International Journal of
Sustainable Energy Planning and Management

Linking Household Waste Segregation to Biogas-Based Energy System Feasibility: A Techno-Economic and Policy Assessment in Rejang Lebong, Indonesia

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ABSTRACT

Reliable feedstock supply is critical to the feasibility of decentralised biogas-based. energy systems, particularly in developing regions where municipal organic waste is largely unsegregated. This study evaluates how household waste segregation performance influences biogas-based electricity generation and energy system feasibility in Rejang Lebong Regency, Indonesia. A cross-sectional survey of 400 households was conducted to determine household waste segregation rates and behavioural conditions. Survey results were integrated into scenario-based techno-economic modelling to estimate recoverable organic waste, biogas production, electricity generation, and financial viability under three segregation scenarios: 38.5%, 60%, and 80%. Results show that improved segregation substantially increases recoverable organic waste and electricity generation and enhances financial feasibility. The model indicates a break-even segregation threshold of approximately 54%, while the 80% scenario provides greater financial feasibility. The findings demonstrate that household segregation performance is a critical determinant of decentralised renewable energy viability rather than merely an environmental behaviour. The study provides policy-relevant evidence for integrating household waste management improvements with decentralised energy planning in resource-constrained regions. Results should be interpreted in light of the planning-level engineering and economic assumptions adopted in the model.

Keywords

Anaerobic digestion;
Biogas;
Household waste segregation;
Municipal solid waste;
Techno-economic analysis;

http://doi.org/10.54337/ijsepm.11479

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Received 13.04.2026 | Accepted 12.08.2026 | Published 19.08.2026

Abbreviations

AD	anaerobic digestion	MSW	municipal solid waste
BIG	Badan Informasi Geospasial	NPV	net present value
BMP	biochemical methane potential	OF	organic fraction
CAPEX	capital expenditure	OPEX	operating expenditure
CE	collection efficiency	ROW	recoverable organic waste
CF	contamination factor	SR	segregation rate
CHP	combined heat and power	TPB	Theory of Planned Behaviour
IDR	Indonesian rupiah	TW	total waste generation
IRR	internal rate of return	VS	volatile solids
LCOE	levelised cost of energy	WTE	waste-to-energy

1. Introduction

The global energy transition requires the accelerated deployment of renewable and decentralised energy systems to reduce greenhouse gas emissions and enhance energy security. Although solar and wind generation are increasingly integrated into electricity systems, their variable output continues to create challenges for system flexibility and reliability [1]. Bioenergy derived from municipal organic waste can provide dispatchable renewable generation that complements variable renewable sources while contributing to waste reduction and circular-economy objectives [2].

Global municipal solid waste (MSW) generation is projected to reach 3.40 billion tonnes annually by 2050, placing increasing environmental and infrastructural pressure on low- and middle-income countries [3]. In many developing regions, biodegradable organic materials, including food waste and household residues, account for 50–70% of MSW [4]. When separated at source, this organic fraction can be converted into biogas through anaerobic digestion (AD) and used to generate electricity, produce heat or supply fuel, while potentially reducing uncontrolled methane emissions from landfill disposal [4].

However, the practical deployment of biogas-based energy systems depends on the availability of consistent, sufficiently clean feedstock rather than solely on theoretical organic-waste quantities. In many developing countries, organic waste is collected together with plastics and other residual materials. Such contamination reduces the usable organic fraction and effective methane yield, increases pre-treatment and processing costs, and can disrupt stable digester operation [5]. These constraints limit the quantity and quality of feedstock that can be reliably recovered for energy generation and contribute to continued reliance on landfill disposal and open dumping.

Indonesia's National Policy and Strategy for Household Waste Management, established through Presidential Regulation No. 97/2017, set targets for 2025 of reducing household and household-like waste by 30% and handling 70% of the generated waste [6]. However, implementation has remained uneven, particularly in small and medium-sized regencies where infrastructure coverage, enforcement capacity and household participation are limited [7].

Rejang Leong Regency in Bengkulu Province provides a relevant case study because its municipal waste stream contains a substantial organic fraction, while household source segregation remains limited. Available local estimates indicate that the regency generates approximately 37 t/d of municipal solid waste, more than half of which consists of organic material [8]. This composition indicates potential for biogas-based electricity generation. However, low segregation performance reduces the quantity and quality of recoverable organic feedstock, thereby constraining the technical performance and modelled financial viability of anaerobic digestion systems.

Municipal waste management in the regency remains predominantly dependent on landfill disposal, with limited infrastructure for source-separated collection and organic-waste recovery. These conditions create a practical need to determine whether improved household segregation could increase the availability of reliable feedstock and support financially viable decentralised biogas-based energy generation under the assumptions adopted in this study. Rejang Lebong therefore offers a relevant setting for examining the relationship between municipal waste-management practices and decentralised renewable-energy planning.

From an energy-systems perspective, feedstock reliability represents a structural constraint on decentralised biogas deployment. Anaerobic digestion facilities require consistent daily feedstock inputs to maintain stable digestion processes and predictable electricity generation. Low or inconsistent household segregation reduces both the quantity and quality of recoverable organic waste, increases variability in plant inputs and may consequently raise operational and investment risks [9]. Household source-segregation behaviour therefore functions not only as an environmental practice but also as a system-level determinant of biogas-based energy-system feasibility.

Existing research addresses the relevant behavioural, technical and economic dimensions largely in isolation. Energy-planning studies have improved understanding of biomass-resource availability, supply-chain design, renewable-energy integration and regional transition pathways, including in Indonesia [9]. However, these studies generally concentrate on aggregate or supply-side resources rather than incorporating observed household source-segregation performance into estimates of usable feedstock. Waste-management studies commonly examine household attitudes, awareness, incentives and governance arrangements [10], whereas waste-to-energy assessments often estimate theoretical energy potential from total organic-waste generation while assuming high recovery rates and limited contamination [11]. Consequently, evidence remains limited on how household segregation performance affects recoverable feedstock, electricity generation and financial feasibility within a single analytical framework [12].

Addressing this gap requires integrating behavioural data with material flow modelling, biogas conversion parameters, and economic feasibility analysis. Local governments considering investment in biogas infrastructure require answers to practical planning questions:

- How much organic waste can realistically be recovered under current segregation conditions?
- How would improve segregation rates influence feedstock availability?
- How much electricity could be generated under alternative scenarios?
- Under what segregation threshold does the system become financially viable?
- Which policy instruments are necessary to support implementation?

This study addresses the identified gap by examining how household waste segregation affects the technical and financial feasibility of biogas-based electricity generation in Rejang Lebong Regency. Survey data from 400 households are integrated into a techno-economic model covering three segregation scenarios: the survey-derived baseline of 38.5% and improvement scenarios of 60% and 80%. The model estimates recoverable organic waste, biogas production, electricity generation, net present value, internal rate of return and levelised cost of energy.

The principal contribution is the integration of empirically derived household segregation behaviour into a decentralised bioenergy feasibility model. This approach enables estimation of the segregation threshold at which project net present value becomes non-negative and provides policy-relevant evidence for coordinating municipal waste-management reform with renewable-energy planning.

2. Literature Review

Waste-to-energy (WTE) systems support low-carbon and circular-economy transitions by recovering energy from municipal solid waste (MSW). For source-separated organic waste, anaerobic digestion (AD) is an established biological conversion route that produces biogas for electricity, heat or biomethane generation [13, 2]. AD can also divert biodegradable material from landfill and produce digestate from which nutrients may be recovered, subject to contamination control and applicable quality standards [14]. These benefits are particularly relevant in developing regions where organic material constitutes a large proportion of the municipal waste stream.

A distinction is nevertheless required between theoretical organic-waste potential and practically recoverable feedstock. Several waste-to-energy and regional energy-planning studies estimate electricity potential from aggregate waste quantities or assumed organic fractions [15]. Although such assessments identify the scale of the resource, their results may be optimistic when source-segregation performance, collection efficiency and contamination are not explicitly represented. Reliable AD operation depends on a sufficiently stable supply of suitable feedstock; variations in its quantity or composition can reduce methane yield, disturb digester performance and increase operational risk [16,17].

Source segregation is therefore an upstream technical and economic variable, rather than solely a household environmental practice. Effective separation increases the recoverable organic fraction and reduces plastics, metals, glass and other materials that require removal before digestion [18]. Poor segregation increases pre-treatment requirements, equipment wear and operating expenditure, potentially raising the levelised cost of energy and extending the payback period [19]. However, waste-management research usually examines participation, awareness and governance, whereas energy-feasibility studies commonly assume that the required feedstock will be available [11,20]. This separation between the behavioural and engineering literature limits the realism of decentralised biogas planning.

The Theory of Planned Behaviour provides a useful contextual explanation of household segregation through attitudes, subjective norms and perceived behavioural control [21]. Nevertheless, the present survey was not designed to estimate these constructs or test causal relationships among them. TPB is therefore used only to explain why infrastructure access, collection reliability and perceived ability may influence participation; it is not treated as part of the analytical framework [22]. The techno-economic model instead uses the observed household segregation rate as an empirical participation indicator. This bounded interpretation avoids implying that the study conducted a formal TPB analysis.

Biogas-project feasibility also depends on the interaction between feedstock supply, technical performance and institutional support [23]. Conventional techno-economic assessments evaluate capital expenditure, operating expenditure, net present value, internal rate of return, payback period and levelised cost of energy [24,25]. Financial outcomes are sensitive to usable feedstock and electricity output, while feed-in tariffs, power-purchase agreements, concessional finance and coordinated waste-management policies can reduce investment risk [26]. Thus, behavioural participation, engineering performance, financing and regulation must be considered together when evaluating decentralised biogas systems.

Table 1 systematically compares representative studies with the present research. Previous studies provide important behavioural, technical, policy or resource-potential evidence, but they generally examine these dimensions separately.

Table 1: Comparison of representative studies and the contribution of the present research

Study and context	Methodology	Limitation relative to the present research question	Advancement provided by the present study
Rezania et al. [2]; developed and developing countries	Review of WTE technologies, policies and circular-economy pathways	Broad synthesis without locally observed household segregation or a project-specific financial threshold	Combines local household evidence with site-specific material-flow and financial modelling
Pandyaswargo et al. [18]; emerging Asian countries	Review and implementation framework for municipal organic-waste management using biogas	Primarily qualitative; does not connect a survey-derived segregation rate to energy output and discounted cash flow	Quantifies the pathway from household participation to recoverable feedstock, electricity generation and financial viability
Cheng [25]; Putrajaya, Malaysia	Household survey with descriptive and correlation analyses of TPB-related factors	Explains segregation behaviour but does not estimate its downstream energy or financial consequences	Uses observed segregation performance as an input to the techno-economic model while treating TPB only as contextual background
González et al. [24]; decentralised urban biogas system	Engineering scenario assessment of food- and garden-waste co-digestion and high-efficiency engines	Assumes waste availability and does not estimate a household-segregation or contamination threshold	Introduces empirical participation and scenario-dependent contamination into the feasibility assessment
Santos et al. [41]; Minas	Primary waste	Emphasises technical energy	Links household behaviour to

Gerais, Brazil	characterisation and regional electricity-potential assessment	potential rather than household compliance or project-level discounted financial feasibility	recoverable feedstock, electricity output, net present value, internal rate of return and levelised cost of energy
Present study; Rejang Lebong Regency, Indonesia	Survey of 400 households integrated with material-flow analysis, AD conversion modelling, discounted cash flow, sensitivity testing and policy review	Relies on self-reported segregation and planning-level technical and financial assumptions	Provides an empirically informed segregation threshold for financial viability and connects waste-management behaviour with decentralised energy planning

The comparison identifies three remaining research gaps. First, resource-potential assessments seldom adjust theoretical organic-waste quantities using empirical household segregation, collection efficiency and contamination. Second, behavioural studies rarely translate segregation performance into recoverable feedstock, electricity generation or financial indicators. Third, few studies integrate household evidence, material-flow estimation, biogas conversion, discounted cash flow, uncertainty testing and policy analysis for a smaller regency outside a major metropolitan area.

The present study addresses these gaps by integrating survey-derived segregation performance from 400 households with scenario-based biogas and techno-economic modelling in Rejang Lebong Regency. Its principal novelty is the quantitative connection between household participation and energy-system feasibility. This integration permits estimation of the segregation level at which project net present value changes from negative to non-negative, thereby reframing household segregation as a measurable determinant of feedstock reliability and decentralised renewable-energy feasibility.

3. Methods

This study applies an integrated analytical framework linking household segregation behaviour with material-flow estimation, biogas-production modelling, electricity-generation calculations, techno-economic assessment and policy analysis. The framework evaluates whether improved household segregation can provide sufficiently reliable organic feedstock to support technically feasible and financially viable biogas-based electricity generation in Rejang Lebong Regency, Indonesia. Empirical household-survey data are combined with engineering conversion parameters and discounted cash-flow analysis. All monetary values are expressed in constant 2025 Indonesian rupiah (IDR).

The study was conducted in Rejang Lebong Regency, Bengkulu Province, Indonesia. Figure 1 shows the location of the regency within Bengkulu Province and Indonesia, together with the administrative boundaries used to define the spatial scope of the household survey, material-flow analysis and techno-economic assessment.

The regency covers approximately 1,515 km² and has a population of about 270,000 residents distributed across 15 sub-districts [27]. The area is characterised by a humid tropical climate, hilly terrain and dispersed settlement patterns, which may influence waste-collection efficiency, transport requirements and the suitability of decentralised waste-to-energy systems. Municipal solid waste generation is estimated at approximately 37 t/d. This value is treated as a planning-level model input rather than as the result of a new comprehensive waste-generation audit. Local composition studies indicate that organic waste represents 55–65% of total waste; for modelling purposes, a midpoint value of 60% was adopted. Waste management remains predominantly landfill-based, and source-segregation performance is limited. The combination of high organic content and moderate segregation rates provides a suitable basis for evaluating biogas potential under alternative behavioural scenarios.

Empirical data on segregation performance were obtained through a cross-sectional household survey conducted between March and May 2025. A stratified random sampling approach ensured representation of both urban and rural households. The minimum sample size was determined using Cochran's formula for large populations at a 95% confidence level and 5% margin of error. Assuming maximum variability ($p = 0.5$), the minimum required sample was 384 households; therefore, 400 households were surveyed to improve representativeness and account for incomplete responses.

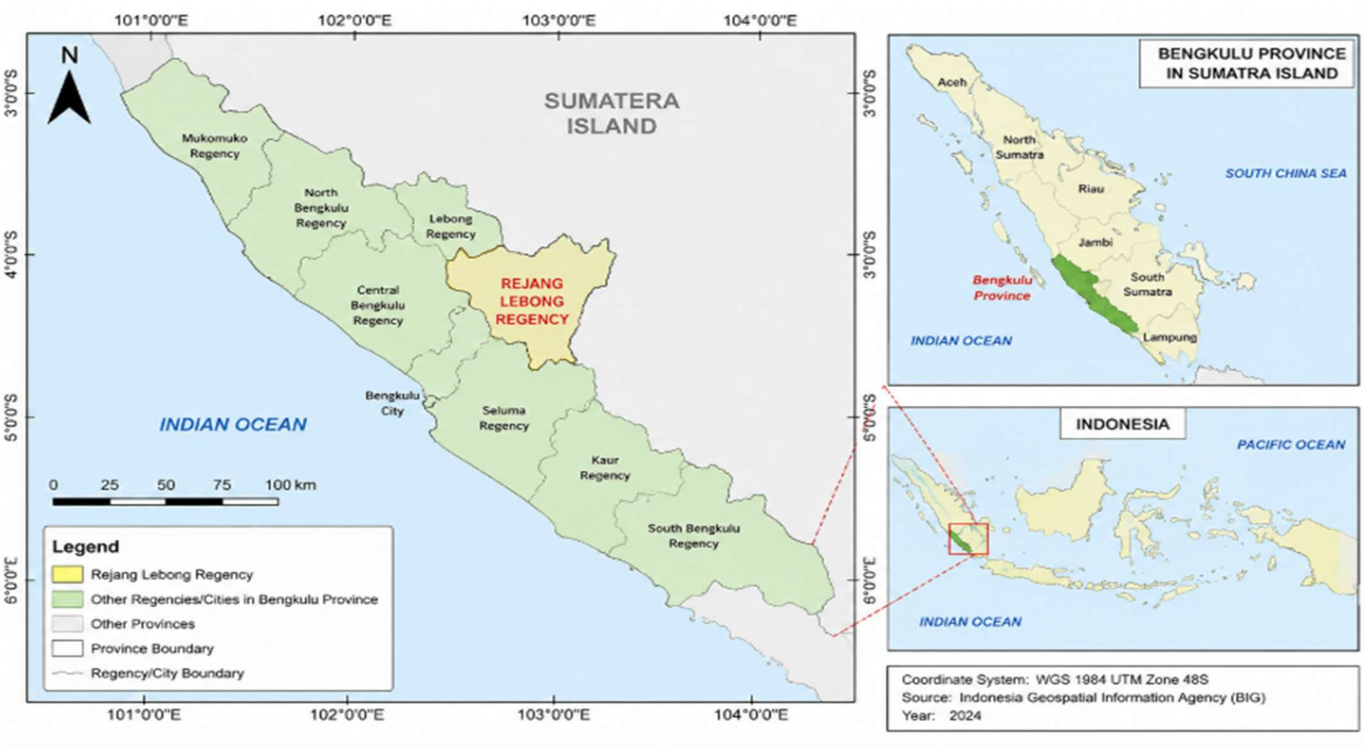

Figure 1: Study area showing the location of Rejang Lebong Regency, Bengkulu Province, Indonesia.
Source: Administrative-boundary data © Badan Informasi Geospasial (BIG), Indonesia (2024), reproduced and adapted with permission. Figure prepared by the authors.

The structured questionnaire collected information on segregation practices, frequency of organic separation, infrastructure access and socioeconomic characteristics. In this study, the segregation rate (SR) represents the share of households reporting consistent source separation of organic waste, expressed as a percentage of surveyed households. SR is therefore a participation or compliance indicator rather than a direct measurement of the mass fraction correctly separated. Although self-reported practice may overstate actual performance, the survey-based SR provides an empirically grounded proxy for feedstock reliability in the absence of continuous waste-composition audits.

The questionnaire did not operationalise the Theory of Planned Behaviour constructs attitudes, subjective norms and perceived behavioural control as validated measurement scales. Consequently, the study does not test a TPB model or its causal relationships. The survey-derived SR is used as the behavioural input to the techno-economic model, while TPB is retained only as contextual background in the literature review.

The observed baseline segregation rate of 38.5% was used as the reference scenario for subsequent modelling. According to the institutional research ethics policy of Universitas Sriwijaya, this anonymous, non-interventional household survey qualified for exemption from formal ethics committee review because it did not collect personally identifiable, medical or sensitive data. Informed consent was obtained from all respondents before survey administration, and all data were anonymised before analysis.

Recoverable organic waste was calculated using:

$$ROW = TW \times OF \times SR \times CE \times (1 - CF) \quad (1)$$

where ROW represents recoverable organic waste, TW is total waste generation, OF is the organic fraction, SR is the segregation rate, CE is collection efficiency and CF is the contamination factor. Collection efficiency was assumed to be 85%, reflecting a planning-level estimate of municipal collection performance. Contamination rates were set at 25% for the baseline scenario, 15% for moderate improvement and 10% for high-performance segregation. These conservative assumptions represent decreasing contamination as household separation and collection discipline improve; their effects on feasibility were examined through sensitivity analysis.

The modelling further assumes that standard mechanical pre-treatment including feedstock-size reduction and the removal of plastics, metals, glass and other contaminants is incorporated into the biogas-processing system before anaerobic digestion. This assumption reflects common engineering practice in municipal anaerobic-digestion facilities and is intended to improve feedstock quality, protect processing equipment and enhance digestion efficiency. The associated equipment, contaminant-removal processes and operating requirements are included in the planning-level CAPEX and OPEX estimates.

This formulation incorporates behavioural compliance and operational performance into feedstock estimation. Biogas production was estimated using standard anaerobic-digestion parameters derived from the engineering literature. Volatile-solids content was assumed to be 75% on a wet basis, specific biogas yield was set at 0.35 m³/kg VS and digestion efficiency was assumed to be 85%.

The resulting effective biogas yield per kilogram of organic waste is:

$$0.75 \times 0.35 \times 0.85 = 0.223\, m^3/kg \quad (2)$$

Daily biogas production was therefore calculated as:

$$Biogas\ (m^3/d) = ROW\ (kg/d) \times 0.223 \quad (3)$$

Gross energy potential was estimated using an average energy content of 6 kWh/m³ of biogas, corresponding to approximately 60% methane content. Electricity generation was modelled using a 30% electrical-conversion efficiency and 330 operating d/y to allow for maintenance downtime. Daily electricity output was calculated as:

$$Electricity\ (kWh/d) = Biogas\ volume\ (m^3/d) \times 6\, kWh/m^3 \times 0.30 \quad (4)$$

Annual electricity production was calculated by multiplying daily output by 330 operating days. Required installed capacity was estimated by dividing daily electricity production by 24 h.

Financial feasibility was assessed using discounted cash-flow analysis over a 20-year project lifetime. A nominal installed capacity of 250 kW was assumed based on the projected high-segregation output. Installed capacity was held constant across scenarios to represent a single investment decision made under planning uncertainty. Under lower segregation performance, the plant operates below its rated capacity and revenue declines accordingly.

The discount rate was set at 8%, and the electricity tariff was assumed to be 1,450 IDR/kWh. Total capital expenditure (CAPEX) was estimated at 28 billion IDR, including digester construction, gas storage, generator installation, civil works and collection infrastructure. Annual operating expenditure (OPEX) was estimated at 2.4 billion IDR, covering labour, maintenance, transport, utilities and administrative costs.

The cost assumptions were benchmarked against published anaerobic-digestion and biogas combined heat-and-power (CHP) feasibility studies. CAPEX comprises: (i) anaerobic digester and tankage; (ii) gas handling, desulphurisation, storage and safety equipment; (iii) the CHP generator and electrical balance of plant; (iv) civil works and site development; and (v) grid interconnection and auxiliary systems. The CAPEX estimate also includes basic source-segregated collection upgrades, including bins, containers and logistics adjustments. OPEX comprises labour and administration, routine maintenance and consumables, collection and transport, utilities and minor repairs. Because detailed local procurement quotations were unavailable, these costs are treated as planning-level estimates and tested through sensitivity analysis.

Financial performance was evaluated using net present value (NPV), internal rate of return (IRR), payback period and levelised cost of energy (LCOE). LCOE was calculated as:

$$LCOE = \frac{\sum_{t=0}^{T} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}} \quad (5)$$

where represents the total cost incurred in year, including CAPEX and OPEX; represents the electricity generated in year; is the discount rate; and is the project lifetime.

In this analysis, comprises the initial CAPEX incurred in Year 0 and the annual OPEX incurred during Years 1–, with all costs expressed in constant 2025 IDR. The base-case LCOE excludes financing structure, taxes, inflation, subsidies, major equipment replacement, and residual value. These exclusions are considered planning-level limitations of the analysis and should not be interpreted as an assumption that such costs or values would be zero in an actual project.

The project was considered financially viable when NPV was greater than or equal to zero and IRR exceeded the 8% discount rate.

Scenario analysis was conducted for three segregation levels: 38.5% (baseline), 60% (moderate improvement), and 80% (high-performance scenario). Table 2 summarizes the key model parameters, indicating which inputs are survey-derived versus assumed and providing data sources.

Table 2: Key model parameters and data sources used in the techno-economic assessment

Parameter	Base value	Sensitivity range	Data type	Source/notes
Total MSW generation (TW)	37 t/d	±10%	Planning-level assumption	Conservative case-study input; requires confirmation through a detailed waste audit before investment
Organic fraction (OF)	60%	55–65%	Assumed midpoint	Reported composition range
Segregation rate (SR)	38.5%/60%/80%	±10% relative variation	Empirical baseline plus scenarios	Survey baseline; policy-driven scenarios
Collection efficiency (CE)	85%	75–95%	Assumed	Planning assumption tested through sensitivity analysis
Contamination factor (CF)	25%/15%/10%	±5 percentage points	Assumed	Scenario-dependent assumption tested through sensitivity analysis
Effective biogas yield	0.223 m^3/kg waste	±15%	Engineering assumption	VS × specific yield × digestion efficiency
Biogas energy content	6 kWh/m^3	±10%	Assumed	Approximately 60% CH_4
Electrical efficiency	30%	25–35%	Assumed	Generator-conversion assumption
Operating days	330 d/y	300–350 d/y	Assumed	Maintenance-downtime allowance
CAPEX	28 billion IDR	±20%	Assumed	Planning-level estimate
OPEX	2.4 billion IDR/y	±20%	Assumed	Planning-level estimate
Tariff	1,450 IDR/kWh	Policy scenarios	Assumed	Base-case revenue assumption
Discount rate	8%	6–12%	Assumed	Planning discount rate

For each scenario, material flow, biogas production, electricity generation and financial indicators were recalculated. Sensitivity analysis examined relative variations of ±10% in segregation rate, ±15% in biogas yield and ±20% in transport cost, together with an absolute variation of ±5 percentage points in the contamination factor.

The break-even segregation threshold was estimated by repeatedly varying SR while holding the other base-case inputs constant. At each candidate SR, recoverable organic waste, biogas production, electricity generation, annual cash flow and NPV were recalculated. Successively smaller SR intervals were evaluated until one model run produced a negative NPV and the adjacent run produced a non-negative NPV. Linear interpolation between these two runs yielded a break-even segregation rate of approximately 54%. The broader change from negative NPV at 38.5% segregation to positive NPV at 60% segregation is reported in Table 6.

A deterministic one-at-a-time sensitivity analysis was selected because the study is a planning-level assessment and reliable local probability distributions and correlations were unavailable for segregation performance, contamination, biogas yield, transport cost, CAPEX and OPEX. This method provides a transparent indication of the influence of each parameter but does not quantify their combined probability of occurrence. Future research should apply Monte Carlo simulation once sufficient local observations are available to define defensible distributions and correlations among model inputs.

Finally, a qualitative review of national waste-management regulations, renewable-energy policies and local institutional frameworks was undertaken to evaluate regulatory readiness for biogas deployment. The review covered Law No. 18/2008 on Waste Management, Government Regulation No. 81/2012 on Household and Household-like Waste Management, Presidential Regulation No. 97/2017 on the National Policy and Strategy for Household Waste Management, and Presidential Regulation No. 109/2025 on processing urban waste into renewable energy [28,29]. Presidential Regulation No. 109/2025 replaced and revoked Presidential Regulation No. 35/2018; therefore, the superseded regulation is not treated as the current legal basis. Policy implications were derived by relating these instruments to the segregation, contamination and collection-efficiency conditions used in the model [30,31].

Table 3: Policy framework relevant to source segregation and waste-to-renewable-energy implementation in Indonesia

Instrument	Scope and objective	Implementation gap	Relevance to SR, CF and CE	Source
Law No. 18/2008 on Waste Management	Establishes the national legal foundation for waste reduction, handling and local-government responsibility	Enforcement capacity and infrastructure coverage vary among regencies	Provides the legal basis for municipal waste-management responsibility	[28]
Government Regulation No. 81/2012	Operationalises household and household-like waste reduction and handling	Local monitoring and contamination control remain limited	Supports source-separation, collection and quality-control mechanisms	[29]
Presidential Regulation No. 97/2017	Establishes national waste-reduction and handling targets to 2025	Achievement remains uneven because of financing, infrastructure and participation constraints	Connects improved household participation with national waste-management objectives	[30]
Presidential Regulation No. 109/2025 on processing urban waste into renewable energy	Provides the current national framework for processing urban waste into renewable energy and revokes Presidential Regulation No. 35/2018	Project bankability, feedstock quality, institutional coordination and local delivery capacity remain important constraints	Reliable segregation, contamination control and collection performance remain necessary for dependable project feedstock and energy production	[31]

As shown in Table 3, the current Indonesian regulatory framework provides a formal basis for source separation and waste-to-renewable-energy development. Nevertheless, implementation capacity at the regency level may constrain achievement and maintenance of the modelled 54% segregation threshold.

4. Results

This section presents the results of the scenario-based material-flow analysis, biogas production, electricity generation, economic feasibility assessment, sensitivity analysis, and integrated scenario comparison. The findings illustrate how variations in household waste-segregation performance influence feedstock recovery, renewable energy generation, and the techno-economic feasibility of decentralised biogas systems in Rejang Lebong Regency.

4.1 Segregation scenarios and organic waste recovery

The household survey identified a baseline segregation rate of 38.5%. Two additional scenarios were modelled to represent feasible policy-driven improvements: 60% and 80%. Collection efficiency was fixed at 85% across scenarios, while contamination rates were assumed to be 25% for the baseline scenario, 15% for the moderate-improvement scenario, and 10% for the high-performance scenario. With total municipal solid waste generation of 37 t/d and an organic fraction of 60%, the theoretical organic-waste potential was calculated as:

$$Theoretical\ organic\ waste = 37\ t/d \times 0.60 = 22.2\ t/d \quad (6)$$

Recoverable organic waste was estimated using the material-flow equation defined in Section 3, incorporating the segregation rate, collection efficiency, and contamination factor. The results for the three scenarios are presented in Table 4.

Table 4: Segregation scenarios and recoverable organic waste in Rejang Lebong Regency, Indonesia

Scenario	Recoverable OW (t/d)	Biogas (m^3/d)	Electricity (kWh/d)	Annual (GWh/y)	Households Powered
38.5%	6.45	1,439	2,590	0.85	≈ 555
60%	10.06	2,243	4,038	1.33	≈ 870
80%	14.32	3,192	5,745	1.90	≈ 1,240

Note: The estimated number of households supplied assumes an average household electricity consumption of 4.2 kWh/d, equivalent to approximately 1,533 kWh/y.

As shown in Table 4, increasing segregation from 38.5% to 80% results in more than a twofold increase in recoverable organic waste. These results indicate that feedstock availability for anaerobic digestion is strongly influenced by household segregation performance. Even where municipal waste has a high organic content, insufficient source separation significantly constrains the amount of usable feedstock that can be recovered.

4.2 Biogas production and electricity generation

Biogas production and electricity generation were calculated using Equations (3) and (4), respectively. Biogas-production estimates are reported in Table 4, while Table 5 summarises daily electricity generation, annual electricity generation, and required installed capacity under the three segregation scenarios.

Table 5: Electricity generation and required installed capacity under different segregation scenarios

Scenario	Daily Electricity (kWh/d)	Annual Electricity* (GWh/y)	Required Installed Capacity (kW)
Scenario 1 (38.5%)	2,590	0.85	108
Scenario 2 (60%)	4,038	1.33	168
Scenario 3 (80%)	5,745	1.90	239

**Assuming 330 operational d/y.*

As shown in Table 5, electricity generation and required installed capacity increase as segregation performance and recoverable feedstock improve. Under the high-performance scenario, corresponding to 80% segregation, daily electricity generation reaches 5,745 kWh/d, equivalent to approximately 1.90 GWh/y. The required installed capacity for Scenario 3 was calculated as:

$$Required\ installed\ capacity = \frac{5{,}745\ kWh/d}{24\ h/d} = 239.4\ kW \quad (7)$$

This result indicates that the assumed 250 kW generator would accommodate the estimated electricity production under the high-segregation scenario, providing a capacity margin of approximately 10.6 kW.

Figure 2 provides a graphical comparison of the biogas-production values reported in Table 4. Biogas production increases substantially across the three scenarios, reflecting the increase in recoverable organic feedstock associated with improved segregation. The relationship is not determined by the segregation rate alone because the assumed contamination factor also decreases as segregation performance improves.

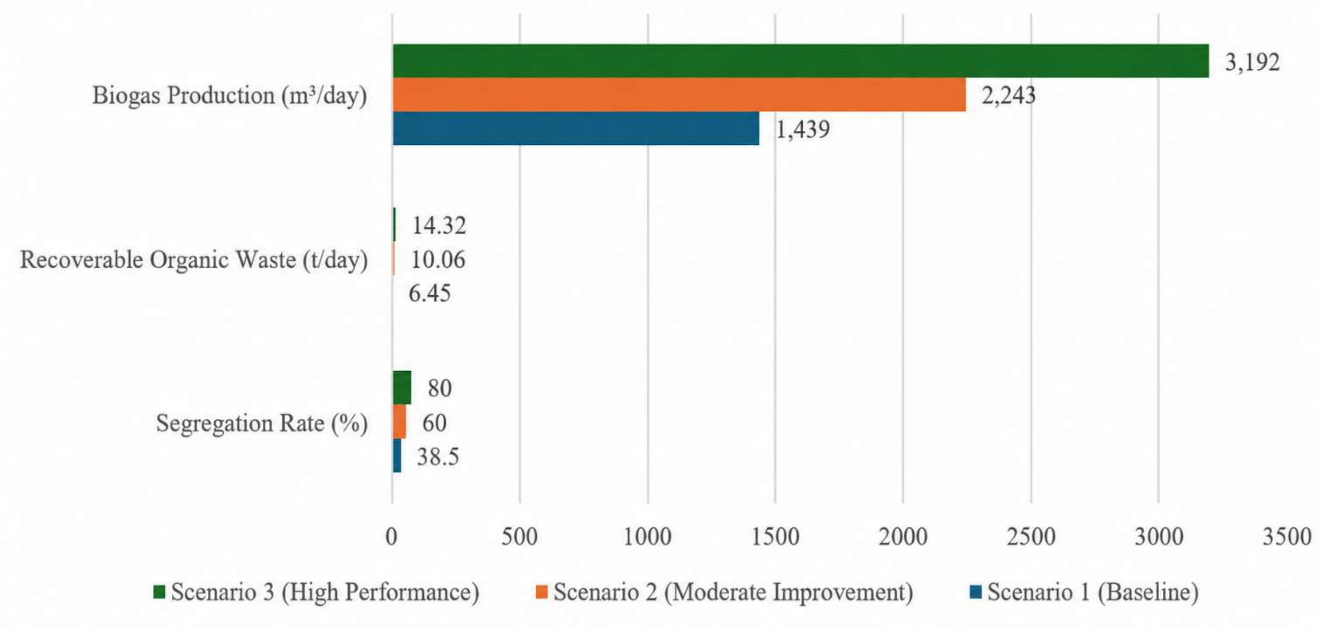

Figure 2: Daily biogas production across segregation scenarios

4.3 Economic feasibility analysis

Financial performance was evaluated using discounted cash-flow analysis over a 20-year project lifetime. The assessment incorporated a capital expenditure (CAPEX) of 28 billion IDR, annual operational expenditure (OPEX) of 2.4 billion IDR, an electricity tariff of 1,450 IDR/kWh, and a discount rate of 8%. These assumptions were applied consistently across all segregation scenarios. Economic viability was assessed using the levelised cost of energy (LCOE), net present value (NPV), internal rate of return (IRR), and payback period.

The base-case financial model includes revenue exclusively from electricity sales. Potential additional revenue from digestate utilisation, tipping fees, avoided landfill costs, heat sales, and carbon-credit mechanisms was not monetised. Under these assumptions, the financial results vary considerably across the segregation scenarios because the amount of electricity available for sale increases with recoverable feedstock. Consequently, the results represent a conservative electricity-only business case rather than the complete economic value of the proposed waste-to-energy system. The recalculated financial results are presented in Table 6.

Table 6: Economic feasibility indicators under different segregation scenarios

Scenario	Segregation (%)	LCOE (IDR/kWh)	Tariff (IDR/kWh)	NPV (bn IDR)	IRR (%)	Payback (years)
1	38.5	2,080	1,450	–6.2	3.8	>15
2	60	1,520	1,450	1.4	8.9	12
3	80	1,140	1,450	7.9	14.2	8

As shown in Table 6, the project is financially infeasible under the current segregation level of 38.5%. The LCOE of 2,080 IDR/kWh exceeds the assumed electricity tariff of 1,450 IDR/kWh, resulting in a negative NPV of −6.2 billion IDR and an IRR of 3.8%, which is below the 8% discount rate. These indicators collectively suggest that investment recovery would not be achievable under baseline conditions.

At a segregation rate of 60%, financial performance improves considerably. The LCOE declines to 1,520 IDR/kWh, approaching tariff parity, while the IRR increases to 8.9%, slightly exceeding the discount rate. The NPV becomes marginally positive at 1.4 billion IDR, and the payback period decreases to 12 years. Although this scenario meets the specified feasibility criteria, its relatively small positive NPV indicates that economic performance remains sensitive to variations in technical and financial parameters.

Under the high-performance scenario, corresponding to 80% segregation, substantially improved financial feasibility is observed under the modelling assumptions. The LCOE decreases to 1,140 IDR/kWh, below the assumed electricity tariff, while the NPV increases to 7.9 billion IDR and the IRR reaches 14.2%. The payback period decreases to eight years, indicating stronger investment potential than under the other scenarios. These results demonstrate that financial feasibility is highly dependent on segregation performance, with improvements around the break-even threshold generating disproportionately large financial gains.

Figure 3 illustrates the inverse relationship between segregation performance and the LCOE. The figure complements Table 6 by showing the decline in unit-energy costs as segregation and recoverable feedstock increase. The curve shows a non-linear reduction in LCOE, underscoring the sensitivity of system economics to household segregation performance and feedstock reliability.

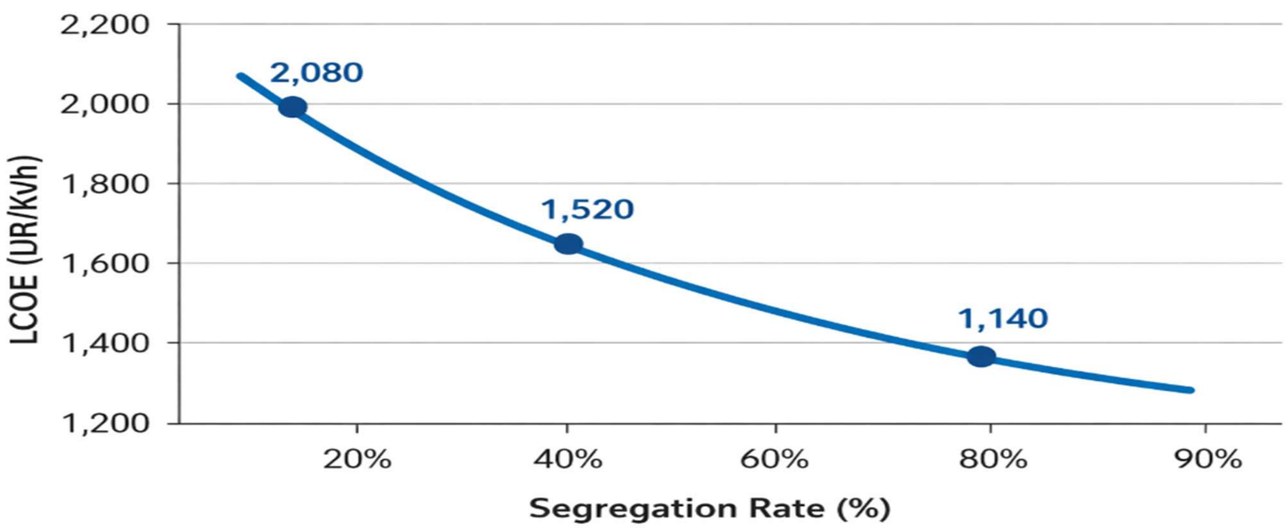

Figure 3: Levelised cost of energy (LCOE) versus segregation rate

4.4 Sensitivity analysis

A one-at-a-time sensitivity analysis was conducted to assess the robustness of the financial model and identify the parameters exerting the greatest influence on economic feasibility. The high-performance scenario, corresponding to an 80% segregation rate, was used as the base case for the tornado analysis. Four parameters were varied individually: segregation rate by ±10%, biogas yield by ±15%, transport cost by ±20%, and contamination factor by ±5 percentage points. After each parameter variation, recoverable organic waste, electricity generation, project cash flows, and NPV were recalculated while all other parameters were maintained at their base-case values.

The break-even segregation rate was defined as the segregation level at which NPV equals zero. The negative NPV at 38.5% segregation and the positive NPV at 60% segregation were first used to establish the interval containing the break-even point. Additional model runs were then conducted within this interval. For each trial segregation rate, recoverable organic waste, biogas production, electricity generation, annual revenue, and NPV were recalculated while the other base-case assumptions were held constant. The interval was progressively narrowed until the transition from a negative NPV to a non-negative NPV was identified. Linear interpolation between the final bounding model runs produced an estimated break-even segregation rate of approximately 54%. The procedure is summarised in Table 7.

Table 7: Determination of the break-even segregation threshold

Segregation condition	NPV outcome	Interpretation
38.5%	−6.2 billion IDR	Financially infeasible
Approximately 54%	Approximately 0 billion IDR	Estimated break-even point
60.0%	1.4 billion IDR	Financially feasible, but marginal

Because the break-even value was obtained from intermediate model runs, it should not be interpreted as a simple interpolation between the three principal scenarios presented in Table 6. Below this estimated threshold, projected electricity revenue is insufficient to recover the assumed capital and operating costs. Above the threshold, financial performance improves as greater quantities of source-separated organic waste become available for biogas and electricity production.

Within the tested ranges, biogas yield produced the largest change in NPV, followed by segregation rate, transport cost, and contamination factor. Under the 80% segregation base case, a 15% reduction in biogas yield decreased the IRR from 14.2% to 10.5%. Although profitability declined, the IRR remained above the assumed discount rate of 8%. A 20% increase in transport cost reduced the NPV by approximately 1.3 billion IDR, from 7.9 billion IDR to approximately 6.6 billion IDR. An increase in the contamination factor reduced the quantity of usable organic feedstock and consequently decreased electricity generation and NPV, whereas a reduction in contamination improved the financial result.

Figure 4 reports the recalculated percentage change in NPV produced by each positive and negative parameter variation. The values displayed on the bars represent changes in modelled NPV, not the percentage changes applied to the input parameters. The input variation applied to each parameter is stated separately in the corresponding variable label. For transport cost and contamination factor, an increase in the parameter decreases NPV, whereas a decrease improves NPV.

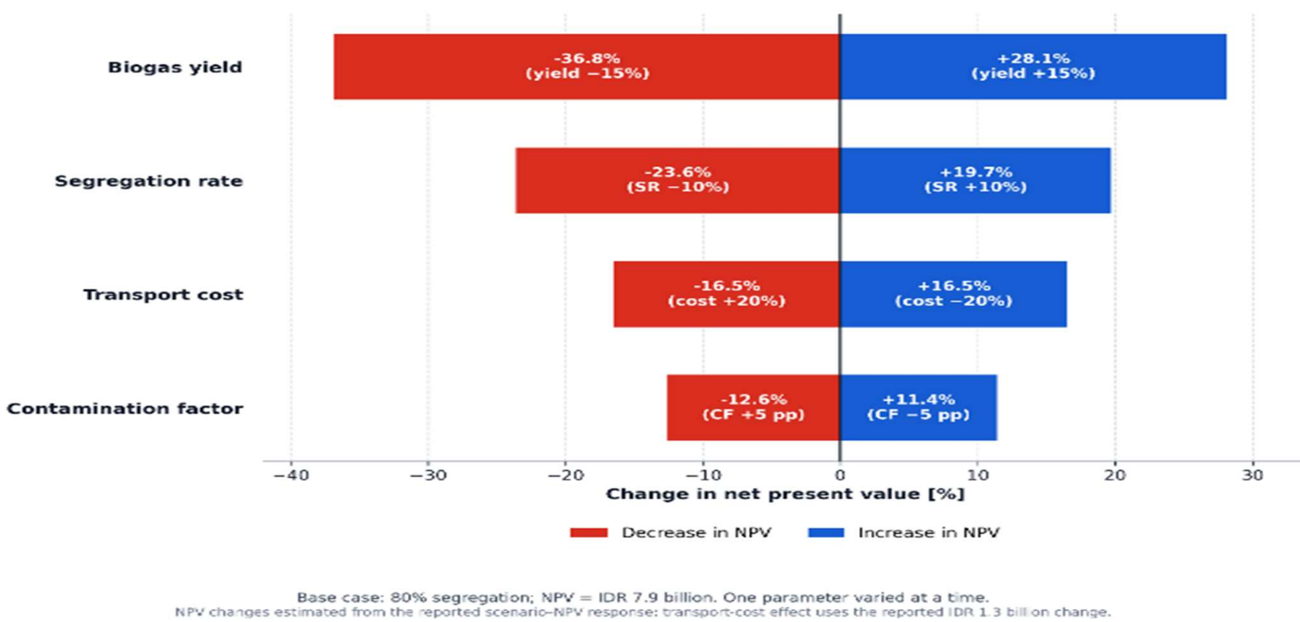

Figure 4: One-at-a-time sensitivity of net present value to segregation rate, biogas yield, contamination factor and transport cost

In Figure 4, each bar represents the recalculated percentage change in NPV obtained by varying one parameter while maintaining all other parameters at their base-case values.

The sensitivity results demonstrate that feedstock availability is the principal determinant of financial performance within the tested ranges. Nevertheless, the results are conditional on the planning-level technical and financial assumptions adopted in the model. A deterministic one-at-a-time analysis was considered appropriate for the present planning-level assessment because its primary purpose was to identify the individual parameters exerting the greatest influence on NPV. In addition, the available local data were insufficient to define defensible probability distributions and correlations for key variables such as segregation performance, contamination, biogas yield, transport cost, CAPEX, and OPEX. Applying a Monte Carlo simulation without empirically supported distributions could therefore create a misleading impression of statistical precision.

The deterministic analysis does not quantify the joint probability of alternative financial outcomes. Future research should address this limitation by collecting longitudinal operational and cost data and applying probabilistic uncertainty analysis, including Monte Carlo simulation, once appropriate distributions and correlations can be established. The estimated break-even segregation rate of approximately 54% should therefore be interpreted as a model-dependent planning estimate rather than a universally fixed threshold.

4.5 Integrated scenario comparison

A comparative analysis of the baseline (38.5%) and high-performance (80%) segregation scenarios reveals substantial technical and economic improvements as segregation performance increases. Organic recovery rises by 122%, leading to an equivalent 122% increase in biogas production and electricity generation. These proportional increases reflect the direct material-flow relationship between segregation behaviour and recoverable feedstock availability. However, the financial indicators demonstrate non-linear improvement. The IRR increases from 3.8% under baseline conditions to 14.2% in the high-performance scenario, while the LCOE declines by approximately 45%, from 2,080 IDR/kWh to 1,140 IDR/kWh.

The magnitude of financial improvement relative to feedstock growth highlights the non-linear structure of capital recovery in bioenergy systems. Once feedstock supply surpasses the economic threshold, revenue gains increase more rapidly than proportional increases in organic input. This dynamic explains why relatively modest improvements in segregation near the break-even point generate disproportionately large gains in profitability. The modelling results indicate the following relationship among the behavioural, technical, and financial components of the system:

Household segregation performance → Recoverable feedstock → Biogas production → Electricity generation → Financial viability

This systems relationship suggests that feedstock reliability, rather than conversion-technology performance alone, critically influences project feasibility. Although anaerobic-digestion efficiency and generator performance remain important, the stability and purity of organic input material exert a substantial influence on investment viability.

The analysis further identifies a modelled break-even segregation threshold of approximately 54%, below which NPV becomes negative. Economic feasibility begins to emerge at around 60% segregation and becomes progressively stronger as segregation approaches 80%. These findings provide a quantitative benchmark for policy design, infrastructure investment, and regulatory enforcement in Rejang Lebong. By translating behavioural performance targets into measurable energy and financial outcomes, the study establishes segregation improvement as an important strategic condition for decentralised renewable-energy development.

However, these results should be interpreted as scenario-based planning estimates. Actual performance may be affected by fluctuations in household participation, contamination of segregated waste, collection interruptions, equipment downtime, maintenance capability, financing conditions, and electricity-purchase arrangements.

5. Discussion

This section interprets the scenario and sensitivity results in relation to local energy planning, environmental performance, feedstock quality, implementation risks, and policy design. It also considers the implications of the planning-level assumptions and limitations adopted in the analysis.

5.1 Policy and energy transition implications

The results demonstrate that household waste segregation operates not merely as an environmental practice but as a critical enabling factor for decentralised renewable-energy systems. Under the high-performance scenario (80% segregation), approximately 1.90 GWh/y of electricity could be generated, equivalent to the annual consumption of approximately 1,240 households based on an average household consumption of 4.2 kWh/d. While modest at the national scale, this level of generation could make a meaningful contribution to local energy security in Rejang Lebong Regency [32].

Biogas-based electricity also offers a degree of operational flexibility because biogas can be stored temporarily and used when electricity is required. However, its dispatchability depends on stable feedstock delivery, adequate gas-storage capacity, reliable generator operation, and appropriate plant management. Household segregation therefore influences local energy-system reliability through its effect on the quantity, quality, and consistency of organic feedstock.

The estimated break-even segregation rate of approximately 54% provides a planning benchmark rather than an absolute policy target. Because household participation and contamination may fluctuate over time, adopting a target only slightly above 54% would leave the project vulnerable to operational and financial underperformance. A higher operational target, such as the modelled 60–80% range, would provide a margin against temporary reductions in participation, collection interruptions, and changes in feedstock quality.

Several complementary policy instruments would be required to achieve and maintain this performance. Mandatory source-separation requirements and enforceable contamination standards could establish minimum feedstock-quality expectations. Dedicated collection schedules, clearly labelled containers, and reliable collection services would make compliance more practical for households. Financial incentives, including fee rebates or differentiated waste charges, could encourage sustained participation. On the energy side, long-term power-purchase agreements, guaranteed electricity offtake, or an appropriate tariff mechanism could reduce revenue uncertainty and improve project bankability [33]. Capital grants or concessional financing may also be necessary to reduce the burden of the initial investment.

Effective implementation would require coordination among local waste-management authorities, environmental agencies, electricity-sector institutions, community organisations, and the prospective plant operator [34]. Responsibilities for household education, segregated collection, contamination monitoring, feedstock delivery, electricity purchase, and regulatory enforcement should therefore be specified before investment. This institutional integration is necessary to translate a household segregation target into a dependable energy supply.

5.2 Environmental benefits

Beyond the financial and energy-system implications, improved segregation performance could provide important environmental benefits. Under the high-performance scenario, approximately 14–15 t/d of organic waste could be diverted from landfill disposal. In conventional landfill conditions, organic waste decomposes anaerobically and produces methane, which has a substantially higher global-warming potential than carbon dioxide [34]. Controlled anaerobic digestion can capture this methane for energy production and thereby reduce its uncontrolled release.

The magnitude of the resulting greenhouse-gas benefit would depend on the landfill management counterfactual, methane leakage from the digestion system, parasitic energy consumption, digestate management, and the source of the electricity displaced [35]. Consequently, the present study identifies the direction and potential significance of the environmental benefit but does not present a complete life-cycle greenhouse-gas assessment. A future life-cycle assessment should quantify emissions from collection, transport, pre-treatment, digestion, electricity generation, digestate use, and avoided landfill disposal.

These potential benefits are consistent with Indonesia's climate-policy objectives, which identify waste-sector reform and renewable-energy development as important mitigation strategies. Diverting organic waste from landfill may also reduce odour, leachate generation, pressure on disposal capacity, and long-term land requirements [36]. Anaerobic digestion could therefore contribute simultaneously to renewable-electricity production and improved municipal waste management [37].

Nevertheless, the environmental benefit depends on the quality of the segregated material. Plastics, glass, metals, grit, and other contaminants can increase pre-treatment requirements, damage equipment, reduce digestion efficiency, and limit the safe use of digestate [38]. A high reported household participation rate should therefore not automatically be interpreted as a high-quality feedstock supply. Segregation performance must be evaluated together with contamination levels, collection efficiency, and the proportion of material rejected during pre-treatment [39].

5.3 Implementation risks and mitigation measures

The transition from modelled feasibility to an operational biogas project involves several practical risks. These risks and corresponding mitigation measures are summarised in Table 8.

Table 8: Principal implementation risks and proposed mitigation measures

Implementation risk	Potential effect on the project	Proposed mitigation measure
Inconsistent household participation	Reduces feedstock supply and may cause unstable digester loading and electricity production.	Introduce phased implementation, reliable collection services, household feedback, continuing education, and participation incentives.
Contamination of segregated organic waste	Increases rejection rates, pre-treatment costs, equipment wear, and the risk of poor-quality digestate.	Provide standardised containers, publish clear acceptance criteria, inspect collected material, tag contaminated bins, and monitor contamination rates.
Operational and maintenance limitations	Equipment failure, inadequate process control, or insufficient technical expertise may reduce methane yield and plant availability.	Establish operator-training requirements, preventive-maintenance schedules, spare-parts inventories, safety procedures, and technical-support contracts.
Financing and revenue constraints	High initial investment and uncertain electricity revenue may delay investment or weaken long-term financial performance.	Use concessional finance, capital support, long-term electricity-purchase agreements, and clearly defined payment mechanisms.
Limited institutional capacity	Unclear responsibilities and insufficient monitoring may weaken collection performance, contract management, and regulatory enforcement.	Assign responsibilities formally, establish inter-agency coordination, allocate monitoring budgets, and adopt measurable performance indicators.
Weak policy enforcement	Households or waste collectors may return to mixed-waste practices when standards are not consistently applied.	Combine progressive enforcement with accessible services, public reporting, inspections, warnings, and proportionate penalties for repeated non-compliance.

Household participation may vary because of changes in motivation, collection reliability, population mobility, or dissatisfaction with municipal services. This variability could produce irregular digester loading and reduce electricity revenue. Participation should therefore be monitored continuously rather than assessed only through a one-time survey. Periodic waste audits could be used to compare reported segregation behaviour with the actual mass and quality of collected organic waste.

Operational risks are equally important. Municipal anaerobic-digestion facilities require trained personnel, preventive maintenance, gas-safety management, process monitoring, and access to replacement components. Failure to maintain pumps, mixers, gas-treatment equipment, or generator units could reduce plant availability even when sufficient feedstock is collected. Procurement planning should therefore include operator training, maintenance contracts, critical spare parts, and contingency arrangements for temporary equipment failure.

Financing arrangements should recognise that the project may remain vulnerable during the early years of operation. A phased approach beginning with a pilot collection area could verify participation, contamination, transport requirements, and methane yield before full-scale investment. Expansion could then be linked to demonstrated performance indicators, including segregation rate, contamination rate, collection efficiency, plant availability, and electricity output. Such an approach would reduce the risk of constructing capacity that cannot be supported by the available feedstock.

5.4 Overall interpretation, limitations, and future research

The findings indicate that biogas-based electricity generation in Rejang Lebong may be technically feasible under the modelled waste-generation conditions. Financial feasibility, however, depends on maintaining sufficient source-separated feedstock and controlling contamination. The estimated 54% break-even segregation rate should therefore be interpreted as a conditional planning estimate derived from the specified technical, cost, and tariff assumptions. It is not a universally applicable threshold.

Although the Theory of Planned Behaviour (TPB) informed the literature review's discussion of household participation, the present study did not measure its individual constructs attitudes, subjective norms, perceived behavioural control, or behavioural intention and did not statistically test a TPB model. The observed segregation rate was used only as an empirical compliance input to the material-flow and techno-economic analysis. Accordingly, the results should not be interpreted as evidence of causal relationships among TPB constructs. Future household research could incorporate validated TPB measures to explain why participation varies and to evaluate which interventions are most likely to improve sustained segregation behaviour.

The effective biogas yield of 0.223 m^3/kg of organic waste was derived from established engineering parameters rather than direct biochemical methane potential (BMP) testing of locally sampled substrates. Variability in food-waste moisture content, volatile-solids concentration, and the lignocellulosic fraction could affect the methane yield achieved in practice [40]. Future research should therefore include waste-composition audits and laboratory-scale BMP testing of locally collected organic material.

The use of deterministic sensitivity analysis was appropriate for identifying which individual parameters had the greatest influence on financial performance at the planning stage. However, the available data were insufficient to define reliable probability distributions and correlations for the principal uncertain variables. The analysis consequently does not estimate the probability that the project will achieve a positive NPV. Once longitudinal data on segregation, contamination, methane yield, plant availability, transport costs, CAPEX, and OPEX become available, future research should apply Monte Carlo simulation or another probabilistic method to estimate the distribution of possible financial outcomes [41,42].

Additional limitations include reliance on self-reported segregation behaviour, the use of assumed contamination and collection-efficiency values, the absence of direct local procurement quotations, and the exclusion of several possible revenue and cost components. Revenue from digestate, tipping fees, recovered heat, avoided landfill costs, and carbon credits was not included. Conversely, major equipment replacement, financing structure, taxation, inflation, and residual value were not modelled explicitly. These omissions mean that the results represent a planning-level electricity-only assessment rather than a complete investment appraisal.

Despite these limitations, the study contributes a useful systems perspective by connecting household segregation performance with recoverable feedstock, energy generation, and financial outcomes. It demonstrates that waste-segregation policy, collection infrastructure, plant operation, and energy-market arrangements must be planned together. This integrated perspective provides a basis for evaluating whether municipal waste-management improvements can support decentralised renewable-energy development in Rejang Lebong and comparable regencies.

6. Conclusion

This study integrated household-survey data, material-flow analysis, biogas modelling, and discounted cash-flow assessment to examine how waste segregation affects biogas-based electricity feasibility in Rejang Lebong Regency. Under the model assumptions, the baseline segregation rate of 38.5% was financially infeasible, while financial feasibility emerged above an estimated break-even segregation rate of approximately 54%. At 80% segregation, the system could generate approximately 1.90 GWh/y and achieve substantially stronger financial performance.

The findings demonstrate that project feasibility depends not only on conversion technology but also on consistent household participation, low contamination, reliable collection, effective operation and maintenance, appropriate financing, institutional capacity, and policy enforcement. Source-separation standards, dedicated collection services, contamination monitoring, community engagement, and secure electricity-purchase arrangements should therefore be developed as an integrated implementation strategy.

The estimated threshold and financial indicators remain conditional on planning-level assumptions concerning costs, tariffs, collection efficiency, contamination, and biogas yield. Future research should verify local feedstock characteristics through waste audits and biochemical methane-potential testing, obtain project-specific cost data, and apply Monte Carlo simulation when reliable probability distributions become available. Overall, the study provides a quantitative basis for connecting household waste-management improvements with decentralised renewable-energy planning.

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