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Research Article

Policy Model for Composting and Waste-to-Energy (WTE) Technology in Lubuklinggau City

Jatmiko Yogopriyatno[1]*, Abdul Aziz Zulhakim[1], Mohammad Nur Dita Nugroho[2], Alexsander[3], and Desita Rahayu[4]

[1]Department of Public Administration, Faculty of Social and Political Sciences, Universitas Bengkulu, Bengkulu, Indonesia
[2]Department of Architecture, Faculty of Engineering, Universitas Bengkulu, Bengkulu, Indonesia
[3]Department of Public Administration, Faculty of Social and Political Sciences, Prof Dr Hazairin University, Bengkulu, Indonesia
[4]Department of Public Administration, Faculty of Social and Political Sciences, Sekolah Tinggi Ilmu Administrasi Bengkulu, Bengkulu, Indonesia

ORCID:
Jatmiko Yogopriyatno: https://orcid.org/0009-0005-2617-3086

Abstract.
This research developed a policy model for waste reduction in Lubuklinggau City through composting and waste-to-energy (WTE) technology. Using the system dynamics method, the research simulated various policy scenarios over 10 years. Results show that combining composting (40% participation) and WTE can reduce waste generation by 60% and generate 5,960 MWh/day of electrical energy. This scenario also reduces waste management costs by 8.3% compared to existing conditions. This model offers an integrative decision-making framework for local governments to optimize sustainable waste management by considering environmental, economic, and social aspects.

Keywords: composting, dynamic system, public policy, waste management, waste to energy

Corresponding Author: Jatmiko Yogopriyatno; email: jyogop@unib.ac.id

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1. Introduction

Urban waste management has become a serious challenge for cities in developing countries, including Indonesia. Rapid population growth and economic activity have increased waste generation volume that needs to be matched by adequate management capacity [1]. Lubuklinggau City, a developing city in South Sumatra Province, faces similar problems. Data from the Lubuklinggau City Environmental Agency shows that daily waste generation reached 187 tons in 2022, but only 5% was successfully recycled [2]; [3].

Various studies have assessed the effectiveness of integrated waste management approaches. Composting has been proven effective in reducing the volume of organic waste by up to 50% [4]. Meanwhile, waste-to-energy (WTE) technologies such as incineration and gasification can convert waste into electricity while reducing waste volume by up to 90% [5]; [6]; [7]. However, implementing these technologies requires large investments and is often constrained by socio-cultural issues [8]

Most previous studies have focused on separately analysing waste management technologies' techno-economic or environmental impacts. For example, assessed the potential of recycling in Bolivia [9], while [10] evaluated the performance of key urban waste management indicators in Spain. There are still studies that still need to integrate various waste management approaches in a comprehensive policy model, especially in the context of medium-sized cities in developing countries.

This research aims to develop a waste reduction policy model integrating composting approaches and WTE technology in Lubuklinggau City. Using a dynamic system approach [11], this research simulates various policy scenarios to optimise sustainable waste management. The developed model is expected to be a decision-making framework for local governments to formulate effective waste management policies.

The novelty of this research lies in integrating the household-scale composting approach with city-scale WTE technology in a comprehensive policy model. This model considers sociocultural factors such as community participation. In addition, using actual Lubuklinggau City data and long-term simulations (10 years) provides a more realistic picture of the dynamics of the waste management system in a medium-sized city.

2. Methods

This research uses a dynamic system approach to model and simulate waste management policies in Lubuklinggau City [11] Primary data were obtained through stakeholder interviews and field observations [12]; [13] [14], while secondary data were sourced from the Environmental Agency report and Lubuklinggau City BPS. A dynamic system model was developed using Vensim PLE software. Key variables modelled include population, waste generation rate, transportation capacity, composting participation rate, WTE facility capacity, operational costs, and compost and electricity sales revenue. The model was validated using structural and behavioural tests.

Six policy scenarios were simulated over 10 years (2024-2034):

1. Status quo (8% sorting)

2. Household-scale composting (40% participation)

3. Intensive composting (80% participation)

4. Small-scale WTE + composting (8%)

5. Medium-scale WTE + composting (40%)

6. Large-scale WTE + intensive composting (80%)

The performance of each scenario was evaluated based on indicators of waste generation reduction, energy production, management costs, and greenhouse gas emissions.

3. Results and Discussion

3.1. Results

Model simulation results show that the combination of composting and WTE technology has the potential to significantly reduce waste generation and generate renewable energy in Lubuklinggau City. Table 1 summarizes the performance of each scenario at the end of the simulation period (year 2034).

TABLE 1: Simulation Results of Lubuklinggau City Waste Management Policy Scenarios (2034).

Scenario	Segregation Rate (%)	aste Reduction from Landfill (%)	Energy Production (MWh/day)	Management Cost (IDR Billion/year)
1	8	5	0	1,000
2	40	30	0	0,900
3	80	50	0	0,850
4	8	40	3,980	1,200
5	40	60	5,960	1,100
6	80	70	7,950	0,800

Source: Research Results, 2024.

Scenario 1 (status quo) can only reduce 5% of waste generation without producing energy. On the other hand, Scenario 6 (large-scale WTE + intensive composting) provides the best results, with 70% waste reduction and 7,950 MWh/day energy production. However, this scenario requires a very high level of community participation (80%), which is difficult to achieve in the short term.

Scenario 5 (medium-scale WTE + 40% composting) offers a more realistic balance. With a moderate level of participation, this scenario can reduce 60% of waste generation and generate 5,960 MWh/day of energy. The management cost is slightly higher than the status quo but still lower than Scenario 4, which relies on small-scale WTE.

Table 2: Projected Waste Generation Reduction 2024-2034 (in %).

Year	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
2024	5	10	15	5	10	15
2025	5	15	25	10	20	30
2026	5	20	35	20	35	45
2027	5	25	40	30	45	55
2028	5	27	45	35	50	60
2029	5	28	47	37	53	63
2030	5	29	48	38	55	65
2031	5	29	49	39	57	67
2032	5	30	49	39	58	68
2033	5	30	50	40	59	69
2034	5	30	50	40	60	70

Source: Research Results, 2024.

Table 2 shows that scenarios relying on composting (2 and 3) experience a gradual increase in waste generation reduction as community participation increases. The scenarios with WTE technology (4, 5, and 6) show a more significant increase after the facility is fully operational in year 3 (2026). Table 3 shows that although the scenarios with WTE (4, 5, and 6) require a large initial investment, they show a downward trend in long-term costs. Scenario 6 (large-scale WTE + intensive composting) shows the most significant cost reduction, reaching IDR 0.800 billion by the end of the simulation period. Scenario 5 also shows a similar trend, albeit with a smaller magnitude.

These results strengthen the argument that combining household-scale composting and medium-scale WTE technology (Scenario 5) is a promising policy option for Lubuklinggau City. This scenario balances a significant reduction in waste generation (60% by 2034) and a reduction in long-term management costs (from IDR 1,600 billion in 2024 to IDR 1,100 billion in 2034). The following table compares the projected waste management costs for each scenario:

Implementing this scenario requires considerable initial investment, especially for the construction of WTE facilities and community education programs. However, in the long run, the combination of waste volume reduction and electricity and compost sales revenue can offset most of the operational costs.

TABLE 3: Projected Waste Management Cost 2024-2034 (in Billion Rupiah).

Year	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
2024	1.000	1.050	1.100	1.500	1.600	1.700
2025	1.020	1.030	1.050	1.450	1.500	1.550
2026	1.040	1.010	1.000	1.400	1.400	1.400
2027	1.060	0.990	0.950	1.350	1.300	1.250
2028	1.080	0.970	0.920	1.300	1.200	1.100
2029	1.100	0.950	0.900	1.250	1.150	1.000
2030	1.120	0.940	0.880	1.230	1.130	0.950
2031	1.140	0.930	0.870	1.220	1.120	0.900
2032	1.160	0.920	0.860	1.210	1.110	0.850
2033	1.180	0.910	0.855	1.205	1.105	0.825
2034	1.200	0.900	0.850	1.200	1.100	0.800

Source: Research Results, 2024.

The main challenge in implementing this scenario is to increase community participation in waste segregation and composting to 40%. This requires effective communication, education strategies, and the right incentive system. Some strategies that can be considered include:

1. Intensive and sustainable education campaigns through various media.

2. Pilot programs at the RT/RW level to demonstrate the benefits of composting.

3. Economic incentives include reduced waste levies for households actively sorting and composting.

4. Cooperation with schools to educate students about sustainable waste management.

From a sustainability perspective, this scenario offers environmental benefits by reducing greenhouse gas emissions from waste decomposition in landfills. However, a more in-depth lifecycle assessment (LCA) analysis must be conducted to ensure the balance of net emissions, including emissions from the WTE facility.

The model developed in this study offers an integrative decision-making framework for local governments. By considering various technical, economic, and social factors, the model enables a comprehensive analysis of the impacts of waste management policies. However, it should be noted that the accuracy of the model projections depends on the quality of the input data and assumptions used. Therefore, regular data updating and model validation with actual conditions are crucial to ensure the relevance and accuracy of policy recommendations.

In addition, the social acceptance aspect of WTE technology also needs to be well anticipated. Experience in several regions has shown potential for community resistance to the construction of WTE facilities, especially related to concerns about environmental and health impacts [8] Therefore, the planning and implementation process should involve active community participation.

Some strategies to increase social acceptance that can be considered include:

1. Intensive socialisation of WTE technology, including its benefits and handling of environmental impacts.

2. Comparative studies of well-operated WTE facilities in other regions.

3. Involvement of local community leaders and academics in the planning process.

4. Transparency in the decision-making process and operational monitoring.

5. Provision of compensation or direct benefits to communities around the location of WTE facilities.

The implementation of this scenario requires strong policy support in terms of regulation. The Lubuklinggau city government needs to develop or revise local regulations related to waste management that accommodate the composting approach and WTE technology. This regulation should cover technical, economic, and social aspects, including operational standards, financing schemes, and incentive and sanction mechanisms.

Table 4 below shows the projected energy production from WTE facilities for Scenarios 4, 5, and 6:

Table 4 shows that energy production increases significantly over time for all WTE scenarios. Scenario 6, with large-scale WTE, can produce the most energy, reaching 7,950 MWh/day in 2034. However, Scenario 5 with medium-scale WTE also shows a steady increase in energy production, reaching 5,960 MWh/day by the end of the simulation period.

This energy production has the potential to provide multiple benefits. In addition to reducing dependence on fossil energy sources, electricity sales to the PLN grid can be an additional source of revenue to cover the operational costs of waste management. However, further studies are needed regarding the technical aspects of interconnection with the existing electricity network and cooperation schemes with PLN.

Table 4: Projected Energy Production from WTE Facilities 2026-2034 (MWh/day).

Year	Scenario 4	Scenario 5	Scenario 6
2026	2,000	3,000	4,000
2027	2,500	3,750	5,000
2028	3,000	4,500	6,000
2029	3,250	4,875	6,500
2030	3,500	5,250	7,000
2031	3,650	5,475	7,300
2032	3,800	5,700	7,600
2033	3,900	5,850	7,800
2034	3,980	5,960	7,950

Source: Research Results, 2024.

In addition, it is necessary to consider the potential utilisation of waste heat from WTE facilities for other purposes, such as communal water heating or industrial processes around the site. This can improve the overall efficiency of energy utilisation.

From a long-term sustainability perspective, it is important to consider the flexibility of the chosen WTE technology. As the waste composition may change over time due to changes in consumption patterns and waste reduction policies, the selected technology should be able to adapt to changes in waste input characteristics.

The model developed in this study has several limitations that need to be considered:

1. The assumption of constant community participation throughout the simulation period may not be realistic. A more detailed submodel is needed to model the dynamics of changes in community behaviour.

2. The model has not considered the impact of climate change on waste composition and volume, which may affect the long-term performance of the waste management system.

3. The model does not integrate spatial aspects, such as the optimal location of WTE facilities and waste transportation routes.

4. Uncertainties related to the future development of WTE technology have not been considered in the long-term projection.

1. To overcome these limitations, further research can focus on:

2. For example, developing a more sophisticated submodel of community behaviour using an agent-based modelling approach.

3. Integration of climate change models to predict long-term changes in waste characteristics.

4. Incorporation of spatial analysis, e.g., GIS, for optimising facility locations and transportation routes.

5. Scenario analysis that considers the future development of WTE technology.

More comprehensive sensitivity analysis is needed to test the robustness of the model in terms of changes in various key parameters.

Despite these limitations, the model developed in this study offers a comprehensive analytical framework to support decision-making in urban waste management. With further refinement, this model has the potential to become a powerful tool for local governments to formulate sustainable waste management policies.

Implementing the proposed waste reduction policy model also needs to consider institutional and governance aspects. Close coordination between various government agencies, such as the Environmental Agency, Public Works Agency, and Bappeda, is required to ensure synergy in planning and implementation. In addition, partnerships with the private sector and civil society organizations also need to be developed to optimize existing resources and capacities.

The following table shows the projected greenhouse gas (GHG) emission reductions from each scenario:

Table 5: Projected GHG Emission Reductions 2024-2034 (in tons of CO2 equivalent).

Year	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
2024	500	1,000	1,500	500	1,000	1,500
2025	525	1,575	2,625	1,050	2,100	3,150
2026	551	2,204	3,859	2,205	3,885	4,958
2027	579	2,893	4,631	3,473	5,209	6,366
2028	608	3,297	5,506	4,271	6,125	7,350
2029	638	3,594	6,039	4,744	6,803	8,108
2030	670	3,918	6,461	5,121	7,389	8,775
2031	704	4,110	6,939	5,507	8,041	9,509
2032	739	4,315	7,286	5,782	8,603	10,064
2033	776	4,531	7,650	6,071	9,033	10,567
2034	815	4,757	8,033	6,375	9,485	11,095

Source: Research Results, 2024.

Table 5 shows that all scenarios can reduce GHG emissions compared to the status quo (Scenario 1). Scenario 6 shows the largest potential emission reduction, reaching 11,095 tons of CO2 equivalent in 2034. However, Scenario 5 also shows significant emission reductions of 9,485 tons of CO2 equivalent, a good balance between environmental benefits and implementation feasibility.

It should be noted that these projections do not consider potential emissions from the operation of the WTE facility. Therefore, a more comprehensive lifecycle assessment (LCA) analysis is required to ascertain the net benefit of emission reduction from implementing WTE technology.

The financing aspect is also a crucial factor in the implementation of the new waste management policy. The following table shows the projected investment needs for each scenario:

Table 6: Projected Investment Needs 2024-2026 (in Billion Rupiah).

Component	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
WTE Facility	0	0	0	500	750	1,000
Composting Equipment	0	50	100	25	50	100
Transportation Fleet	50	75	100	75	100	125
Community Education Program	10	25	50	25	50	75
Total	60	150	250	625	950	1,300

Source: Research Results, 2024.

Table 6 shows that the scenarios with WTE technology (4, 5, and 6) require significantly more initial investment than those that rely solely on composting. However, as shown in Table 3 earlier, these scenarios can potentially provide significant long-term operational cost savings.

To meet these investment needs, the Lubuklinggau City Government will need to explore various financing options, including:

1. APBD allocation

2. Special Allocation Fund (DAK) from the central government

3. Cooperation with the private sector through the Public-Private Partnership (PPP) scheme

4. Soft loans from multilateral financial institutions such as the World Bank or the Asian Development Bank

5. Green bonds or other sustainable financing instruments

The selection of an appropriate financing scheme must consider the region's fiscal capacity, the project's financial feasibility, and the long-term implications for the regional budget.

Implementing this new policy also requires capacity building of waste management human resources. Training and certification should be provided to WTE facility operational officers, waste collection officers, and community composting program facilitators. Collaboration with universities and training institutions can be established to develop appropriate curriculum and training modules.

3.2. Discussion

This research produced a waste reduction policy model that integrates composting approaches and WTE technology for Lubuklinggau City. Simulation results show that combining household-scale composting (40% participation) and medium-scale WTE facilities can reduce waste generation by 60% and generate 5,960 MWh/day of electrical energy. This scenario also offers the potential for long-term waste management cost savings.

Implementing this policy requires significant initial investment but promises long-term environmental and economic benefits. The main challenge is increasing public participation in waste segregation and composting. Therefore, intensive education strategies and appropriate incentive schemes are needed.

The developed model can be a tool for policymakers in formulating optimal waste management strategies. However, periodic validation and adjustment are needed to ensure the model's relevance to actual conditions. Further research is recommended to examine the social acceptance and environmental impacts of WTE technology implementation in more detail.

Systematic monitoring and evaluation are also key to successfully implementing this new policy. An integrated waste management information system must be developed to monitor various performance indicators such as waste reduction rate, energy production, operational costs, and community participation rate. The resulting data can be used for periodic policy adjustments.

Finally, it is important to consider the potential socio-economic impacts of this waste management system transformation, especially on the informal sector, such as waste pickers. An equitable transition program needs to be designed to ensure this vulnerable group is not marginalized, such as through new skills training or priority hiring at WTE facilities.

Considering the above aspects, implementing the proposed waste reduction policy model has the potential to address the waste problem in Lubuklinggau City and contribute to the achievement of broader sustainable development goals, including GHG emission reduction, renewable energy provision, and green job creation.

In addition to the previously discussed aspects, it is also important to consider the potential integration of digital technology and innovation in implementing the new waste management policy. Some examples of technology applications that can improve the efficiency and effectiveness of waste management systems include:

1. An IoT (Internet of Things)-based monitoring system to optimize waste transportation routes and monitor bin fill levels.

2. Mobile applications for public education and reporting of waste-related issues.

3. Blockchain will improve transparency and accountability in the waste management value chain.

4. Artificial Intelligence for operational optimization of WTE facilities.

Implementing these technologies can improve operational efficiency and service quality, but it also requires additional investment and the development of relevant human resource capacity. The following table shows the projected job creation potential of each scenario:

Table 7: Projected Job Creation 2024-2034 (in number of workers).

Year	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
2024	100	150	200	150	200	250
2025	105	175	250	200	275	350
2026	110	200	300	250	350	450
2027	115	225	350	300	425	550
2028	120	250	400	350	500	650
2029	125	275	450	400	575	750
2030	130	300	500	450	650	850
2031	135	325	550	500	725	950
2032	140	350	600	550	800	1050
2033	145	375	650	600	875	1150
2034	150	400	700	650	950	1250

Source: Research Results, 2024.

Table 7 shows that all scenarios have the potential to create new jobs, with Scenario 6 showing the greatest job creation potential, reaching 1250 workers by 2034. Scenario 5 also shows significant job creation at 950 workers. These jobs cover various sectors, including WTE facility operations, waste transportation, composting program facilitators, and administrative and managerial positions.

This job creation can have a positive impact on the local economy. However, some of these new jobs may replace existing informal jobs in the waste sector. Therefore, inclusive training and transition programs are very important.

Another aspect to consider is the potential for developing a circular economy based on waste management. Some opportunities that can be developed include:

1. Small and medium-scale recycling industry
2. Compost production and marketing
3. Utilization of WTE residues for construction materials
4. Development of innovative products made from recycled waste

The development of this circular economy can not only create economic added value, but also support the achievement of long-term waste reduction goals.

A comprehensive set of key performance indicators (KPIs) needs to be developed to measure the successful implementation of this new policy. The following is an example of KPIs that can be used:

Table 8: Key Performance Indicators (KPIs) for Waste Management.

Category	**Indicator**	**Target 2034**
Environment	Percentage of waste reduction to landfil	60%
	GHG emission reduction (tons CO2 equivalent/year)	9,500
	Percentage of waste recycled	30%
Economy	Operational cost savings (%)	20%
	Revenue from energy sales (Billion IDR/year)	50
	Number of new jobs created	950
Social	Community participation rate in composting (%)	40%
	Level of community satisfaction with services (%)	80%
Operational	Waste transportation efficiency (%)	90%
	Energy production from WTE (MWh/day)	5,960

Source: Research Results, 2024.

KPIs must be monitored regularly and reported to the public to ensure transparency and accountability in policy implementation.

The implementation of this new policy also needs to consider potential risks and mitigation strategies. Some risks that need to be anticipated include:

1. Community resistance to the construction of WTE facilities

2. Fluctuations in waste composition and volume that can affect the performance of WTE facilities

3. Market uncertainty for recycled and composted products

4. Regulatory changes related to renewable energy that may affect the financial viability of the project 4.

Risk mitigation strategies need to be developed for each of these potential risks.

Finally, it is important to ensure that the new waste management policy is in line with and integrated with the city's broader development policies and plans. This includes linkages with spatial plans, local economic development strategies, and the city's climate change action plan. Considering the above aspects, implementing the proposed waste reduction policy model has the potential to address the waste problem in Lubuklinggau City and can also be a catalyst for transformation towards a more sustainable and resilient city.

Overall, the simulation results indicate that combining household-scale composting and medium-scale WTE technology (Scenario 5) is a promising policy option for Lubuklinggau City. This scenario balances waste generation reduction, energy production, and implementation feasibility. A 60% reduction in waste generation will extend the life of the existing landfill, while electricity production of 5,960 MWh/day can meet the needs of about 30% of households in the city.

Implementing this scenario requires an initial investment in constructing WTE facilities and community education programs on sorting and composting. However, in the long run, revenue from electricity and compost sales can offset some of the operational costs. In addition, a significant reduction in waste volume will reduce the budget burden for landfill transportation and management.

The main challenge in implementing this scenario is to increase community participation in waste segregation and composting to 40%. This requires an intensive and sustained education campaign and the right incentives. The experience of other cities shows that a combination of sanctions and economic incentives (such as reduced waste levies) can effectively encourage participation [15]).

From a sustainability perspective, this scenario also offers environmental benefits in reducing greenhouse gas emissions from waste decomposition in landfills. However, further studies are needed on the potential emissions from WTE facilities to ensure a net emissions balance. The social acceptance aspect of WTE technology also needs to be anticipated, given several cases of community rejection in other areas [8] The model developed in this study offers an integrative decision-making framework for local governments. By considering various technical, economic, and social factors, the model enables a comprehensive analysis of the impact of waste management policies. However, it should be noted that the accuracy of the model's projections depends on the quality of the input data and assumptions used. Therefore, regular data updating and model validation with actual conditions are crucial.

4. Conclusion

Based on the analysis, waste management in Lubuklinggau City shows promising potential through a combination of household-scale composting (with 40% participation) and medium-scale Waste-to-Energy (WTE) technology. The simulation model shows that this scenario can reduce waste generation by 60% and generate 5,960 MWh/day of energy in 2034. From an economic perspective, this scenario can potentially reduce management costs from IDR 1,600 billion in 2024 to IDR 1,100 billion in 2034 despite requiring an initial investment of IDR 950 billion. Additional benefits include the reduction of greenhouse gas emissions by 9,485 tons of CO2 and creating around 950 new jobs.

To realize this transformation, several key policy recommendations are proposed. First, adopting an integrated waste management approach that combines household-scale composting and WTE technologies is supported by the development of appropriate regulations and operational standards. Second, budget allocation for waste management infrastructure, including the construction of WTE facilities and procurement of composting equipment, by utilizing various financing options such as public-private partnerships and green financing instruments.

Intensive and sustainable public education programs are also needed to increase community participation in waste segregation and composting. Incentive and disincentive systems must be developed to encourage good waste management behaviour. Human resource capacity building, partnerships with the private sector and civil society organizations, and integrating digital technology in the waste management system are also important parts of the recommendations.

The successful implementation of this policy depends on strong political commitment, active community participation, and good coordination between stakeholders. With a comprehensive and gradual approach, transforming the waste management system in Lubuklinggau City is expected to create a more effective, efficient, and sustainable system, which will ultimately improve environmental quality, public health, and local economic development.

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