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A dynamic system model for sustainable waste management in Bantaeng regency

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ABSTRACT

Waste is a critical issue in urban areas, including Bantaeng Regency, which, despite its reputation as a clean city, continues to face major challenges in its waste management system. Limitations in infrastructure, insufficient landfill (TPA) capacity, and suboptimal waste handling methods have led to 35.62% of waste remaining unmanaged in 2024. This study aims to develop a dynamic system model to evaluate the performance of the existing waste management system and simulate alternative policy scenarios to achieve sustainable waste governance. A quantitative-descriptive approach was employed using the Vensim software. Data were obtained through field observations, stakeholder interviews, and secondary sources from relevant agencies. The model includes variables such as population, waste generation, transport and processing capacities, and vehicle trip frequency. Model validation was conducted through mean comparison and error variance tests. Four scenarios were simulated: existing, moderate, optimistic, and Regional Waste Management Strategy. The results show that under the existing scenario, only about 35% of waste is properly managed, and if no intervention is implemented, unmanaged waste is projected to increase to 38% or approximately 12,000 tons per year. The moderate and optimistic scenarios improved performance, reaching 52% and 60% waste handling, respectively. The Jakstrada Regional Waste Management Strategy scenario yielded the most optimal results, with 71% of waste handled and 29.8% reduced, achieving the national target of 100% waste management. This study confirms the effectiveness of dynamic system modeling in evaluating data-driven policy decisions. The Jakstrada scenario is recommended as the most realistic and context-appropriate strategy to support sustainable waste management goals in Bantaeng regency.

Keywords: system dynamics, sustainable waste management, Bantaeng regency.

INTRODUCTION

The increasing rate of urbanization and population growth in Indonesia has intensified the challenges of solid waste management in many regions. Urban areas, especially in developing countries, face mounting pressure as waste generation continues to rise while infrastructure development and institutional capacity often lag behind. Globally, solid waste generation has reached 2.01 billion tons annually, and this figure is expected to increase with urban populations projected to grow to nearly 70% by 2050 (World Bank, 2020). The imbalance between urban expansion and the provision of public service infrastructure can lead to a decline in environmental quality due to the increasing volume and complexity of waste. According to a World Bank report, urban areas around the world generate approximately 2.01 billion tons of solid waste per year, and this figure is projected to continue rising in line with global urbanization forecasts, which are expected to reach 68–75% in the coming decades. Without appropriate waste management strategies, cities risk facing severe environmental degradation, health issues, and declining urban quality of life (Cao et al., 2017; Thamrin, 2022).

Waste management is not merely a technical issue but a multifaceted challenge that involves regulation, governance, finance, technology, and public participation (Rodić and Wilson, 2017). Indonesian Law No. 18 of 2008 defines waste management as a systematic, comprehensive, and sustainable activity that includes both waste reduction and handling. Local governments are required to formulate their Regional Policies and Strategies to address these responsibilities. However, in practice, many regions still struggle to meet national waste management targets due to fragmented implementation and limited data integration.

Bantaeng regency, located in south Sulawesi, is historically recognized for its clean urban environment, having received the Adipura Award consecutively from 2010 to 2018. Nonetheless, the population growth, which reached over 211,000 in 2023, has contributed to a steady increase in waste generation, amounting to 30,377.78 tons annually. According to the Ministry of Environment and Forestry (Kementerian Lingkungan Hidup dan Kehutanan (KLHK), 2023), the regency fell short of its 2023 targets—achieving only 25% waste reduction and 34.65% handling, well below the targets of 27% and 72% respectively. Alarmingly, nearly 40% of the total waste remains unmanaged.

This situation is compounded by the limited operational infrastructure, overburdened final disposal facilities, and the continued use of open dumping methods. Such practices not only threaten public health and ecosystems but also hinder the achievement of long-term sustainability goals. There is an urgent need for regional governments to adopt integrated and forward-looking approaches that are grounded in system-based thinking and long-term scenario evaluation.

Dynamic system modelling has emerged as an effective tool for addressing the complex interactions within urban waste systems. It allows planners to simulate changes over time, analyse feedback loops, and test policy scenarios under different assumptions. Previous applications of this method in the field of environmental infrastructure have proven successful in identifying optimal strategies and avoiding short-sighted policy decisions (Ding et al., 2018; Kala et al., 2022). Salim et al, (2024) highlighted the importance of system integration in accelerating plastic waste mitigation, emphasizing how modelling can support sustainable infrastructure decision-making.

Moreover, research has shown that predictive and circular economy approaches can enhance resource efficiency and waste minimization. Studies focusing on waste valorisation and eco-materials (Darhamsyah et al., 2025; Satria et al., 2025) have demonstrated how waste-based inputs can reduce environmental loads. These findings highlight the relevance of integrated system approaches not only in material innovation but also in institutional planning. The use of modelling to inform strategic waste management planning, therefore, offers both ecological and economic benefits.

This study aims to develop a dynamic system model that reflects the current waste management structure in Bantaeng regency and simulate alternative scenarios to identify the most effective strategies. Through this approach, the study contributes to formulating data-driven, adaptive, and sustainable waste policies at the regional level. The model is expected to assist local decision-makers in understanding system behaviour, projecting long-term outcomes, and prioritizing interventions that ensure both environmental and institutional sustainability.

METHODS

This study employs a quantitative descriptive method using a dynamic system modeling approach. The data used to develop the model were collected through direct observation and interviews with relevant stakeholders, as well as secondary data obtained from government agencies and previous studies. Demographic and economic data were sourced from the Central Statistics Agency, while data related to waste management including waste generation, sources, composition, and historical records of waste processing facilities and final disposal sites—were obtained from the Environmental Agency (DLH) and the Ministry of Environment.

The policy analysis method applied in this study is model simulation using Vensim 10.2.1 software. Model development began with the conceptualization of the waste management system in the form of a causal loop diagram, which was then translated into a stock and flow diagram structure.

The developed model was evaluated and validated by comparing simulation results with historical data. Validation was conducted using two evaluation metrics: mean comparison (E1) and error variance (E2). The model is considered valid if the value of E1 is less than 0.5 and E2 is less than or equal to 30%.

Once validated, the model was used to formulate several alternative policy scenarios aimed at improving the performance of the waste management system. These scenarios were simulated using the dynamic system model, and the results were analyzed to determine the most effective strategy to be recommended for waste management policy in Bantaeng regency. The validation was determined based on Equation 1 and Equation 2.

$$E1 = \left|\frac{S - A}{A}\right| \times 100\% \quad (1)$$

where: S – mean value of simulation results, A – mean value of actual data.

$$E2 = \left|\frac{Ss - Sa}{Sa}\right| \times 100\% \quad (2)$$

where: Ss – standard deviation of simulation results, Sa – Standard deviation of actual data.

RESULTS AND DISCUSSION

General overview of the study area

Bantaeng regency is located approximately 120 kilometers south of Makassar City, south Sulawesi, with a total land area of 390.97 km². Administratively, the regency is divided into eight sub-districts and shares borders with Jeneponto, Bulukumba, and Gowa regencies, as well as the Flores Sea to the south. According to 2024 data, the population of Bantaeng regency reached 217,267 inhabitants, with an average population density of 556 people per square kilometer. The most densely populated sub-district is Bantaeng sub-district (1,455 people/km²), followed by Bissappu and Pa'jukukang.

Existing waste management conditions in Bantaeng regency

Waste management in Bantaeng regency encompasses two main aspects: waste handling (including sorting, collection, transportation, processing, and final disposal) and waste reduction (including waste generation limitation, recycling, and reuse). These activities are carried out by the local government, communities, and the informal sector through various facilities such as temporary waste storage sites (TPS), composting houses, waste banks, and TPS3R (reduce, reuse, recycle processing sites). Data on existing conditions were obtained from the DLH, BPS, and field surveys.

The volume of waste has increased annually in line with population growth. In 2024, the total waste generation reached 30,896.96 tons/year. The composition of waste is dominated by food waste (30.13%), followed by wood and branches (27.5%), as well as plastic and paper waste. The trend of increasing waste generation is illustrated in Figure 1.

Waste management in Bantaeng regency encompasses two main aspects: handling (including sorting, collection, transportation, processing, and final disposal) and reduction (including waste generation limitation, recycling, and reuse). These activities are carried out by the local government, communities, and the informal sector through various facilities such as temporary TPS, composting houses, waste banks, and TPS3R (reduce, reuse, recycle processing sites). Existing condition data were obtained from the DLH, BPS, and field surveys.

Waste is collected directly from the source to the Bonto Salluang landfill using dump trucks, arm roll trucks, and motor tricycles. The average volume of waste delivered to the landfill is approximately 27.49 tons per day. However, waste sorting is mostly performed by limited community groups such as waste banks and schools. A major constraint in the system is the condition of the transport fleet, with many vehicles being either damaged or unfit for operation, thus reducing transportation efficiency.

Several critical issues remain, including limited transportation capacity, insufficient processing facilities, and landfill overcapacity. According to National Waste Management Information System data (2024), approximately 35.67% of waste remains unmanaged. Furthermore, the informal sector plays a dominant role in waste reduction efforts (65%), while the potential of structured waste management approaches – such as waste banks, 3R waste treatment site, composting site, small composting, and BSF processing methods – has not yet been fully optimized.

Dynamic system model of waste management

System identification is a crucial initial step in constructing a dynamic waste management model, as it aims to recognize key variables that

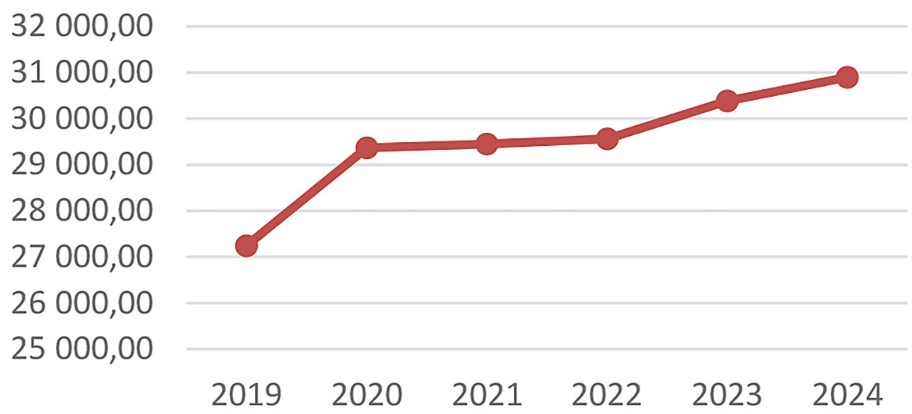


Figure 1. Waste production

influence the overall system behavior. The dynamic system model is developed using a causal loop diagram to map cause-and-effect relationships among variables. This diagram illustrates both positive and negative feedback loops that affect system performance. For instance, an increase in population leads to higher waste generation (positive loop), whereas the enhancement of facilities such as 3R Waste Treatment Site or waste banks contributes to reducing unmanaged waste volumes (negative loop). Furthermore, factors such as community participation, fleet capacity, and collection frequency also play a role in either reinforcing or balancing the waste management system. The causal loop diagram is presented in Figure 2.

The development of the stock and flow diagram serves to quantitatively describe the system by incorporating elements of time and accumulation. In this model, variables are categorized into stocks (e.g., population size, waste generation) and flows (e.g., daily waste collection and treatment). Additionally, auxiliary variables and parameters are included to support model

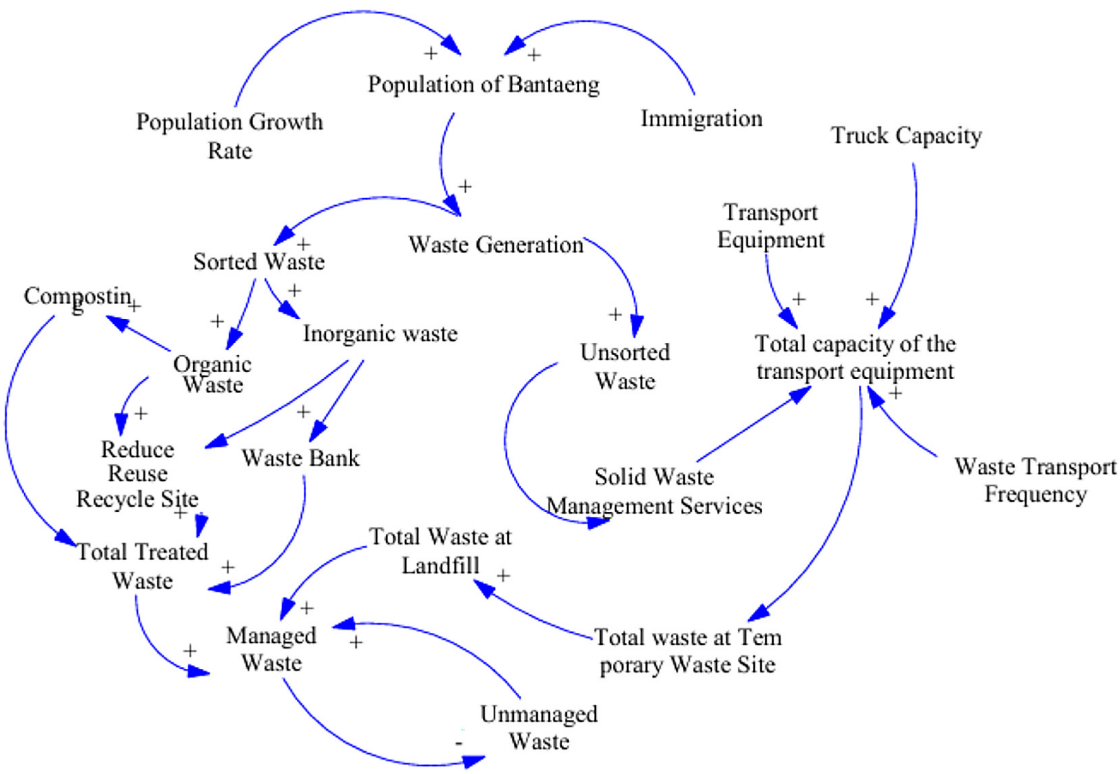


Figure 2. Causal loop diagram

calculations. The waste treatment pathways involve waste banks, 3R Waste Treatment Sites, composting, and informal collectors, while the residual waste is directed to the final disposal site (landfill) based on the available transport capacity and collection frequency (ritation). This model is constructed using empirical data and is simulated to evaluate the effectiveness of policy interventions. The list of variables is presented in Table 1, and the baseline (existing) model used in this study is illustrated in Figure 3.

Model validation

Validation is a process used to determine whether a model accurately conceptualizes and represents a real-world system (Hoover and Perry, 1989). It is the process of assessing the accuracy of a simulation model based on an acceptable representation of reality (Kala et al., 2022) The purpose is to evaluate whether the developed model appropriately reflects the actual system. In this study, model validation was carried out using mean comparison and error variance methods. The validation was performed using historical data from Bantaeng regency, including population data and municipal solid waste generation from 2020 to 2024 (Table 2).

Validation testing was conducted using mean comparison and error variance to assess the level of accuracy between the simulation results and actual data. The following presents the calculation of mean comparison and error variance.

$$E1\ (Mean\ Comparison) =$$

$$= \left|\frac{204{,}594 - 204{,}578}{204{,}578}\right| \times 100\%$$

$$E1\ (Mean\ Comparison) = 0.0078$$

Based on the Mean comparison results, the E1 value falls below the 5% threshold, indicating that the average simulation output is valid and closely approximates the mean of the actual data.

$$E2\ (Mean\ Comparison) =$$

$$= \left|\frac{7676 - 8295}{8295}\right| \times 100\%$$

$$E1\ (Mean\ Comparison) = 8.064\%$$

Existing scenario simulation model

The existing or business as usual (BAU) scenario illustrates the current condition of the municipal solid waste management system in Bantaeng regency, without any new policy interventions or additional facilities. The simulation was conducted for the period of 2025–2035 using the last five years of historical data. The results indicate a consistent increase in waste generation in line with population growth, while the percentages of waste reduction and waste handling remain stagnant at approximately 26% and 34%, respectively. The proportion of unmanaged waste is projected to increase to 42.5% by 2035, potentially exacerbating the burden on the already overcapacity final disposal site (TPA). The simulation results for this scenario are presented in Table 3.

Observational findings indicate that by 2035, approximately 42.49% of waste in Bantaeng regency is projected to remain unmanaged, primarily due to the limited capacity of waste transportation fleets. Furthermore, over 50% of the waste composition consists of organic waste, with 30% comprising food residues, highlighting a substantial potential for waste processing. In light of these conditions, the development

Table 1. Model variable

Componen	Variable list
Input	Population growth rate, Mortality rate, Immigration, Emigration, Waste generation per capita, Fractional increase in waste banks, Fractional increase in 3R Waste Treatment Sites, Fractional increase in composting facilities, Fractional increase in composting units, Processing capacity per unit (waste bank, 3R Waste Treatment Site, composting house, small-scale composting), Waste bank processing efficiency, 3R Waste Treatment Site processing efficiency, Composting house processing efficiency, Informal collector processing efficiency, Transportation efficiency, Number of vehicles (dump trucks, arm roll trucks, motorcycle trailers)
Output	Total waste generation, Total treated waste, Waste treated through waste banks, Waste treated through 3R Waste Treatment Sites, Waste treated through composting houses, Waste treated through unit composting, Total waste handled, Waste transported to landfill, Waste delivered to informal collectors, Total unprocessed residual waste, Percentage of unhandled waste, Percentage of waste reduction, Percentage of waste treatment, Percentage of untreated waste

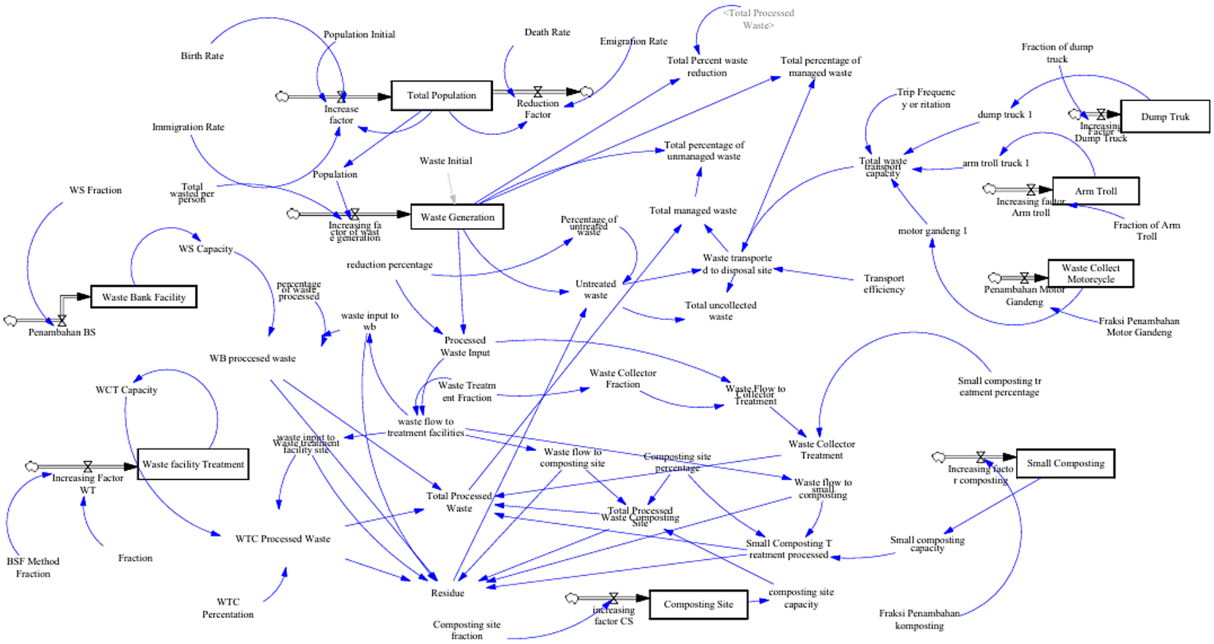


Figure 3. Dynamic model of Bantaeng waste management

Table 2. Validation using population number

Population (People/Year)		
Year	Actual	Simulation
2020	196,716	196,716
2021	197,886	197,920
2022	199,399	199,132
2023	211,623	211,701
2024	217,267	217,502
Mean	204,578	204,594

of 3R waste treatment sites based on the BSF method is considered a strategic solution, given its effectiveness in processing organic waste rapidly, efficiently, and with economic value. The scenario formulation in this study is grounded in empirical data and accounts for both the existing conditions and the potential for waste processing technology development. Prior to simulation, several fundamental assumptions were established as the basis for dynamic system modeling, as presented in Table 4.

Scenario simulation comparison

Simulation results in Figure 4, indicate that the Regional Waste Management Strategy scenario achieves the highest waste handling rate at 71%, followed by the optimistic scenario (60%) and the moderate scenario (52%). Compared to the existing scenario, which only reaches 35%, this improvement highlights the effectiveness of interventions in technical and operational aspects, particularly the addition of transport vehicles and collection frequency (ritation). In the moderate scenario, although ritation is increased, a significant portion of waste remains uncollected due to the limited number of available transport units. This performance underscores the critical importance of balancing fleet size, carrying capacity, and trip frequency, all of which substantially influence the efficiency of waste management systems (Bányai et al., 2019; Setyoadi, 2018).

Regarding waste reduction, the optimistic scenario shows the highest performance due to the expansion of treatment facilities, including 3R Waste Treatment Sites and waste banks. Meanwhile, both the Regional Waste Management Strategy and moderate scenarios demonstrate comparable outcomes, based on the assumption of enhanced efficiency in existing facilities up to 100%. Field observations reveal that most current waste reduction is conducted by informal recyclers, while there remains substantial potential for scaling up waste banks and 3R waste treatment sites. This is particularly crucial considering that more than 50% of waste generated in Bantaeng regency is organic waste, with the largest fraction originating from food scraps.

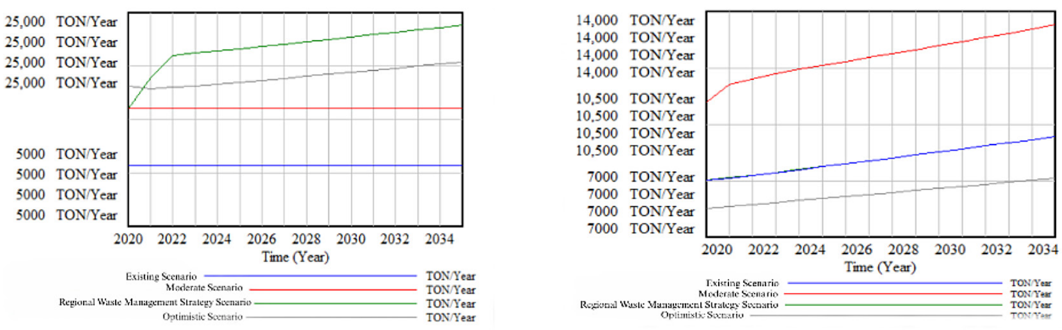
Based on the simulation results and comprehensive evaluation, the Regional Waste

Table 3. Existing simulation result

No	Year	Waste generation (Ton/year)	Waste reduction (%)	Waste managed (%)	Unmanaged waste (%)
1	2024	30.490	26.66	35.07	38.25
2	2025	30.794	26.60	34.72	38.67
3	2026	31.101	26.53	34.38	39.07
4	2027	31.409	26.47	34.04	39.47
5	2028	31.719	26.41	33.71	39.87
6	2029	32.031	26.35	33.38	40.26
7	2030	32.345	26.29	33.06	40.64
8	2031	32.661	26.23	32.74	41.02
9	2032	32.979	26.17	32.42	41.39
10	2033	33.298	26.11	32.11	41.76
11	2034	33.620	26.05	31.81	42.13
12	2035	33.944	26.00	31.50	42.49

Table 4. Waste management scenario

Variable	Waste management scenario		
	Moderate scenario	Optimistic scenario	Regional waste management strategy scenario
Increase in waste bank efficiency	80	100	100
Increase in small-scale composting efficiency	100	100	100
Increase in 3R waste treatment site efficiency	100	100	100
Addition of 3R waste treatment site (black soldier fly)	-	1	2
Increase in transport frequency (trips per day)	3	4	3
Addition of waste transport fleet	-	2 DT, 2 MT	2 DT, 2 AT, 2 MT
Percentage of waste reduction	30%	40%	30%
Percentage of waste managed	50%	60%	70%
Percentage of unmanaged waste	≤20%	0	0



(a) (b)

Figure 4. (a) percentage of managed waste comparison, (b) percentage of waste reduction comparison

Management Strategy is selected as the most realistic and effective policy strategy. In addition to meeting the national target (30% reduction and 70% handling), this scenario addresses existing constraints while proposing phased interventions. The addition of 2 dump trucks, 2 arm roll trucks, 2 motorcycle haulers, and 1 unit of 3R waste treatment site using BSF technology are key components in achieving the desired outcomes.

CONCLUSIONS

This study demonstrates that the waste management system in Bantaeng regency continues to face critical challenges, particularly in terms of treatment facility capacity and transportation fleet limitations. The dynamic system model developed in this research successfully mapped the interrelationships among key variables and was validated against historical data. Simulation results indicate that the existing scenario manages only approximately 35% of the total waste, with 26.8% treated and around 36% remaining unhandled. Comparative analysis of the scenarios reveals that the Regional Waste Management Strategy scenario performs the best, achieving 71% in waste handling and 29.8% in waste reduction, aligning with the national targets. Among all scenarios, the Regional Waste Management Strategy is the most optimal and contextually appropriate. The implementation of this scenario presents Bantaeng regency with the opportunity to establish a sustainable and adaptive waste management system that can effectively respond to future environmental challenges.

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