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System Dynamics Modelling of Population Growth and Waste Management Landfill Capacity Sustainability in Palangka Raya

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This study analyzes the growing challenges of municipal solid waste management in Palangka Raya, driven by rapid population growth and limited landfill capacity. The research aims to develop an integrated dynamic system model combining population dynamics and waste management performance to project future conditions and evaluate policy interventions. Using a system dynamics approach, the study models population growth, household waste generation, landfill accumulation, and waste reduction strategies. Primary data were collected through field measurements of existing waste volumes and landfill capacities, while secondary data were obtained from official statistics and relevant reports. Model validation demonstrates high accuracy in projecting population growth, a key driver of increasing waste generation. Simulation results indicate that, under the current conditions, the Bukit Tunggal landfill will reach overload in 2018, revealing an unsustainable system. Moderate interventions produce minimal improvement, while an optimistic scenario delays landfill overload only until 2026. The findings demonstrate that achieving long-term landfill sustainability requires an extreme waste reduction strategy of at least 85% through significant enhancement of recycling, composting, and waste diversion efforts. The study concludes that incremental policies are inadequate to address the worsening waste crisis. Instead, a transformative shift toward high-performance waste processing and decisive policy intervention is essential to maintain landfill functionality and support sustainable urban development. The integrated model developed in this research provides a valuable tool for policymakers to design effective and long-term waste management strategies.

Keywords: Waste management, System dynamics modeling, Landfill capacity, Population growth, Waste reduction strategies

INTRODUCTION

Rapid urbanization has intensified municipal solid waste (MSW) management challenges worldwide. Population growth directly increases waste generation, placing sustained pressure on landfill infrastructure (Lima, 2025; Nguyen et al., 2025). In many developing cities, landfill expansion is constrained by land availability, environmental regulation, and fiscal limitations, making long-term capacity sustainability a critical concern. Under these conditions, landfill overcapacity not only creates environmental risks but also imposes increasing financial burdens on local governments (Hibiki, 2024; Xiao et al., 2020).

Low recycling rates further aggravate this problem. Although recycling contributes to waste diversion, resource recovery, and energy savings (Eneh, 2021), suboptimal implementation limits its effectiveness in reducing landfill dependency (Mtetwa, 2024; Rafew & Rafizul, 2021). As a result, recyclable waste continues to accumulate in landfills, accelerating capacity depletion. These pressures highlight the importance of understanding the interaction between demographic growth and waste diversion mechanisms in maintaining landfill sustainability (Urugo et al., 2024).

System dynamics modelling has been widely applied to analyse waste management systems due to its ability to capture feedback loops and long-term behavioural patterns. Previous studies have examined recycling optimisation, landfill lifespan estimation, and policy scenario simulations (Giannis et al., 2017; Moradikia et al., 2024; Xiao et al., 2020). However, several structural limitations remain evident. First, population growth is frequently treated as an exogenous projection parameter rather than as an endogenous subsystem governed by internal feedback mechanisms such as birth, death, and migration rates. Second, landfill capacity dynamics and financial implications are often analysed separately, resulting in partial system representation. Third, while scenario comparisons are common, fewer studies explicitly identify quantitative sustainability thresholds required to prevent landfill overload within a defined simulation horizon.

Waste management systems inherently involve dynamic interactions among demographic growth, waste generation, recycling performance, landfill accumulation, and fiscal expenditures. These processes evolve over time and exhibit non-linear feedback behaviour. Static or descriptive approaches are therefore insufficient to capture the long-term implications of demographic pressure on landfill sustainability. A dynamic system framework enables analysis of accumulation processes, feedback mechanisms, and policy impacts within a consistent structural model.

In rapidly growing secondary cities such as Palangka Raya, landfill capacity constraints are strongly influenced by demographic expansion patterns. However, limited modelling research simultaneously integrates (1) endogenous population growth mechanisms, (2) landfill accumulation limits, and (3) fiscal consequences of waste diversion policies within a unified analytical framework that allows identification of measurable sustainability thresholds.

This study addresses this structural limitation by developing a system dynamics model that links demographic growth to waste generation, landfill saturation dynamics, and financial implications within a single framework. The model treats population dynamics and waste management processes as interdependent subsystems influencing landfill sustainability over time.

The objectives of this study are threefold. First, to model population growth as an endogenous subsystem with internal feedback loops that structurally drive waste generation. Second, to identify a quantitative waste reduction threshold required to maintain landfill functionality within the 2013–2033 projection period through scenario simulation and sensitivity analysis. Third, to integrate physical landfill capacity dynamics with fiscal evaluation in order to assess operational and economic sustainability simultaneously. By framing landfill sustainability as a dynamic threshold-based problem under sustained demographic pressure, this study provides a structurally integrated analytical approach for evaluating long-term waste management strategies in rapidly growing urban contexts.

METHOD

Research Design

This study was conducted in Palangka Raya, a rapidly growing secondary city experiencing increasing pressure on landfill capacity due to sustained demographic expansion. The map of the research location is presented in Figure 1. This research employs a system dynamics modelling approach to analyse the interaction between population growth, waste generation, landfill capacity accumulation, and fiscal implications. The model is designed to capture feedback mechanisms and long-term behavioural patterns within the municipal solid waste management system.

The simulation time horizon covers the period 2013–2033. The baseline year (2013) was selected due to the availability of consistent and complete data on population, waste generation, landfill capacity, and financial records. A 20-year projection period was considered sufficient to capture long-term accumulation dynamics, landfill saturation behaviour, and policy impact trajectories under sustained demographic pressure. The selected timeframe also aligns with medium- to long-term municipal planning cycles. The model utilizes complete secondary time-series data obtained from municipal administrative records and official statistical reports for the period 2013–2023. The dataset represents the full available records rather than a statistical sample; therefore, sampling terminology is not applicable in this modelling context. Scenario simulations and sensitivity analyses were conducted to evaluate the effects of varying waste reduction rates on landfill sustainability and fiscal performance over the simulation period.

Model Assumptions

The system dynamics model incorporates several simplifying assumptions to maintain structural clarity and analytical tractability. Demographic parameters, including birth rate, death rate, and net migration rate, are treated as constant average annual values derived from historical municipal data (2013–2023). These parameters represent long-term average demographic tendencies rather than short-term fluctuations. The assumption of constant demographic rates does not imply demographic stability over time. Instead, it allows the model to isolate structural interactions between population growth, waste generation, landfill accumulation, and fiscal dynamics without introducing exogenous demographic volatility. Similarly, baseline per capita waste generation is assumed constant in the reference scenario. This assumption serves as a structural benchmark for evaluating policy-driven waste reduction scenarios. These assumptions limit the model's ability to capture sudden demographic shocks or behavioural shifts. Therefore, the results should be interpreted as structural dynamic projections under stable demographic conditions rather than precise demographic forecasts.

Model Validation

Model validation was conducted to assess the structural consistency and behavioural reliability of the system dynamics model. The validation process combines quantitative historical comparison and structural verification procedures. First, the population subsystem was validated quantitatively by comparing simulated population growth with historical municipal demographic data for the period 2013–2023. The simulation results reproduce the historical growth trend with acceptable deviation, indicating that the demographic feedback structure adequately represents observed population dynamics. Second, the waste generation and financial subsystems were verified through structural validation procedures rather than independent statistical calibration.

Parameter values were derived from official municipal records, and dimensional consistency checks were performed to ensure logical coherence within the model structure. Behavioural plausibility testing was also conducted to confirm that simulated waste accumulation and expenditure trends respond logically to changes in population and policy scenarios. Because the primary objective of the model is to explore structural dynamic interactions and sustainability thresholds, the validation approach emphasizes behavioural reproduction and internal consistency rather than precise predictive calibration for all subsystems. Therefore, the model should be interpreted as structurally valid for analysing long-term dynamic interactions under defined assumptions, while acknowledging that full empirical calibration of all subsystems remains a limitation.

Population and Sample

This study employs a saturated sample technique, where all members of the population are included as a sample, encompassing all residents of Palangka Raya City, Central Kalimantan Province, from 2013 to 2022. The data integrated to build the model consists of population variables, Total Waste per Capita calculated at 0.4234 tons/Year/Head of Household (Muaja et al., 2025). The condition of the waste management infrastructure is reflected by the maximum capacity of the Bukit Tunggal Landfill of 613,200 tons, with an initial fill volume of 459,900 tons in 2022 (Adzkia et al., 2025).

Data Collection Techniques

Primary data is obtained through direct measurements in the field to determine the volume of existing waste and measure the actual capacity of the landfill. Meanwhile, secondary data were collected from official reports, including those from the Central Kalimantan Provincial BPS and the Directorate General of Cipta Karya, as well as various NGOs and relevant academic journals. This secondary data includes information on population dynamics, landfill size, waste management policies, and other statistical data required for the initialization of the model, including key parameters such as household waste generation corroborated by recent comparative studies and field studies, so that all data covering the population (population) and samples (saturated samples) can be included as inputs in the quantitative model.

Data Analysis Techniques

Data analysis was conducted using a dynamic system, beginning with the identification of key issues, including population size and waste production. A conceptual model is created using causal loop diagrams to visualize the interactions between variables. Quantitative models are formulated using equations that describe the change in variables over time. The collected data is then validated to ensure the accuracy of the model, using available secondary sources. This process enables the projection of future scenarios and the development of more effective waste management policies.

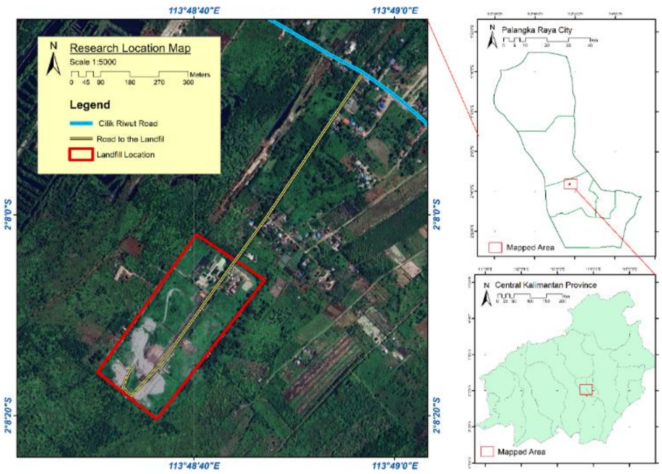

Figure 1. Bukit Tunggal Palangka Raya Landfill on Research Location Map

RESULT AND DISCUSSION

Identify Problems, Objectives, and Limitations

Waste management in Palangka Raya City is currently centred on addressing the operational sustainability of the Bukit Tunggal Landfill, the city's sole waste disposal facility. The landfill, which has been operating since 2000, is approaching capacity constraints. Of its seven landfill cells, only two remain active, while the remaining five are inactive until 2024. This condition indicates increasing pressure on the facility's remaining operational space. Population growth, projected at approximately 3.57% per year, contributes directly to the continuous rise in waste generation. In 2023, daily waste generation in Palangka Raya is estimated at 110–130 tons per day. Based on the simulation results, total annual waste generation is projected to increase progressively, reaching approximately 270,175 tons per year by 2034. This figure represents annual waste generation rather than daily output, and the unit has been standardised to ensure physical consistency across the analysis. To mitigate capacity limitations, the local government has expanded the landfill area by 4.4 hectares, with an estimated capacity of 440,000 m³ intended to support operations for approximately 10 years. However, model projections indicate that capacity expansion alone may only delay saturation under continued demographic growth, rather than structurally resolving long-term accumulation dynamics.

These findings suggest that landfill sustainability in Palangka Raya is structurally influenced by the interaction between population growth and waste generation. Under baseline conditions, without significant waste reduction measures, landfill capacity approaches critical limits within the simulation horizon. Figure 2 presents documentation of the increasing waste accumulation observed at the Bukit Tunggal Landfill, illustrating the physical manifestation of the projected capacity pressure. It is important to note that this study relies on secondary data and assumes that historical data are accurate and representative. The iterative nature of system dynamics modelling allows structural refinement based on feedback mechanisms and simulation outputs. Therefore, the results should be interpreted as structural dynamic projections under defined assumptions, rather than precise predictive forecasts. The model identifies the magnitude of intervention required to maintain landfill sustainability under current structural conditions; however, practical policy implementation would require further assessment of institutional capacity, financial feasibility, and socio-behavioural considerations beyond the scope of the present study.

Figure 2. Observed Waste Accumulation at the Bukit Tunggal Landfill, Palangka Raya.

Conceptualization of the Model

In this study, two key variables are examined: population dynamics and landfill capacity. The relationship between these two variables is depicted with the symbol (+) to indicate a positive influence and (-) to indicate a negative impact. The following is Figure 3, which is an overview of the causal loop diagram used in this study.

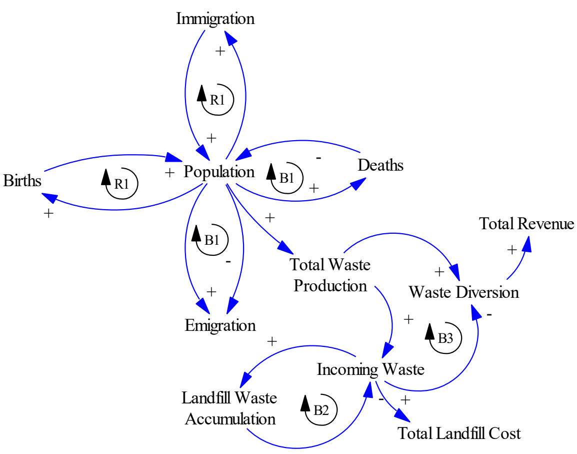

Figure 3. Casual Loop Diagram Model of Population Dynamics and Capacity of Palangka Raya City Landfill

Figure 3 above is an integrated Causal Loop Diagram (CLD) image that models the dynamic interactions between two main subsystems: population dynamics and waste management. The population subsystem acts as an exogenous driver controlled by two internal feedback mechanisms. First, a booster loop (R1: Population Growth), where the increase in the Population stock drives the rate of Birth/Immigration, which further contributes positively to the Population stock. Second, a balancing loop (B1: Population Balancer), where a larger stock of Population also increases the rate of Death/Emigration, which provides negative feedback to inhibit population growth. The Population stock variable of this subsystem serves as a crucial link, exhibiting a direct positive correlation with the rate of total waste production and acting as a key trigger for the waste management subsystem.

The waste management subsystem itself is characterized by the interaction of two opposing balancing loops that determine the fate of the waste. Loop B2 (Full Capacity) represents a systemic problem, where the flow of Incoming Waste progressively increases the Accumulation of Waste in the landfill. As this accumulation approaches the physical capacity of the landfill, it will provide negative feedback that inhibits the flow of incoming waste, further highlighting the capacity crisis. To counter this dynamic, the solution intervention loop (B3: Recycling Intervention) is designed proactively. This loop shifts a portion of Total Waste Production towards Waste Diversion (e.g., recycling and composting), which directly reduces (gives negative feedback) the rate at which Waste enters landfills, thereby slowing down the rate of accumulation. The final implications of this system are measured through economic outcomes. The positive correlation between Waste Diversion and Total Revenue assesses the effectiveness of loop B3. In contrast, the consequences of loop B2 are reflected in the positive relationship between Incoming Waste and Total Landfill Costs.

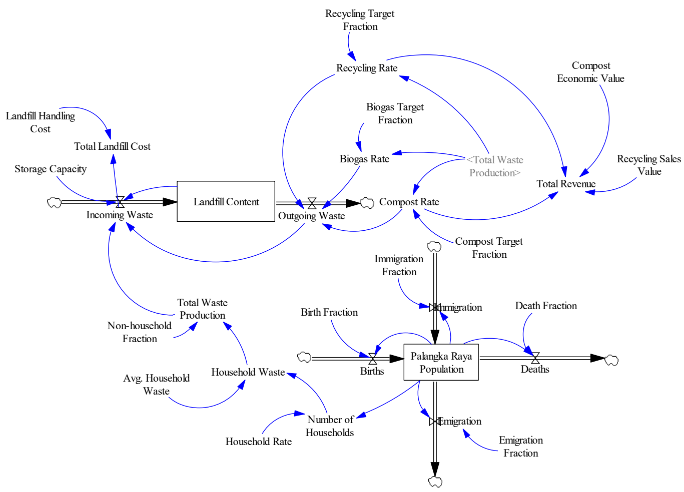

Figure 4. Stock Flow Diagram Model of Population Dynamics and Capacity of Landfill in Palangka Raya City

The Stock Flow Diagram (SFD) provides an overview of the future population growth in Palangka Raya city and its impact on waste production and landfill capacity, as shown in Figure 4. The above illustrates SFD for population projection simulation, additional waste production, maximum landfill capacity, and recycling rate.

Model Specifications

The dynamic system model developed in this study is structured into two crucial subsystems that demonstrate functional interdependence: the Palangka Raya City Population Dynamics Model and the Land Waste Management Dynamics Model. This grouping is based on the principle that changes in one domain inherently affect dynamics in the other, thus creating a feedback loop that is important for the overall sustainability of the system. The linkage between these two models is mediated by interconnected variables, where population growth serves as a key driver for increased waste generation, which in turn puts direct pressure on the capacity and technical lifespan of waste management facilities. Therefore, analyzing the two models in an integrated manner is crucial for formulating comprehensive and adaptable policies.

1. Palangka Raya City Population Dynamics Model

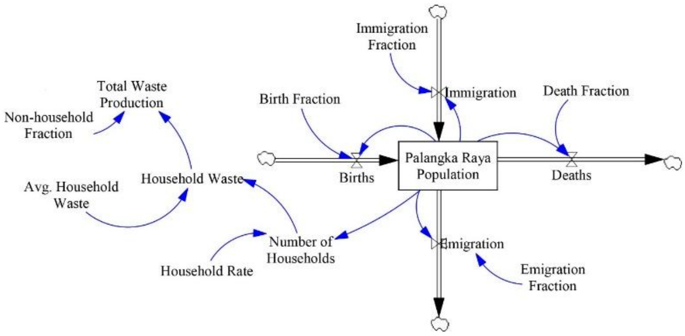

Figure 5. A Population Dynamics Model that causes waste generation

In Figure 5. The above equation represents the mathematical relationship between the Population Dynamics of Palangka Raya City in the Vensim Language. This model calculates population changes over time based on birth, death, immigration, and emigration rates.

Stock (Akumulasi): Palangka Raya Population. INTEG (Immigration+Births-Emigration-Deaths, 307165)
Flow (Inflow): Births. Birth Fraction*Palangka Raya Population
Flow (Inflow): Immigration. Immigration Fraction*Palangka Raya Population
Flow (Outflow): Deaths. Death Fraction*Palangka Raya Population
Flow (Outflow): Emigration. Emigration Fraction*Palangka Raya Population
Constanta: Birth Fraction. 0.025
Constanta: Death Fraction. 0.007
Constanta: Immigration Fraction. 0.01
Constanta: Emigration Fraction. 0.003

The Population Dynamics Model focuses on the projected population growth of Palangka Raya City over time, serving as a fundamental subsystem in the overall simulation. The core of this model is the Palangka Raya Population stock variable, which reflects the total accumulated population. Changes in the stock variable were driven by four main flow variables: inflows, including births and Immigration, and outflows, including deaths and Emigration. Each stream is calculated as a fixed percentage (fraction or constant) of the total population in the current year. For example, Births are computed using a Birth Fraction of 0.025 per year. This model assumes a constant demographic rate, allowing the simulation to project future population sizes accurately. The primary output of this demographic model, specifically the Palangka Raya Population, serves as a crucial input for the Waste Management Dynamics Model, as it informs the calculation of the Number of Households, which directly determines the level of Household Waste produced.

2. Waste Management Dynamics Model

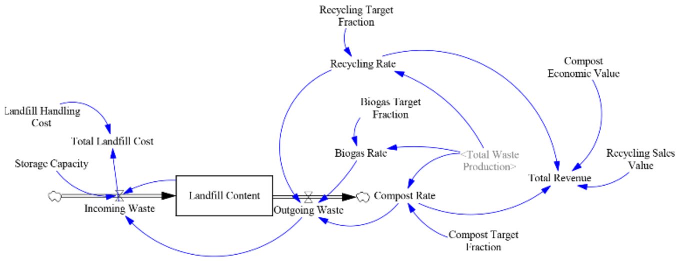

Figure 6. Integrated Waste Management Dynamics Model and Financial Analysis

Figure 6 above illustrates a mathematical equation from the Waste Management Dynamics Model. This model calculates the accumulation of waste in landfills, production rates, waste handling (3R), and financial impact. This model is driven by the output of Model 1 (Population).

Stock (Akumulasi) Landfill Content: INTEG (Incoming Waste-Outgoing Waste, 459900)
Stock (Akumulasi) Incoming Waste: IF THEN ELSE(Landfill Content<Storage Capacity,Total Waste Production-Outgoing Waste,0)
Flow (Outflow) Outgoing Waste: Biogas Rate+Recycling Rate+Compost Rate
Constanta Storage Capacity: 613200
Auxiliary Utama Total Waste Production : Household Waste/(1-"Non-household Fraction")
Auxiliary Household Waste: Number of Households*"Avg. Household Waste"
Link ke Model 1 Number of Households: Palangka Raya Population/Household Rate
Constanta Household Rate: 4*1
Constanta Avg. Household Waste: 1.16*365/1000

Constanta Non-household Fraction: 0.3
Biogas Rate: Total Waste Production*Biogas Target Fraction
Compost Rate: Total Waste Production*Compost Target Fraction
Recycling Rate: Total Waste Production*Recycling Target Fraction
Biogas Target Fraction: 0.0002
Compost Target Fraction: 0.001
Recycling Target Fraction: 0.003
Total Landfill Cost: Incoming Waste*Landfill Handling Cost
Total Revenue : Recycling Rate*Recycling Sales Value+Compost Rate*Compost Economic Value
Landfill Handling Cost: 150000
Compost Economic Value: 200000
Recycling Sales Value: 500000

The Waste Management Dynamics Model is a crucial subsystem that projects the burden on landfill infrastructure and assesses the effectiveness of waste reduction efforts. This model is centered on the Landfill Content stock variable, which reflects the total accumulation of waste buried in landfills. The change in this stock is controlled by the flow of Incoming Waste, which is the remainder of Total Waste Production after subtracting Outgoing Waste. The inflow of landfills has an absolute limit, namely Storage Capacity, which will stop the flow of waste if the capacity is exceeded. Outgoing Waste itself is an aggregation of the 3R-based waste processing rates, which include the Recycling Rate, Compost Rate, and Biogas Rate, all of which are driven by the set target fraction. In addition to the physical aspect, this model integrates financial analysis by calculating the Total Landfill Cost of incoming waste and comparing it with the Total Revenue generated from the sale of processed materials. Thus, this model serves as a diagnostic tool to evaluate the operational continuity of the landfill and the economic sustainability of the waste management system.

Model Simulation and Validation

The dynamic system model projects a stable and sustainable population growth in Palangka Raya City throughout the simulation period. Data show that the number of people is predicted to increase significantly from 244,454 in 2013 to 305,290 in 2022, and is expected to reach 400,566 by the end of the projection period in 2033. This increase is consistent, with approximately 7,000 to 8,000 people added per year over the last decade of the simulation (2022–2033). This constant growth rate reflects a higher rate of birth and immigration than the rate of death and emigration, guaranteeing that the population will continue to grow. This significant growth projection confirms the continued demographic pressures on urban infrastructure, particularly in terms of service provision and resource management, including an increased burden on the waste system in the future. Here is Figure 7. Below is a prediction of the population development in Palangka Raya City using Vensim.

Table Time Down

Time (Year)	"Palangka Raya Population" Runs: Current	Palangka Raya Population
2013		244454
2014		250565
2015		256829
2016		263250
2017		269831
2018		276577
2019		283492
2020		290579
2021		297843
2022		305290
2023		312922
2024		320745
2025		328763
2026		336983
2027		345407
2028		354042
2029		362893
2030		371966
2031		381265
2032		390796
2033		400566

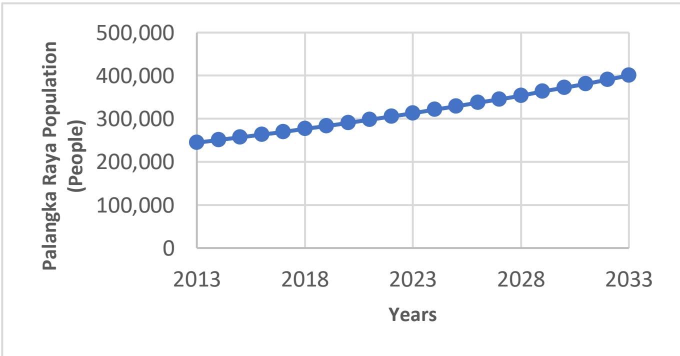

Figure 7. Population development in Palangka Raya City

Dynamic model validation is a crucial effort to ensure that the model being run accurately reflects the input logic of dynamic factors and accurately represents empirical conditions in the field. The quantitative validation test in this study was conducted through the calculation of Mean Absolute Percentage Error (MAPE), a key metric for assessing the accuracy of the projection model, particularly in population projections. The calculation process begins by calculating the Absolute Percentage Error (APE), which represents the absolute error between the projected data (simulated data from Vensim results) and the actual data from the BPS of Central Kalimantan Province. (BPS Provinsi Kalimantan Tengah, 2024). These errors are then converted to error percentages by dividing them based on the actual value per period. The MAPE value is obtained by accumulating and flattening all the absolute error percentages. The interpretation of MAPE results is beneficial for assessing the quality of the model:

a value below 10% indicates excellent projection accuracy, 10%-20% is considered good, 20%-50% is reasonable, and a value above 50% suggests poor accuracy. By providing measurable error measures, MAPE enables decision-makers to formulate policies based on accurate and reliable demographic projections. (Tofallis, 2013). An overview of the MAPE test results is presented in Table 1. Below.

Table 1
MAPE Test Results Comparison of Actual Data and Simulation Results

No	Period	Simulation	Current	APE
1	2013	244454	244454	0,00%
2	2014	250565	252105	0,61%
3	2015	256829	259865	1,17%
4	2016	263250	267757	1,68%
5	2017	269831	275667	2,12%
6	2018	276577	283612	2,48%
7	2019	283492	291667	2,80%
8	2020	290579	293457	0,98%
9	2021	297843	298954	0,37%
10	2022	305290	305907	0,20%
	MAPE (Average APE)	**1,49%**		

Validation of demographic models is a crucial step in ensuring the credibility of all simulations of dynamic systems. The accuracy test was conducted by calculating the Mean Absolute Percentage Error (MAPE), comparing the population projection model with historical actual data from the Central Kalimantan Provincial BPS for the period 2013-2022. The validation results showed a very low MAPE value of 1.49%. This value is well below the "excellent" accuracy threshold (below 10%), confirming that the model has high validity and accuracy to replicate population growth dynamics in the field. With the validated model, the simulation projects stable and sustainable population growth (supported by positive birth and immigration ratios), which in turn will be the primary driver for the Waste Management Dynamics Model. This increase in population directly contributes to the rise in Total Waste Production, a critical factor that will burden landfill capacity in the future.

Scenario Model

The simulation of policy scenarios in the Waste Management Dynamics Model is a crucial continuation of the validation test of the demographic model, which has been proven to have high accuracy (MAPE 1.49%). This scenario analysis is based on the critical finding that the waste management system of Palangka Raya City is in an emergency condition, where the basic scenario (Business As Usual / BAU) projects the Bukit Tunggal landfill to reach overload in 2018, a condition caused by a very minimal waste reduction fraction (only 0.42%). The primary objective of formulating this scenario is to assess the model's sensitivity to various policy interventions and determine the thresholds for landfill sustainability. The BAU scenario serves as a benchmark for inertia, aiming to quantify the critical consequences for the environment and costs if policies and budgets remain static. Furthermore, the Moderate (10% reduction) and Optimistic (35% reduction) scenarios were formulated to assess the effectiveness of the phased intervention. However, the simulation results confirm that the Optimistic Scenario is only able to postpone the crisis until 2026. Therefore, a Survival Scenario was identified that requires a much more extreme reduction commitment, reaching 85%, as a technical prerequisite to ensure that landfills can maintain their functions until the end of the simulation period in 2033. This comparative analysis enables decision-makers to quantify the policy gap between current efforts and the actual need to achieve system sustainability. An overview of the Waste Management Policy Model Scenario for Palangka Raya City (2013–2033) is presented in Table 2. Below.

Table 2
Critical Scenarios and Results of the Palangka Raya City Waste Management Policy Model (2013–2033)

No	Skenario	Total Reduction Fraction (Target)	Waste Entering the Landfill (Percentage)	Full Landfill Year (Overload)	Status of landfills in 2033
1	BAU	0,42%	99,58%	2018	Overload
2	Moderat	10,02%	89,98%	2018	Overload
3	Optimis	35,02%	64,98%	2026	Overload (Recently delayed)
4	Survival	85,02%	14,98%	Not Full	Available

Table 2. The above explains that the Waste Management Dynamics Model functions as a crucial subsystem that measures population pressure on the Bukit Tunggal Final Processing Site (TPA) facility, Palangka Raya City. Analysis of sensitivity scenarios shows that the system is in an urgent capacity crisis. The baseline scenario (Business As Usual / BAU), which assumes a minimal waste reduction fraction, projects that landfills will

be overloaded by 2018, indicating potential system failure in the short term. Further testing of the policy proves that even measurable interventions (such as 10% reductions) are insufficient to change this tipping point. Therefore, the sustainability of landfills until the end of the projection period (2033) requires the establishment of a Survival Scenario, which mathematically requires an extreme Total Reduction Factor (close to 85%). These results underscore that the solution to the Palangka Raya waste crisis does not lie in piecemeal efforts, but in radical policy transformation to significantly increase Outgoing Waste (3R processing) and exceed the rate of increase in Total Waste Production driven by population growth. Here is Figure 8. Below is an overview of how policy interventions affect the critical capacity of landfills over time.

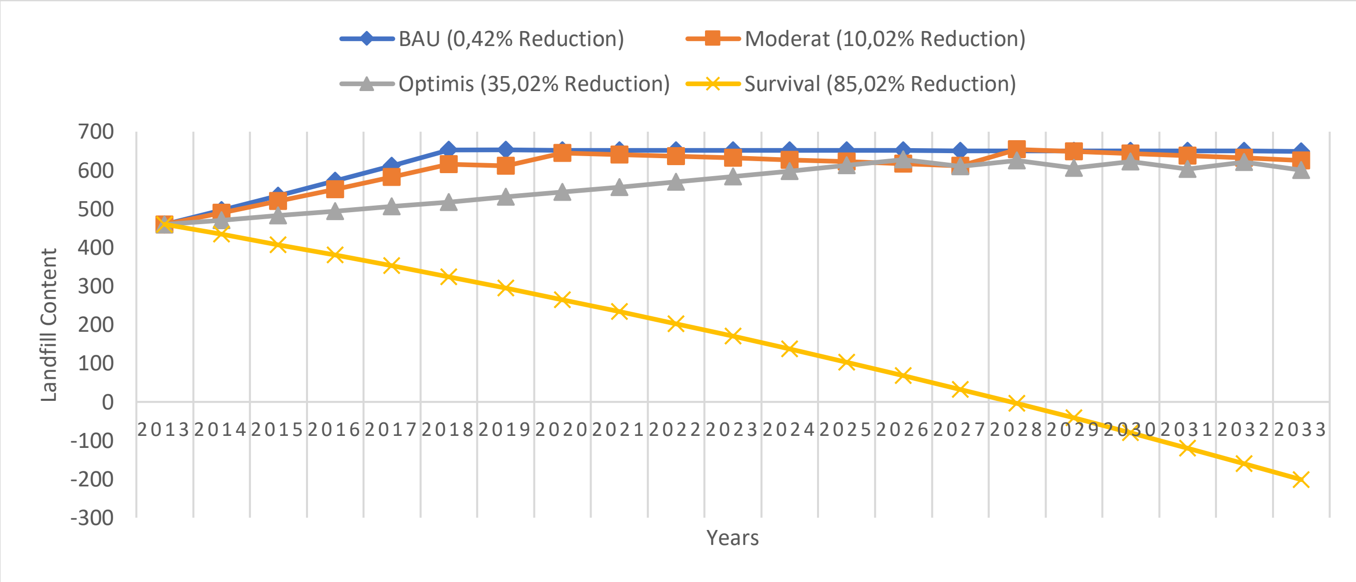

Figure 8. Waste Reduction Policy Interventions on Landfill Critical Capacity from Time to Time

Figure 8 above is the result of a comprehensive analysis of the Landfill Content Projection for the 2013–2033 period, which shows that the sustainability of the Bukit Tunggal Landfill infrastructure is extremely sensitive to waste reduction policy interventions. The simulation results are supported by the validity of the tested demographic model (MAPE 1.49%) and underscore the critical condition of the landfill. The baseline scenario (Business As Usual / BAU), with a reduction fraction of at least 0.42%, predicts system failures due to overload in 2018. More crucially, the Moderate Scenario, despite increasing the reduction to 10.02%, failed to delay the landfill crisis and still experienced overload in the same year. This failure clearly demonstrates that the initial waste load (459,900 tons) is too high, rendering policy efforts that are only incremental in nature unable to overcome the inertia of the rate of incoming waste.

To test the limits of intervention capability, the Optimistic Scenario (35.02% reduction) demonstrates significant success in time management, delaying the capacity crisis until 2026. This eight-year delay is a positive outcome of the policy; however, the model establishes that this delay is not a sustainable solution. Landfills remain full, indicating that this policy is only effective as a short-term strategy. To ensure that the landfill can maintain its function until the end of the 2033 simulation period and ensure that the remaining capacity is available, a Survival Scenario is needed. This scenario requires an extreme Total Reduction Faction, which is 85.02%. This figure represents a technical prerequisite for sustainability, signaling the need to divert almost all waste (organic and inorganic) from landfills through massive investment in 3R infrastructure. These projections serve as a policy foundation, clearly measuring the gap between the current efforts that have proven ineffective and the technical targets that are necessary to ensure the integrity of the city's landfill infrastructure. In Figure 9. Below is a Visualization of Total Revenue Projections (3R Revenue) with scenarios from 2013 to 2033.

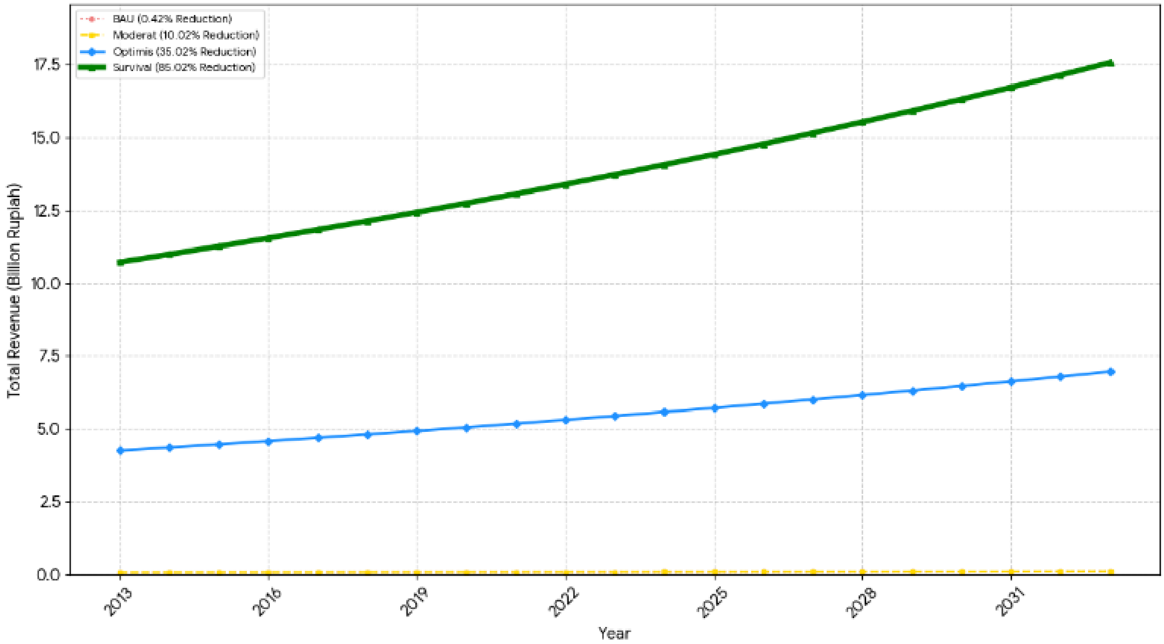

Figure 9. Comparison of 3R Revenue Trends and the Impact of Reduction Scenarios on the Financial System (2013–2033)

Figure 9 illustrates the visualization of the Total Revenue Projection (3R Revenue), which dramatically highlights the financial gap (Revenue Gap) that the City of Palangka Raya must overcome, confirming the economic mandate to achieve the high reduction target. On the chart, the BAU (0.42% Reduction) and Moderate (10.02% Reduction) lines are seen almost converging at the base (near zero). Numerically, BAU and Moderate revenues are in the range of tens of millions of Rupiah (≈70−100 Million in 2022), which makes them insignificant and visually depressed on a Y-axis scale that includes up to tens of billions of Rupiah. This invisible difference indicates that reduction efforts below 10% are still in the zone of total financial failure, as the revenue generated is insufficient to cover the landfill's operating costs.

In contrast, the Optimistic Scenario (35.02% reduction) and the Survival Scenario (85.02% reduction) produce substantially higher projected revenues measured in billion Rupiah. The Optimistic Scenario reaches approximately IDR 6.96 billion in 2033, indicating improved cost recovery potential within the structural assumptions of the model. The Survival Scenario yields the highest projected revenue, reaching approximately IDR 17.57 billion in 2033.These projections indicate that higher diversion rates are structurally associated with improved fiscal performance within the model framework. However, these results should not be interpreted as a guaranteed fiscal transformation mechanism. The financial projections are conditional upon constant price assumptions for compost and recyclable materials and do not incorporate market volatility, investment costs, infrastructure expansion requirements, or institutional capacity constraints.

Therefore, the findings represent structural economic implications under controlled modelling assumptions rather than a comprehensive market feasibility assessment. In addition to fiscal effects, higher diversion rates contribute to maintaining landfill capacity within the simulation horizon.

This study operates within several methodological boundaries. Demographic parameters (birth, death, and migration rates) and baseline per capita waste generation are treated as constant averages derived from historical data, allowing structural clarity but limiting sensitivity to demographic shocks or behavioural change. Model validation is partial: the population subsystem is quantitatively validated (MAPE 1.49%), while waste and financial subsystems are structurally verified rather than fully empirically calibrated. Community behaviour, institutional capacity, and governance dynamics are not endogenously modelled, and the identified 85% reduction threshold emerges from scenario-based simulation rather than formal mathematical optimisation. Accordingly, the findings should be interpreted as structural sustainability projections under defined assumptions rather than predictive or optimisation-based policy prescriptions.

CONCLUSIONS

This study develops a system dynamics model to examine the long-term interaction between population growth, waste generation, landfill accumulation, and financial implications in Palangka Raya during the 2013–2033 projection period. By modelling population growth as an endogenous subsystem and linking it structurally to waste generation and landfill capacity dynamics, the study provides an integrated analytical framework for evaluating landfill sustainability under sustained demographic pressure. The simulation results indicate that incremental waste reduction policies are insufficient to prevent landfill overload within the projection horizon. Scenario analysis suggests that substantially higher diversion rates are required to maintain landfill functionality over time. Within the structural assumptions of the model, the identified reduction threshold represents a technical condition for system sustainability rather than a definitive policy prescription.

The financial projections demonstrate that higher diversion rates are structurally associated with improved fiscal performance under constant price assumptions. However, these results do not account for market volatility, investment costs, institutional capacity, or behavioural feasibility. Therefore, the financial outcomes should be interpreted as indicative structural implications within the model framework rather than as guaranteed revenue forecasts.

The findings highlight the importance of analysing landfill sustainability as a dynamic threshold problem shaped by demographic growth and waste diversion performance. The conclusions apply within the limits of the model's assumptions, including constant demographic parameters, fixed price structures, and scenario-based simulation. Future research may extend this framework by incorporating behavioural factors, market dynamics, and formal optimisation techniques to provide a more comprehensive policy assessment.

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