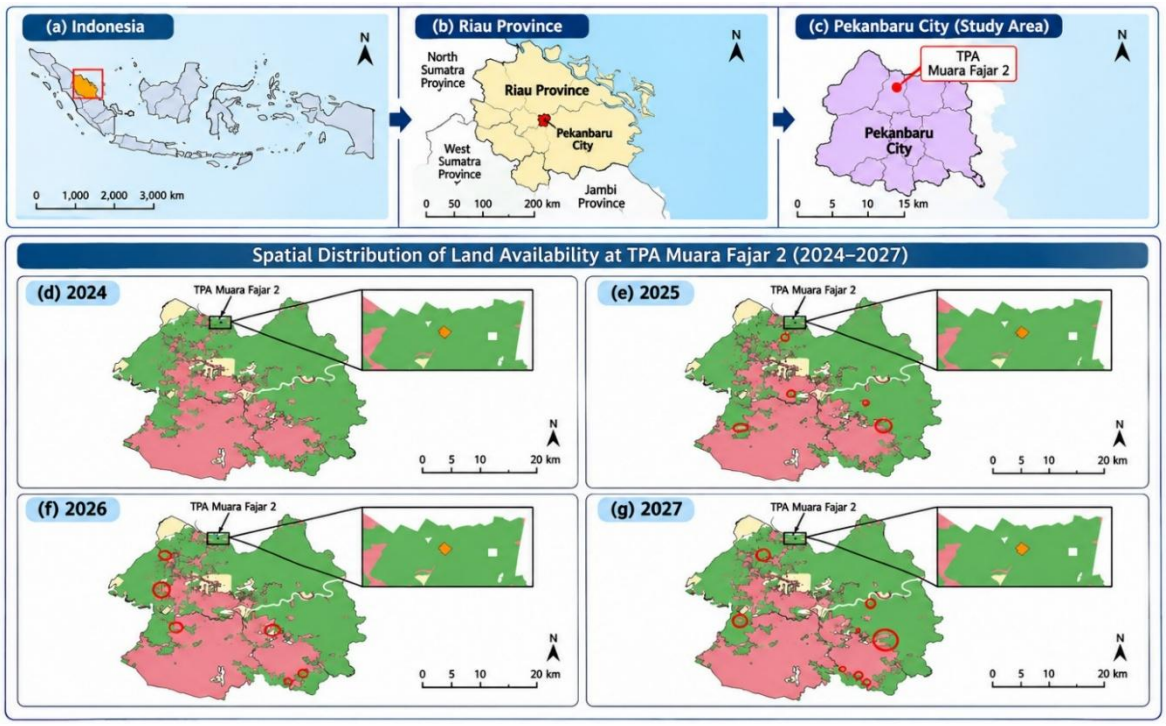


Figure 4. Spatial Visualization of Projected Landfill Area Availability at Muara Fajar 2 Under Baseline Conditions.

3.5. Policy Scenario Analysis

Based on the critical landfill capacity conditions identified in the baseline simulation, nine alternative policy scenarios were developed to evaluate strategies for extending the operational lifespan of Muara Fajar 2 landfill. The scenarios incorporated three principal policy interventions: improving waste management performance, increasing waste reduction rates, and expanding landfill capacity through additional land allocation. These interventions were organized into three scenario groups (A, B, and C), each comprising three levels of landfill expansion. Group A represented the highest waste management and reduction rates, followed by Groups B and C, which reflected progressively lower intervention levels. The scenarios were evaluated based on projected waste quantities and remaining landfill area in 2045.

Figure 5 illustrates the projected changes in remaining landfill area under the nine policy scenarios from 2019 to 2045. The simulation demonstrated that landfill availability varied considerably according to the intensity of waste management interventions and the amount of additional land allocated. A sharp increase in available landfill area occurred in 2027 because the model introduced additional landfill area as a single-step expansion at that time. The newly allocated land was assumed to become operational immediately, without accounting for construction or infrastructure development delays. Following expansion, landfill availability continued to decline as waste accumulated. However, scenarios with higher waste management and reduction rates exhibited slower landfill depletion, demonstrating the importance of reducing the quantity of waste requiring final disposal.

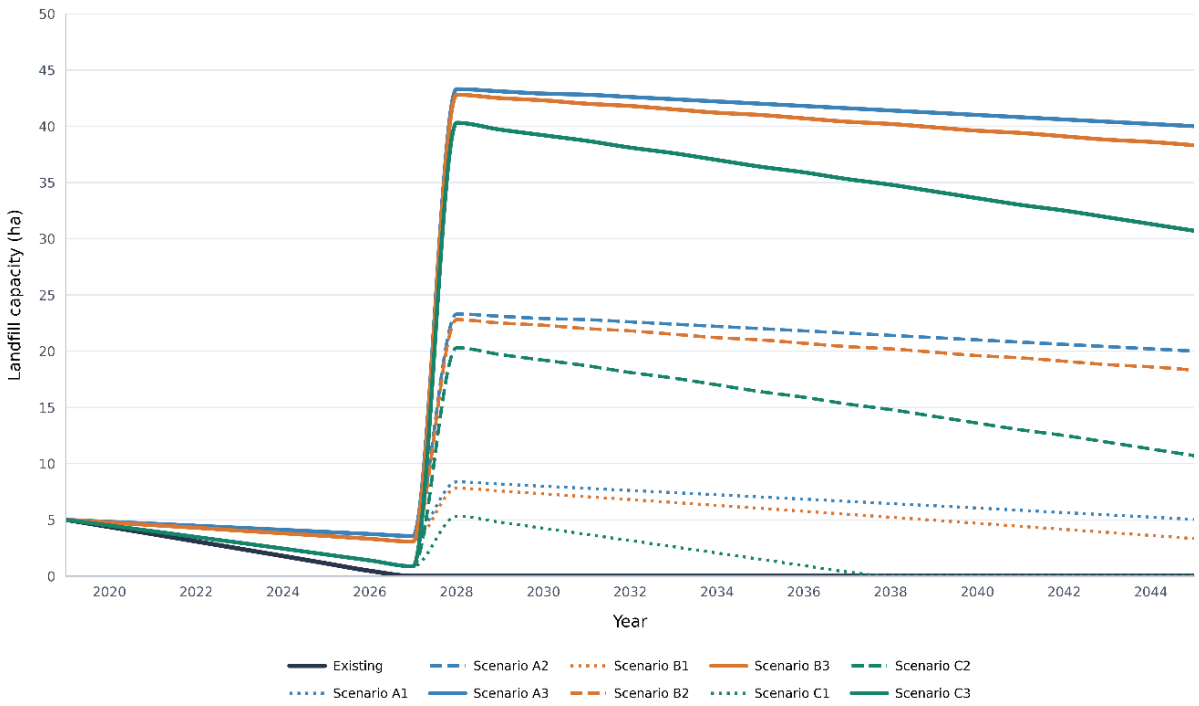


Figure 5. Comparison of projected remaining landfill area under nine policy scenarios from 2019 to 2045.

Table 3 summarizes the waste management rates, waste reduction rates, additional landfill areas, projected waste quantities, and remaining landfill capacities for all nine scenarios in 2045. Group A, characterized by 73% waste management and 40% waste reduction, produced the lowest projected waste quantities, ranging from 1,619,250 to 1,619,290 tonnes. Group B, incorporating 70% waste management and 30% waste reduction, generated between 2,043,860 and 2,043,920 tonnes. In contrast, Group C, with 55% waste management and 20% waste reduction, produced the highest projected waste quantities, ranging from 3,524,830 to

3,524,940 tonnes. Within each group, differences in waste quantities were negligible, indicating that landfill expansion had little influence on the simulated waste quantities compared with waste management and reduction interventions.

Table 3. Comparison Of Policy Scenarios and Projected Waste Quantities and Remaining Landfill Area in 2045.

Scenario	Waste management (%)	Waste reduction (%)	Additional landfill area (ha)	Projected waste (tonnes)	Remaining landfill area (ha)
A1	73	40	5	1,619,250	7.51
A2	73	40	20	1,619,260	22.51
A3	73	40	40	1,619,290	42.51
B1	70	30	5	2,043,860	6.67
B2	70	30	20	2,043,890	21.67
B3	70	30	40	2,043,920	41.67
C1	55	20	5	3,524,830	3.70
C2	55	20	20	3,524,880	18.70
C3	55	20	40	3,524,940	38.70

Among the evaluated scenarios, A1 achieved the lowest projected waste quantity (1,619,250 tonnes) while maintaining 7.51 ha of remaining landfill area in 2045. This scenario combined a 73% waste management rate, a 40% waste reduction rate, and an additional landfill area of only 5 ha. Although scenarios A2 and A3 provided greater remaining landfill areas, they required substantially more land without meaningfully reducing projected waste quantities. Therefore, Scenario A1 represented the most land-efficient option among the nine scenarios evaluated, based on the criteria of projected waste quantity and remaining landfill availability. However, this finding should not be interpreted as demonstrating overall economic or environmental superiority because implementation costs and greenhouse gas emissions were not evaluated.

The findings support the principles of integrated solid waste management, which prioritize waste prevention, reduction, reuse, recycling, and treatment before final disposal. Improving waste management performance could reduce dependence on landfill expansion while extending the operational lifespan of existing facilities. Practical interventions may include strengthening waste segregation at source, expanding community-based waste banks, improving recycling infrastructure, and promoting collaboration with micro, small, and medium enterprises (MSMEs) and informal waste collectors. Furthermore, transitioning from open dumping to controlled or sanitary landfill operations could improve environmental protection and operational efficiency. These measures should be supported by appropriate regulatory frameworks, institutional coordination, and public participation.

Nevertheless, the findings should be interpreted in light of several limitations. The model relied on historical data and assumed intervention rates, while additional landfill areas were considered immediately operational following expansion. The analysis did not incorporate construction lead times, implementation costs, greenhouse gas emissions, or uncertainty in future land-use changes. Consequently, the projected outcomes represent conditional scenarios rather than definitive forecasts. Future research should incorporate economic and environmental indicators, assess the feasibility of landfill expansion, and evaluate uncertainty through sensitivity analysis to provide a more comprehensive basis for sustainable waste management planning.

4. Conclusions

This study developed a SSD model integrating SD and GIS to project landfill capacity and evaluate waste management strategies in Pekanbaru, Indonesia. The model demonstrated acceptable agreement with historical data from 2019 to 2024, with mean absolute percentage error (MAPE) values of 9.09%, 9.93%, and 5.47% for population, waste volume, and landfill capacity, respectively. Dimensional consistency checks and expert assessments further supported the model's structural reliability. Under baseline conditions, Muara Fajar 2 landfill was projected to reach full capacity by 2027 without policy intervention, primarily due to increasing waste generation driven by population growth. Among the nine evaluated scenarios, Scenario A1, combining 73% waste management, 40% waste reduction, and 5 ha of additional landfill area, achieved the lowest projected waste volume (1,619,250 tonnes) while maintaining 7.51 ha of remaining landfill area in 2045. Although this scenario demonstrated favorable outcomes, its overall optimality could not be established because economic costs and greenhouse gas emissions were not evaluated. The findings highlight the importance of improving waste management efficiency, strengthening household waste segregation and recycling programs, transitioning toward sanitary landfill operations, and planning additional disposal capacity. However, uncertainties associated with model parameters, limited spatial data, and loosely coupled SD–GIS integration should be considered when interpreting the projections. Future research should incorporate economic assessments, greenhouse gas emissions, climate-related influences, and emerging waste treatment technologies to support more comprehensive and sustainable landfill management decisions.

Acknowledgments

The authors gratefully acknowledge the Pekanbaru Department of Environment and Sanitation (DLHK) for providing the data and information necessary to conduct this research.

Author Contributions

All authors contributed equally to conceptualization, methodology, formal analysis, investigation, data curation, visualization, writing—original draft preparation, and writing—review and editing. All authors have read and approved the final version of the manuscript.

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the research reported in this manuscript.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

References

[1] Zhang, Z.; et al. (2024). Municipal solid waste management challenges in developing regions: A comprehensive review and future perspectives for Asia and Africa. *Science of the Total Environment*, *930*, 172794. https://doi.org/10.1016/j.scitotenv.2024.172794.

[2] Kota Pekanbaru dalam Angka 2026. (accessed on 21 June 2026) Available online: https://pekanbarukota.bps.go.id/id/publication/2026/02/27/c54e16ff737217110b0bbe7f/kota-pekanbaru-dalam-angka-2026.html.
[3] Setiawan, Y.; Nugroho, S.; Saputri, A.D.C.D. (2022). Analisis timbulan dan komposisi sampah perumahan Kecamatan Muara Badak dihubungkan dengan tingkat pendidikan, pendapatan, dan perilaku masyarakat. *Jurnal Teknologi Lingkungan UNMUL*, *6*, 44–48. https://doi.org/10.30872/jtlunmul.v6i1.8478.
[4] Nisa', S.Q.Z.; Murti, R.H.A.; Jawwad, M.A.S. (2023). Estimasi luas lahan tempat pembuangan akhir (TPA) Kota Kediri dengan pendekatan sistem dinamik. *Envirotek: Jurnal Ilmiah Teknik Lingkungan*, *15*, 39–43. https://doi.org/10.33005/envirotek.v15i1.212.
[5] Artika, I.; Chaerul, M. (2020). Model sistem dinamik untuk evaluasi skenario pengelolaan sampah di Kota Depok. *Jurnal Wilayah dan Lingkungan*, *8*, 261–279. https://doi.org/10.14710/jwl.8.3.261-279.
[6] Henry, R.K.; Yongsheng, Z.; Jun, D. (2006). Municipal solid waste management challenges in developing countries – Kenyan case study. *Waste Management*, *26*, 92–100. https://doi.org/10.1016/j.wasman.2005.03.007.
[7] Ahmad, S.; Simonovic, S.P. (2004). Spatial system dynamics: New approach for simulation of water resources systems. *Journal of Computing in Civil Engineering*, *18*, 331–340. https://doi.org/10.1061/(ASCE)0887-3801(2004)18:4(331).
[8] Cai, Z.; Wang, B.; Cong, C.; Cvetkovic, V. (2020). Spatial dynamic modelling for urban scenario planning: A case study of Nanjing, China. *Environment and Planning B: Urban Analytics and City Science*, *47*, 1380–1396. https://doi.org/10.1177/2399808320934818.
[9] Kollikkathara, N.; Feng, H.; Yu, D. (2010). A system dynamic modeling approach for evaluating municipal solid waste generation, landfill capacity and related cost management issues. *Waste Management*, *30*, 2194–2203. https://doi.org/10.1016/j.wasman.2010.05.012.
[10] Ye, H.; Li, L.; Wang, C.; Yi, S. (2008). Integrating GIS and urban spatial system dynamic model for urban expansion analysis. In Proceedings of SPIE; Liu, L., Li, X., Liu, K., Zhang, X., Chen, A., Eds.; SPIE: Bellingham, WA, USA; Volume 7143, 714315. https://doi.org/10.1117/12.812565.
[11] Lamonda, R.; Supriatna; Hernina, R.; Manessa, M.D.M.; Ristya, Y. (2019). Spatial dynamics model for land carrying capacity prediction in Tangerang Selatan City. *E3S Web of Conferences*, *125*, 01006. https://doi.org/10.1051/e3sconf/201912501006.
[12] Firmansyah, F.; Adnan, F.; Nugroho, S. (2024). Perencanaan kapasitas TPA di Kecamatan Kembang Janggut dan Kecamatan Kenohan Kabupaten Kutai Kartanegara. *Jurnal Teknologi Lingkungan UNMUL*, *8*, 1–10. https://doi.org/10.30872/jtlunmul.v8i1.10931.
[13] Rahimi, S.; Hafezalkotob, A.; Monavari, S.M.; Hafezalkotob, A.; Rahimi, R. (2020). Sustainable landfill site selection for municipal solid waste based on a hybrid decision-making approach: Fuzzy group BWM-MULTIMOORA-GIS. *Journal of Cleaner Production*, *248*, 119186. https://doi.org/10.1016/j.jclepro.2019.119186.
[14] Langa, C.; Hara, J.; Wang, J.; Nakamura, K.; Watanabe, N.; Komai, T. (2021). Dynamic evaluation method for planning sustainable landfills using GIS and multi-criteria in areas of urban sprawl with land-use conflicts. *PLoS ONE*, *16*, e0254441. https://doi.org/10.1371/journal.pone.0254441.
[15] Kontokosta, C.E.; Hong, B.; Johnson, N.E.; Starobin, D. (2018). Using machine learning and small area estimation to predict building-level municipal solid waste generation in cities. *Computers, Environment and Urban Systems*, *70*, 151–162. https://doi.org/10.1016/j.compenvurbsys.2018.03.004.
[16] Hénault-Ethier, L.; Martin, J.-P.; Housset, J. (2017). A dynamic model for organic waste management in Quebec (D-MOWIQ) as a tool to review environmental, societal and economic perspectives of a waste management policy. *Waste Management*, *66*, 196–209. https://doi.org/10.1016/j.wasman.2017.04.021.

[17] Inghels, D.; Dullaert, W. (2011). An analysis of household waste management policy using system dynamics modelling. *Waste Management & Research*, *29*, 351–370. https://doi.org/10.1177/0734242X10373800.
[18] Karavezyris, V.; Timpe, K.-P.; Marzi, R. (2002). Application of system dynamics and fuzzy logic to forecasting of municipal solid waste. *Mathematics and Computers in Simulation*, *60*, 149–158. https://doi.org/10.1016/S0378-4754(02)00010-1.
[19] Wanore, T.D.; Angello, Z.A.; Fetanu, Z.M. (2023). Optimized landfill site selection for municipal solid waste by integrating GIS and multicriteria decision analysis (MCDA) technique, Hossana town, Southern Ethiopia. *Heliyon*, *9*, e21257. https://doi.org/10.1016/j.heliyon.2023.e21257.
[20] Wang, C.; Zou, F.; Yap, J.B.H.; Tang, R.; Li, H. (2022). Geographic information system and system dynamics combination technique for municipal solid waste treatment station site selection. *Environmental Monitoring and Assessment*, *194*, 457. https://doi.org/10.1007/s10661-022-10077-w.
[21] Sterman, J.D. (2000). Business Dynamics: Systems Thinking and Modeling for a Complex World; Irwin/McGraw-Hill: Boston, MA, USA.
[22] Mulyadi, A.; Meirizha, S.N.; Qurthuby, M.; Sundari, M. (2023). The analysis of blood supply chain performance based on supply chain operation reference model and causal loop diagram approach. *Jurnal Manajemen Industri dan Logistik*, *7*, 205–218. https://doi.org/10.30988/jmil.v7i2.1223.
[23] Forrester, J.W. (1961). Industrial Dynamics; MIT Press: Cambridge, MA, USA.
[24] Saputro, M.R.; Noor, F.M.; Maulana, R.N.; Sahrupi (2024). Model sistem dinamis ketersediaan air PDAM Cilegon Mandiri. *Metode: Jurnal Teknik Industri*, *10*, 93–102. https://doi.org/10.33506/mt.v10i1.3123.
[25] Longley, P.A.; Goodchild, M.F.; Maguire, D.J.; Rhind, D.W. (2015). Geographic Information Science and Systems, 4th ed.; Wiley: Hoboken, NJ, USA.
[26] Goodchild, M.F. (2000). Communicating geographic information in a digital age. *Annals of the Association of American Geographers*, *90*, 344–355. https://doi.org/10.1111/0004-5608.00198.
[27] Barlas, Y. (1996). Formal aspects of model validity and validation in system dynamics. *System Dynamics Review*, *12*, 183–210. https://doi.org/10.1002/(SICI)1099-1727(199623)12:3<183::AID-SDR103>3.0.CO;2-4.
[28] Damanhuri, E.; Handoko, W.; Padmi, T. (2014). Municipal solid waste management in Indonesia. In Municipal Solid Waste Management in Asia and the Pacific Islands; Pariatamby, A., Tanaka, M., Eds.; Environmental Science and Engineering; Springer: Singapore, Singapore; pp. 139–155. https://doi.org/10.1007/978-981-4451-73-4_8.



© 2026 by the authors. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).