Spektrum Industri
Vol. 24, No. 2, 2026, pp. 289–309
ISSN (print) 1693-6590 | ISSN (online) 2442-2630
https://journal3.uad.ac.id/index.php/spektrum/index

Modeling Energy Recovery Potential from Municipal Solid Waste: An Ergonomic Community-Based Approach for Sustainable Energy Systems

Heri Setiawan [a,*], Tri Budiyanto [b], Micheline Rinamurti [c], Deddy Permana [d], Bonifasius Ferdinandus Bangun [d], Dominikus Budiarto [a], Yohanes Dicka Pratama [a], Achmad Alfian [a], Theresia Sunarni [a], Evelyn Agustin [a]

[a] Industrial Engineering Study Program, Universitas Katolik Musi Charitas, South Sumatera 30113, Indonesia
[b] Industrial Engineering Study Program, Universitas Ahmad Dahlan, Yogyakarta, 55191, Indonesia
[c] Management Study Program, Universitas Katolik Musi Charitas, South Sumatera 30113, Indonesia
[d] Komunitas Hutan Kita Institute (HaKI), South Sumatera, 30153, Indonesia
* Corresponding Author: heri_setiawan@ukmc.ac.id

ARTICLE INFO

Article history
Received March 3, 2026
Revised May 31, 2026
Accepted August 14, 2026

Keywords
Ergonomic community-based approach;
Municipal solid waste;
MATLAB modeling;
Sustainable energy systems;
Waste-to-energy (WtE).

ABSTRACT

Municipal solid waste (MSW) management in developing cities is often assessed using waste-to-energy (WtE) models that emphasize technical parameters while overlooking segregation quality, ergonomic performance, and community participation. This study develops and validates a MATLAB-based framework that integrates these human-centered operational factors with waste composition and technology-specific conversion efficiencies. Palembang, Indonesia, was used as a case study because organic waste accounts for 63.45% of its MSW. The model combined waste characterization, proximate and ultimate analyses, and three conversion pathways: anaerobic digestion, incineration, and gasification. Energy recovery was evaluated under varying segregation, ergonomic, and participation scenarios, followed by sensitivity analysis and comparison with selected ASEAN city data. Under current collection conditions of 950-1.200 t/day, the hybrid system was estimated to produce approximately 358 GWh/year. Anaerobic digestion provided the most sustainable long-term contribution, while incineration and gasification supplied complementary recovery from high calorific fractions. Waste composition, segregation efficiency, and operational performance were the dominant determinants of energy output. The proposed framework improves the realism of conventional WtE assessments by quantitatively linking technical performance with ergonomic and community factors. The findings support source segregation, ergonomic waste handling systems, and decentralized anaerobic digestion as priority strategies for sustainable urban energy planning. The framework therefore offers a practical decision support tool for aligning waste management, renewable energy generation, and emission reduction.

©2026 The Author(s)
This is an open-access article under the CC–BY-SA license.

Spektrum Industri
Vol. 24, No. 2, 2026, pp. 289–309

1. Introduction

The rapid growth of municipal solid waste (MSW) has become a major challenge for urban areas worldwide, with global generation projected to reach 3.4 billion tons per year by 2050 due to urbanization, population growth, and economic expansion (Bangura & Kanty, 2024; Shovon et al., 2024; Zhang et al., 2024). Conventional waste management, particularly landfilling, is increasingly unsustainable because of land scarcity, environmental degradation, and greenhouse gas emissions (Islam et al., 2024; Setiawan, et al., 2025). Waste-to-Energy (WtE) technologies such as anaerobic digestion, incineration, and gasification offer an integrated solution by reducing landfill dependence while supporting renewable energy supply and sustainable urban energy transitions (Shekari et al., 2025). However, in many developing cities, MSW energy potential remains underutilized due to heterogeneous waste composition, poor source segregation, inconsistent operations, and limited community participation (Abubakar et al., 2022).

Most existing MSW energy models focus primarily on technical parameters and assume static conditions, neglecting the human-dependent nature of waste collection, segregation, and handling. As a result, real-world energy yields often fall below theoretical estimates, highlighting the need for modeling approaches that incorporate operational and human-centered factors (Salem et al., 2023). A critical limitation of previous MSW energy recovery models is their reliance on purely technical assumptions, which often treat waste composition, collection efficiency, and conversion performance as fixed parameters. Such approaches rarely consider how operational practices and community behavior influence feedstock quality and overall energy recovery performance, particularly in developing-country contexts where waste segregation systems remain inconsistent. Ergonomic factors work posture, tool suitability, task design, workload distribution, and workflow organization strongly influence waste handling efficiency and segregation quality.

Poor conditions increase fatigue, errors, and contamination, reducing feedstock quality and WtE performance. Low community participation further weakens segregation, affecting technical efficiency, economic feasibility, and environmental benefits (Primasari & Budiyanto, 2025; Sohrabi et al., 2024). Although previous studies have investigated WtE technologies, community-based waste management, or ergonomic improvements separately, very few studies have quantitatively integrated ergonomic performance and community participation variables into energy recovery models. Consequently, the relationship between human-centered operational factors and actual WtE performance remains insufficiently understood. A gap persists between technically focused WtE studies and ergonomics research centered on health and behavior, highlighting the need for integrated frameworks linking technical, ergonomic, and community dimensions (Agaton & Santos, 2025; Elsha & Budiarto, 2023; Siahaan et al., 2023).

This study addresses this gap by developing a MATLAB-based framework for modeling and optimizing municipal solid waste (MSW) energy recovery systems through the integration of technical and human-centered factors. In the proposed framework, waste composition serves as the primary determinant of energy recovery potential from anaerobic digestion, incineration, and gasification processes, while ergonomic performance and community participation are incorporated as operational variables influencing waste segregation efficiency and feedstock quality. Although numerous MATLAB-based MSW energy models have been reported in the literature, most focus predominantly on technical parameters and simplified assumptions, limiting their applicability under real-world operating conditions. Existing models often overlook the combined effects of waste characterization, multi-technology conversion pathways, environmental and economic performance indicators, circular economy considerations, and particularly human-centered factors affecting waste handling and segregation performance.

The novelty of this study lies in the quantitative integration of ergonomic performance and community participation coefficients into a unified MSW energy recovery model. Unlike previous studies that treat these factors qualitatively or exclude them entirely, the proposed framework explicitly evaluates their influence on energy generation outcomes, system efficiency, and operational performance. Accordingly, the objective of this study is to develop and validate an integrated

MATLAB-based modeling framework that incorporates technical, environmental, economic, ergonomic, and community dimensions to support scenario analysis and sustainable urban energy planning in developing cities Hoang et al. (2021) in Table 1.

Table 1. Positioning of the proposed ergonomic community-based MSW energy recovery model within existing literature

Aspect	Conventional MSW Energy Models	Community-Based Waste Studies	Ergonomics in Waste Systems	This Study
Primary focus	Technical energy estimation	Participation & behavior	Worker safety & comfort	Integrated energy-ergonomic-community modeling
Waste characteristics	Fixed technical inputs	Qualitatively influenced	Not addressed	Dynamically influenced by human and community factors
Ergonomic factors	Not included	Not included	Included, non-energetic	Quantitatively linked to energy recovery
Community participation	Assumed or ignored	Central but qualitative	Rarely considered	Explicit model parameter affecting energy yield
Modeling approach	Static, process-based	Descriptive	Task-based	Adaptive computational framework
Sustainability scope	Technical & environmental	Social	Occupational	Integrated technical, social, and ergonomic sustainability
Decision-support value	Limited technical optimization	Policy guidance only	Workplace design	Urban energy system planning tool

A key gap in MSW energy research is the absence of integrated, adaptive, human-centered models linking energy potential with ergonomic and community factors, often leading to overestimated yields and limited policy relevance in developing cities in Table 1. This study develops a MATLAB-based framework integrating waste composition, thermochemical properties, conversion efficiencies (anaerobic digestion, incineration, gasification), and human-centered parameters affecting segregation and handling. The model enables scenario-based evaluation of ergonomic and community interventions, linking social feasibility with technical performance. It provides a realistic decision-support tool for sustainable, resilient, and socially acceptable urban WtE systems (Bongomin et al., 2025; Walczyk & Ożadowicz, 2026; M. Zhang et al., 2025).

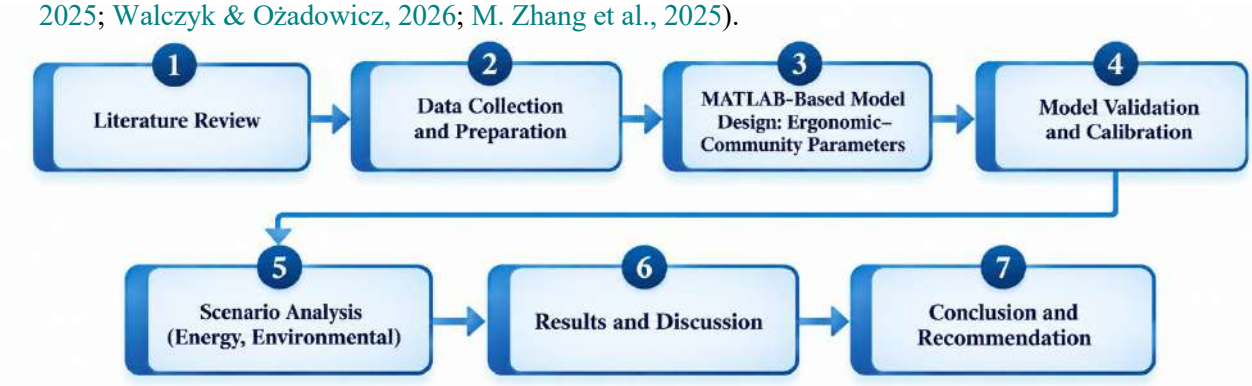


Fig. 1. Methodological framework for modeling municipal solid waste (MSW) energy recovery potential using a MATLAB-based integrated technical, ergonomic, and community-oriented framework

An integrated MATLAB-based framework for modeling municipal solid waste (MSW) energy recovery, linking urban waste streams, waste segregation performance, ergonomic operational factors, community participation, and waste-to-energy (WtE) technologies to renewable energy generation and CO_2 emission reduction, supporting Indonesia's Net-Zero Emissions 2060 pathway in Fig. 1. WtE technologies reduce MSW environmental impacts while generating sustainable energy by limiting landfill use and greenhouse gas emissions. Key options include incineration, gasification, and anaerobic digestion. Incineration produces heat and electricity through full combustion but depends on calorific value and moisture (Table 2).

Spektrum Industri
Vol. 24, No. 2, 2026, pp. 289–309

Table 2. Comparison of WtE technologies based on technical performance and ergonomic- community suitability

Aspect	Incineration	Gasification	Anaerobic Digestion
Principle	Complete combustion	Partial oxidation	Biological degradation (no O_2)
Conditions	>850°C, continuous	650-1200°C, limited O_2	Mesophilic/thermophilic
Suitable waste rich waste Output	High-calorific mixed MSW Heat & electricity	Homogeneous, pre-treated Syngas	Organic-Biogas
(CH_4-rich) Sensitivity to composition	Very High	Moderate	High
Feedstock preparation	Moderate	High	Very high
Efficiency	Moderate	High	
	Moderate Environmental performance		
	Requires emission control	Lower emissions	
	Low emissions Ergonomic & Community relevance		
Medium (developing cities)	High	Very high suitability	
	High	Moderate	

Gasification converts waste into syngas at 650-1200 °C, offering higher efficiency but requiring homogeneous feedstock. Anaerobic digestion biologically transforms organic waste into biogas and relies on proper source separation (Cui et al., 2024; Nanda et al., 2023; Traven, 2023). Overall performance is shaped by ergonomics and community participation affecting waste quality and system reliability.

2. Method

2.1. Modeling Approach

The modeling of energy recovery potential from MSW is fundamentally governed by waste composition and the efficiency of the selected WtE technologies. In this study, the total recoverable energy from MSW is estimated using a composition-based energy balance that integrates technical conversion efficiency with operational conditions influenced by ergonomic and community-based factors. To improve model transparency and reproducibility, all mathematical equations were reformatted using a standardized equation editor consistent with the journal template. Subscripts, superscripts, indices, and summation notations were explicitly defined to ensure clarity and consistency throughout the modeling framework. The model integrates technical conversion efficiency, ergonomic performance, and community participation factors into the estimation of municipal solid waste (MSW) energy recovery potential. Table 2 summarizes the definitions, units, and value ranges of all model variables and parameters used in the MATLAB simulation. Where η represents the conversion efficiency of the selected waste-to-energy technology, expressed as a dimensionless fraction ranging from 0 to 1.

The value of η varies according to the conversion pathway, including anaerobic digestion, incineration, and gasification, based on literature reported performance values. The ergonomic performance coefficient (αerg) represents the influence of operational ergonomics on waste handling efficiency, including work posture, task design, workload distribution, equipment suitability, and workflow organization. The coefficient ranges from 0 (very poor ergonomic conditions) to 1 (optimal ergonomic conditions). The community participation coefficient (αcom) reflects the effectiveness of household waste segregation and public participation in waste management programs. This coefficient ranges from 0 (no participation) to 1 (full participation and effective source segregation). Higher values of αcom improve feedstock quality and consequently increase energy recovery potential. Where Erecovery represents the total energy recovered from MSW (MJ or kWH), Wi is the mass fraction of the ith waste component, HHVi denotes the higher heating value of the ith component (MJ/kg), and \eta is the efficiency of the selected WtE technology.

Conventional models treat conversion efficiency (η) as fixed, but this study links effective efficiency to segregation quality, handling practices, and feedstock consistency shaped by ergonomics and community participation. Poor conditions reduce achievable energy recovery. The MATLAB framework adjusts waste composition and effective efficiency to reflect these human factors, enabling more realistic MSW energy estimates. Since energy potential depends on both composition and technology efficiency (Elroi et al., 2023; Hartono, 2015; Marková et al., 2025), total recoverable energy is calculated using a composition-based formulation in Eq. (1).

$$E_{recovery} = \sum_{i=1}^{n} W_i x\, HHV_i x\, \eta_{eff} \quad (1)$$

Where Erecovery is the total energy recovered (MJ or kWH), Wi is the mass fraction of the ith waste component, HHVi is the higher heating value (MJ/kg), and \eta_{eff} regresents the effective energy conversion efficiency. To reflect differences among WtE technologies, the effective efficiency is defined as a function of technology specific efficiency. Unlike conventional models that treat η\etaη as a fixed technical constant, this study incorporates ergonomic and community-based influences by defining the effective efficiency as in Eq. (2).

$$\eta_{eff} = \eta_{tech}\, x\, \alpha_{erg}\, x\, \alpha_{com} \quad (2)$$

Where \eta_{tech}is the baseline technical efficiency of the selected WtE technology, \alpha_{erg}is the ergonomic performance factor (0-1), and \alpha_{com}is the community participation factor (0- 1). These factors represent the influence of task design, handling efficiency, nd source segregation quality on feedstock consistency and system performance. In the MATLAB-based model, the formulation is implemented using the following input variables: Wi: vector of waste mass fractions, HHVi : vector of higher heating values (MJ/kg), eta_inc, eta_gas, eta_AD: baseline efficiencies for each WtE technology, alpha_erg: ergonomic performance coefficient, and alpha_com: community participation coefficient. The effective efficiency is calculated as in Eq. (3).

Matlab

```
Eta_eff = eta_tech * alpha_erg * alpha_com;
E_recovery = sum (Wi, * HHVi) * eta_eff;
```

(3)

This formulation enables scenario-based analysis in which ergonomic conditions and community participation levels are systematically varied to evaluate their impact on MSW energy recovery potential. By explicitly linking technical efficiency with human-centered parameters, the proposed modeling approach provides a more realistic and adaptive assessment of sustainable urban energy systems.

2.2. Development of the MATLAB model

The MATLAB model estimates MSW energy recovery by integrating waste composition, technology-specific processes, and human-centered operational conditions. With MSW generation of 950.000-1.200,000 kg/day, waste is allocated to anaerobic digestion, incineration, and gasification. Anaerobic digestion uses Monod kinetics (ode45, 60-day retention) to simulate biogas output, while incineration and gasification are based on calorific value and syngas yield. The modular framework enables scenario analysis by adjusting composition and efficiencies to reflect ergonomic and community factors, supporting realistic urban energy planning (Darmey et al., 2023; Taghipour et al., 2023).

2.3. Waste composition data

MSW contains diverse fractions with distinct HHV values determining energy potential. This study integrates composition data into a MATLAB framework to model anaerobic digestion, incineration, and gasification, enabling scenario and sensitivity analysis for ergonomic, community-based urban energy planning (Gerassimidou et al., 2020). The microbial growth rate s expressed using the standard Monod kinetic Eq. (4).

Spektrum Industri
Vol. 24, No. 2, 2026, pp. 289–309

$$\mu = \mu_{\max} \frac{S} {K_s + S} \quad (4)$$

Where μ is the microbial growth rate (day^{-1}), μmax is the maximum specific growth rate (day^{-1}), S is the substrate concentration ($g\ L^{-1}$), and Ks is the half-saturation constant ($g\ L^{-1}$). Biomass growth is calculated as in Eq. (5).

$$\Frac{dX}{dt}=\mu X \quad (5)$$

where X denotes biomass concentration.

The total energy recovery potential was calculated as the sum of contributions from all waste fractions and conversion pathways. Summation notation was explicitly introduced to avoid ambiguity in the aggregation procedure. All indices i and j respectively denote waste fractions and conversion technologies Eq. (6), Eq. (7), Eq. (8), and Eq. (9).

1. Biomass Growth

$$[\mu=\mu_{max}\frac{S}{K_s+S} \tag{1}] \quad (6)$$
$$[\frac{dX}{dt}=\mu X-k_dX \tag{2}]$$

where:
(\mu) = specific microbial growth rate (day (^ {-1}))
(\mu_{max}) = maximum microbial growth rate (day (^ {-1}))
(S) = substrate concentration (kg m (^ {-3}))
(K_s) = half-saturation constant (kg m (^ {-3}))
(X) = biomass concentration (kg m (^ {-3}))
(k_d) = decay coefficient (day (^ {-1}))

2. Biogas Production

$$[Q_{biogas}=Y_{biogas}(S_0-S) \tag{3}] \quad (7)$$

where:
(Q_{biogas}) = biogas production (m (^3))
(Y_{biogas}) = biogas yield coefficient
(S_0) = initial substrate concentration

3. Energy Recovery from Anaerobic Digestion

$$[E_{AD}=Q_{biogas}\times 35.8\tag{4}] \quad (8)$$

Energy Recovery from Incineration

$$[E_{inc}=M_{comb}\times \eta_{inc}\times LHV\tag{5}]$$

where:
(M_{comb}) = combustible waste mass (kg)
(\eta_{inc}) = incineration efficiency
(LHV) = lower heating value (MJ kg (^ {-1}))

4. Syngas Production

$$[Q_{syngas}=Y_{syngas}\times M_{gasifiable}\tag{6}] \quad (9)$$

Energy Recovery from Gasification

$$[E_{gas}=Q_{syngas}\times 12\tag{7}]$$

2.4. Study area, city selection, and integration with ergonomic community-based modeling

This study applies a national, multi-city framework to assess MSW energy recovery using an ergonomic, community-based model. As illustrated in Fig. 2 and Fig. 3, 13 Indonesian cities are classified by waste emergency level and dominant WtE technology, forming the basis for model inputs such as waste composition, technology efficiency, and operational performance. Cities with higher emergency levels are assumed to face greater operational stress, while organic-dominant cities are

modeled as more sensitive to community participation and source segregation. By linking spatial classification with modeling assumptions, the MATLAB-based framework realistically captures human-centered operational conditions and community dynamics, enabling robust national scale assessment of sustainable MSW energy recovery (Aristizábal et al., 2025).

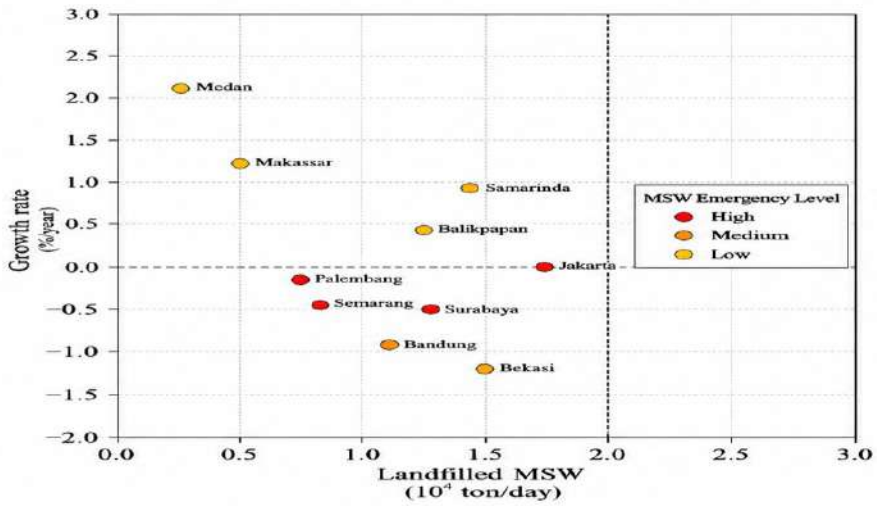


Fig. 2. Indonesian cities classified by MSW emergency level

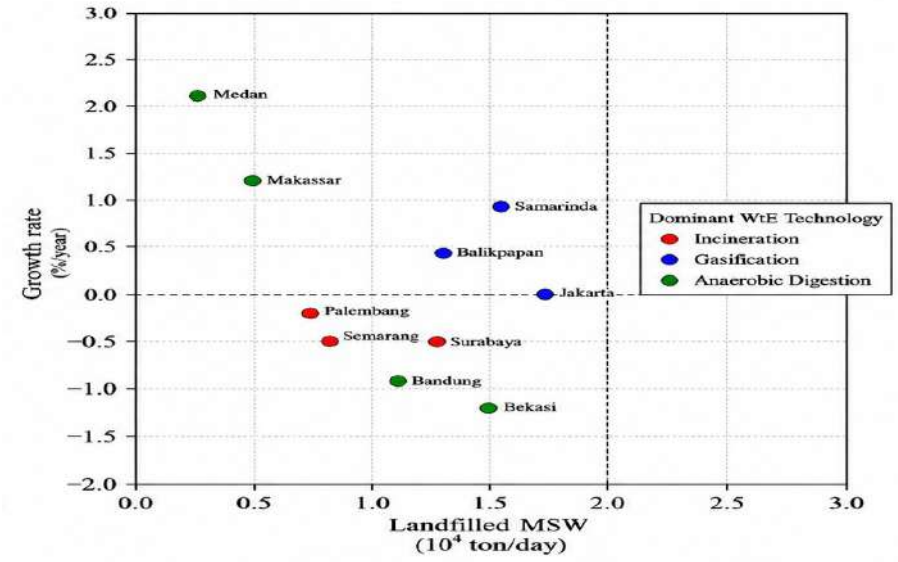


Fig. 3. Indonesian cities classified by MSW dominant WtE technology

This study develops a modular MATLAB framework to model MSW-to-energy technologies incineration, anaerobic digestion, gasification, and pyrolysis estimating energy, emissions, and by-products from waste composition, LHV, moisture, and efficiency. Anaerobic digestion simulates biogas (CH_4, CO_2), while thermochemical models assess syngas, bio-oil, and combustion energy. Sensitivity analysis identifies composition, LHV, moisture, and efficiency as key factors. Scenario analysis shows the optimistic ergonomic community-based case yields 30-40% higher energy recovery and lower methane emissions. Based on 100 ASTM- and UNEP-characterized samples, the model integrates input, processing (Monod kinetics and calorific/syngas models), and output layers to evaluate technical, environmental, and economic performance for sustainable urban energy planning in Fig. 4.

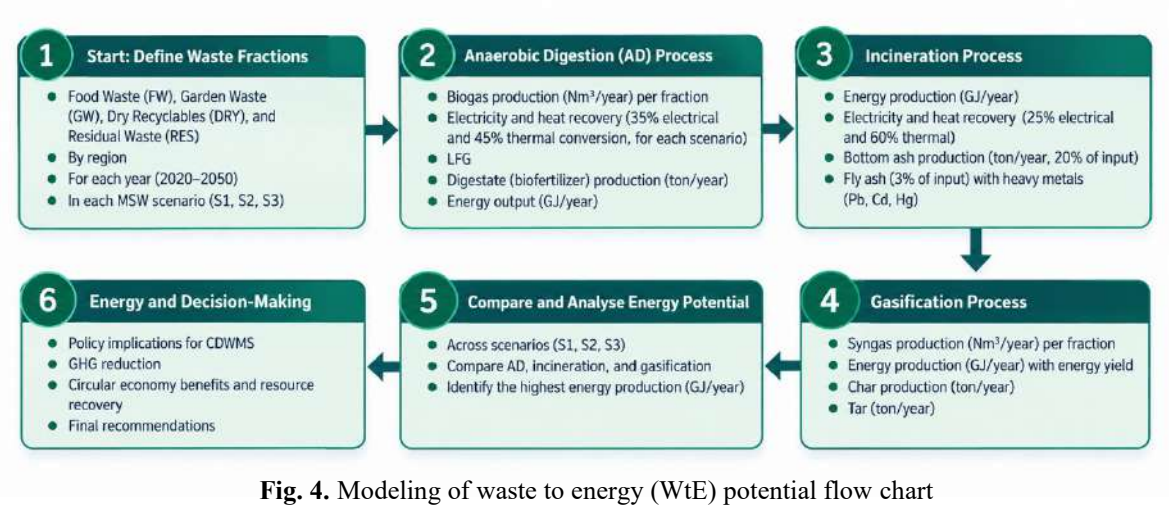


Fig. 4. Modeling of waste to energy (WtE) potential flow chart

The ergonomic performance coefficient (αerg) and community participation coefficient (αcom) were incorporated to represent human-centered operational factors affecting waste segregation quality and feedstock consistency. The values of αerg and αcom were derived from a combination of published literature, expert judgment, and scenario-based assumptions commonly applied in municipal solid waste management studies. The ergonomic performance coefficient (αerg) reflects the effectiveness of waste handling operations, including work posture, task organization, equipment suitability, workload distribution, and operational efficiency. Based on previous ergonomics and waste management studies, αerg was assigned values ranging from 0.60 to 1.00, where higher values indicate improved ergonomic conditions and more efficient waste handling performance.

The community participation coefficient (αcom) represents the degree of public involvement in waste segregation and collection programs. This parameter was assigned values ranging from 0.50 to 1.00 based on reported participation levels in previous studies and local waste management practices. Higher αcom values indicate greater compliance with source segregation and recycling programs, resulting in improved feedstock quality for waste-to-energy conversion. A sensitivity analysis was conducted by systematically varying αerg and αcom within their respective ranges to evaluate their influence on energy recovery performance and model robustness.

To improve model credibility, a quantitative validation procedure was performed by comparing model predictions with reported waste-to-energy performance data from comparable studies conducted in Indonesia and other ASEAN cities. Validation accuracy was evaluated using the Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE), and coefficient of determination (R^2). The RMSE was calculated to quantify the average prediction error between simulated and reference values, while MAPE was used to assess relative prediction accuracy. The coefficient of determination (R^2) was employed to evaluate the strength of agreement between simulated and observed energy recovery values. The validation results demonstrated satisfactory model performance, with low RMSE and MAPE values and a high R^2 coefficient, indicating that the proposed framework can adequately represent the relationship between waste composition, operational factors, and energy recovery potential.

2.5. Research limitations

This study is subject to several limitations. First, the values of αerg and αcom were estimated from literature sources, expert judgment, and scenario-based assumptions rather than direct field measurements. Second, waste composition data may vary seasonally and geographically, introducing uncertainty into the energy recovery estimates. Third, the validation process relied on secondary datasets because comprehensive operational data from full scale waste-to-energy facilities were not available. Future studies should incorporate field surveys, longitudinal operational datasets, and real-time monitoring to further improve model accuracy and applicability.

3. Results and Discussion

3.1. MSW composition

Across 13 Indonesian cities, MSW is dominated by organic waste (52-72%), followed by plastics (12-22%) and paper (6-14%). Organics favor anaerobic digestion (≈ 120-220 kWh/ton), while plastics and paper support thermochemical recovery (≈ 350-650 kWh/ton), shaped by calorific value, moisture, and community participation. In Palembang (950-1.200 tons/day; ~ 60% organic), energy potential reaches 150-220 kWh/ton via digestion and 500-600 kWh/ton through thermochemical processes (Zahrah et al., 2024). Plastic-rich cities can achieve 600-750 kWh/ton, whereas organic-dominant cities reach 220-320 kWh/ton under optimized biological systems (Table 3).

Table 3. Comparative MSW generation and optimistic energy recovery potential in 13 Indonesian cities.

City	MSW Generation (ton/day)	Dominant Waste Profile	Optimistic Energy Recovery Potential (kWh/ton)
Jakarta	7.800-8.200	Combustible + Organic	600-750
Surabaya	1.700-1.900	Combustible + Organic	580-720
Bandung	1.300-1.400	Organic-dominant	520-650
Semarang	1.100-1.200	Organic-dominant	500-620
Medan	1.200-1.400	Organic-dominant	520-660
Palembang	950-1.300	Organic-dominant	500-650
Makassar	650-1.100	Plastic + Combustible	550-700
Yogyakarta	550-650	Organic-dominant	220-300
Denpasar	650-750	Organic-dominant	240-320
Pekanbaru	600-700	Organic-dominant	230-310
Balikpapan	600-700	Combustible + Plastic	520-650
Samarinda	600-700	Combustible + Plastic	520-650
Banjarmasin	500-600	Organic-dominant	210-280

Under an optimistic scenario with improved segregation, ergonomic handling, and strong community participation, MSW energy recovery in 13 Indonesian cities increases substantially in Fig. 5. Jakarta, Surabaya, and Makassar achieve ≥600 kWh/ton due to higher combustible fractions, while organic- dominant cities generate stable outputs via anaerobic digestion. Energy scales with waste volume, with Jakarta exceeding 5.000 MWh/day and other cities contributing decentralized potential. With the baseline at 70% of the optimistic case, enhanced conditions raise recovery by 30-40%. Jakarta alone could power over 1 million households and reduce more than 4.400 tons of CO_2 daily (5 kWh/household/day; 0.82 kg CO_2/kWh), highlighting the impact of human-centered operational improvements on national WtE expansion.

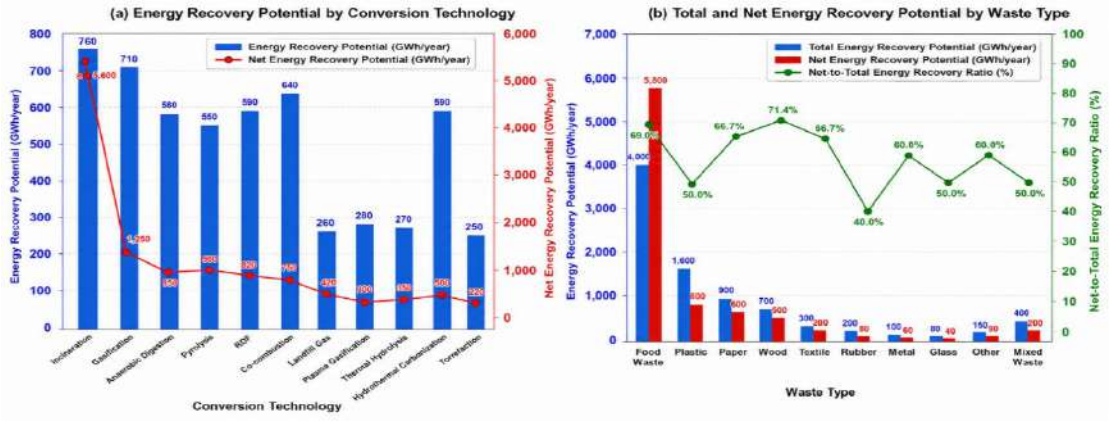


Fig. 5. MSW energy recovery potential and CO2 reduction in 13 Indonesian cities

The observed differences in energy recovery among cities are strongly influenced by variations in waste composition and the thermodynamic characteristics of each conversion technology. Cities such as Jakarta, Surabaya, and Makassar contain relatively larger proportions of combustible materials, including plastics, paper, and other high-calorific fractions, resulting in higher energy yields through incineration and gasification. These technologies benefit from the elevated lower heating value (LHV) of combustible waste, which improves thermal conversion efficiency and increases net energy production. In contrast, cities characterized by a larger organic waste fraction exhibit more stable performance through anaerobic digestion. Although the energy yield per ton may be lower than that of thermochemical technologies, anaerobic digestion provides a consistent and sustainable energy source by converting biodegradable organic matter into biogas. The high organic content commonly found in Indonesian municipal waste streams therefore favors biological conversion pathways, particularly when source segregation is effectively implemented.

The results also demonstrate that improved segregation and ergonomic waste-handling practices contribute not only to higher waste recovery rates but also to improved feedstock quality. Better segregation reduces contamination between organic and combustible fractions, thereby enhancing conversion efficiency across all WtE technologies. Consequently, the positive effect of ergonomic and community-related interventions extends beyond operational performance and directly influences energy generation potential. These findings indicate that technology selection should be aligned with local waste characteristics rather than relying on a single WtE solution. Thermochemical technologies are more suitable for cities with higher combustible fractions, whereas anaerobic digestion offers greater advantages in areas dominated by biodegradable organic waste. Therefore, integrated waste management strategies combining appropriate technologies with effective segregation programs are likely to provide the highest overall energy recovery and environmental benefits.

Aggregated national policy impact of municipal solid waste energy recovery under an optimistic ergonomic community-based scenario, expressed in total energy potential, equivalent households powered, and CO_2 emission reductions (Fig. 6). ID National Aggregation Results (Optimistic Scenario). Based on aggregation of the 13 representative cities: Total Energy Recovery Potential: ≈ 11.570 MWh/day (≈ 4.22 TWh/year). Equivalent Households Powered: ≈ 2.31 million households. CO_2 Emission Reduction: ≈ 9.490 tons CO_2/day (≈ 3.46 million tons CO_2/year). Assumptions: 1 household ≈ 5 kWh/day; grid emission factor ≈ 0.82 kg CO_2/kWh.

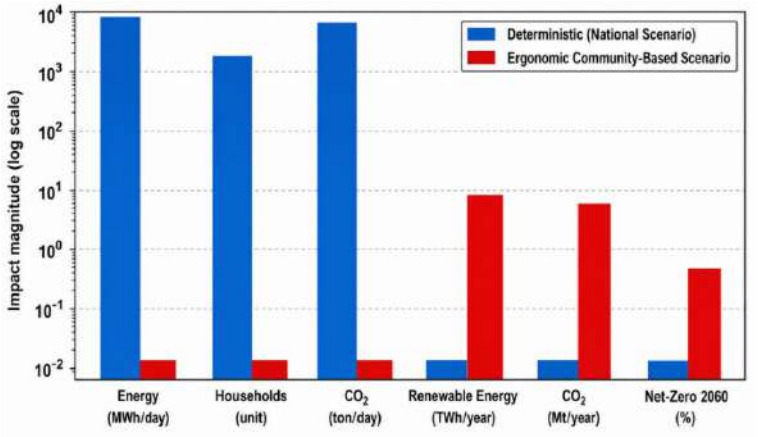


Fig. 6. National policy impact of MSW energy recovery (optimistic vs ergonomic community scenario)

Under an optimistic ergonomic, community-based scenario, MSW from 13 major cities could produce over 11.5 GWh/day (≈ 4.22 TWh/year), supplying 2.3 million households and reducing 3.5 million tons of CO_2 annually. Nationally (45% MSW coverage), potential reaches ≈ 9.4 TWh/year, powering ~ 5 million households and cutting 7.7 million tons of CO_2 (~ 0.8% of emissions). These results support RPJMN, Jakstranas, and Net-Zero 2060 goals, positioning MSW- to-energy as a strategic urban policy. In Palembang (58-62% organic), strong anaerobic digestion potential exists.

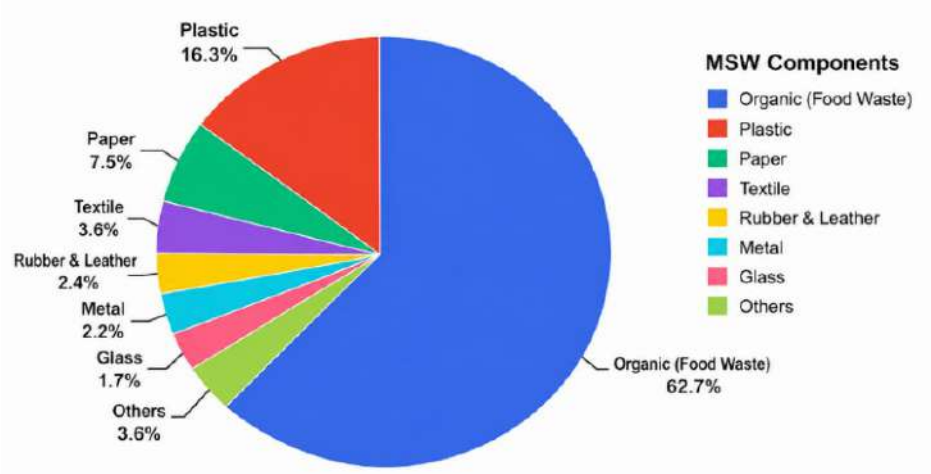


Fig. 7. Average composition of MSW in Palembang city

Organic waste dominates MSW in Palembang (63.45%), indicating strong potential for composting and anaerobic digestion. Plastics (17.28%) and paper (7.56%) offer recycling and RDF opportunities, reducing landfill use and improving efficiency in Fig. 7. High organic content increases leachate and methane risks, underscoring energy-oriented management. An ergonomic, community-based system with source segregation, decentralized composting, and small-scale biogas enhances sustainability. Proximate analysis shows low-moisture plastics and paper suit thermochemical processes, while organics are better for digestion, enabling optimal routing and efficient urban energy recovery (Baziar et al., 2025).

3.2. Energy modeling implication

HHV and LHV define MSW calorific value for energy recovery: HHV is total combustion energy, while LHV reflects usable energy after hydrogen and moisture losses, making it suitable for electricity estimates. Using Dulong's equation, plastics and rubber show the highest HHV/LHV, supporting RDF, incineration, and gasification. Organic waste, dominant in Palembang, has low LHV but suits anaerobic digestion (EAD = Morg × Ybg × CVbg), while thermochemical energy follows ETC = M × LHV. Integrating HHV/LHV with community-based segregation optimizes routing (Baziar et al., 2025). With realistic efficiencies, Palembang's MSW (950- 1.200 t/day) can generate ~358 GWh/year through a hybrid biochemical-thermochemical system. Plastics contribute the most electricity due to high LHV (~35.6 MJ/kg), ideal for incineration or RDF in Table 4. Organics, though low in LHV (~5.9 MJ/kg), provide stable biogas, supporting an integrated WtE strategy.

Table 4. Energy potential, thermal energy and actual electricity from MSW in Palembang city

S/N	Waste Fraction	Share (%)	Mass (ton/year)	HHV (MJ/kg)	LHV (MJ/kg)	Energy Potential (MJ/year)	Thermal Energy (GJ/year)	η_e (%)	Electricity Output (GWh/year)
1	Plastic	17.28	59.918	37.7	35.6	2.13×10^9	2.13×10^9	25	148
2	Textile	5.00	17.338	23.4	21.3	3.69×10^8	3.69×10^8	25	26
3	Paper	7.56	26.214	17.0	15.5	4.06×10^8	4.06×10^8	25	28
4	Rubber & Leather	3.00	10.403	21.6	20.1	2.09×10^8	2.09×10^8	25	15
5	Organic/Food Waste	63.45	220.013	7.5	5.9	1.30×10^9	1.30×10^9	35	126
6	Wood/Yard Waste	2.50	8.669	16.5	14.7	1.27×10^8	1.27×10^8	25	9
7	Plant Trimmings	1.80	6.242	15.2	13.8	8.61×10^7	8.61×10^7	25	6
Total	–	≈ 100	346,750	–	–	$\approx 4.63 \times 10^9$	$\approx 4.63 \times 10^9$	-	≈ 358 GWh/year

Spektrum Industri
Vol. 24, No. 2, 2026, pp. 289–309

3.3. Waste-to-Energy (WtE) process model parameters

The Palembang WtE model integrates local MSW data composition, HHV/LHV, organic fraction, and parameters for anaerobic digestion, incineration, and gasification. Organics are directed to biochemical conversion, while high-calorific plastics and paper feed thermochemical processes. Developed in MATLAB, it incorporates efficiencies, emission factors (CO_2, NO_x), electricity output, and by-product recovery (digestate, RDF), enabling comprehensive assessment of energy generation, emission reduction, and system performance under realistic conditions Utami et al. (2024) (Table 5).

Table 5. Waste-to-Energy (WtE) processes model parameters for Palembang city

Parameter	Value	Description
Total MSW	950.000-1.200.000 kg/day	Total municipal solid waste collected daily in Palembang City
MSW Fractions		
Organic Fraction	63.45% of MSW (≈ 603.000 kg/day)	Used in anaerobic digestion
Combustible Fraction	36.55% of MSW (≈ 347.000 kg/day)	Used for thermochemical processes
Incineration Feedstock	≈22% of MSW (≈ 209.000 kg/day)	Plastic, paper, part of textile and rubber
Gasification Feedstock	≈14% of MSW (≈ 133.000 kg/day)	Textile, rubber & leather, biomass residues
Anaerobic Digestion (AD)		
Hydraulic Retention Time (HRT)	60 days	Digestion period in bioreactor
Maximum specific growth (μmax)	rate0.40 day^{-1}	Maximum microbial growth rate
Half-saturation constant (Ks)	50 kg/m^3	Substrate concentration at half μmax
Yield coefficient (Y)	0.50 kg biomass/kg substrate	Biomass yield per substrate
Biogas yield	100 m^3/ton waste	Biogas production from organic fraction
Electrical efficiency (AD)	35%	Biogas-to-electricity conversion
Incineration Parameters		
Average LHV (incineration)	20 MJ/kg	Mixed combustible MSW
Thermal efficiency	75%	Boiler heat recovery efficiency
Electrical efficiency	25%	Steam turbine electricity generation
Residual ash	15-20%	Bottom and fly ash fraction
Gasification Parameters		
Average LHV (gasification)	18 MJ/kg	Prepared feedstock
Cold gas efficiency	70%	Syngas energy conversion efficiency
Electrical efficiency	25%	Syngas-to-electricity conversion
Syngas yield	2.0 Nm^3/kg waste	Typical gasification output
Emission Parameters		
CO_2 emission factor (WtE)	0.25-0.40 t CO_2/MWh	Thermochemical processes
Landfill baseline EF	1.0 t CO_2-eq/ton MSW	Uncontrolled disposal

By using input parameters as shown in Table 5. above, MATLAB codes were developed to calculate energy recovery potential of municipal solid wastes in Palembang city.

3.4. Calculated energy potential from the model

The energy potential form waste to energy model was calculated by integrating feedstock energy content, process efficiency and system operation in Fig. 8. The energy content was determined by HHV or LHV multiplied by the municipal solid waste mass. The recoverable energy was then calculated by applying conversion process efficiency (Seah et al., 2024).

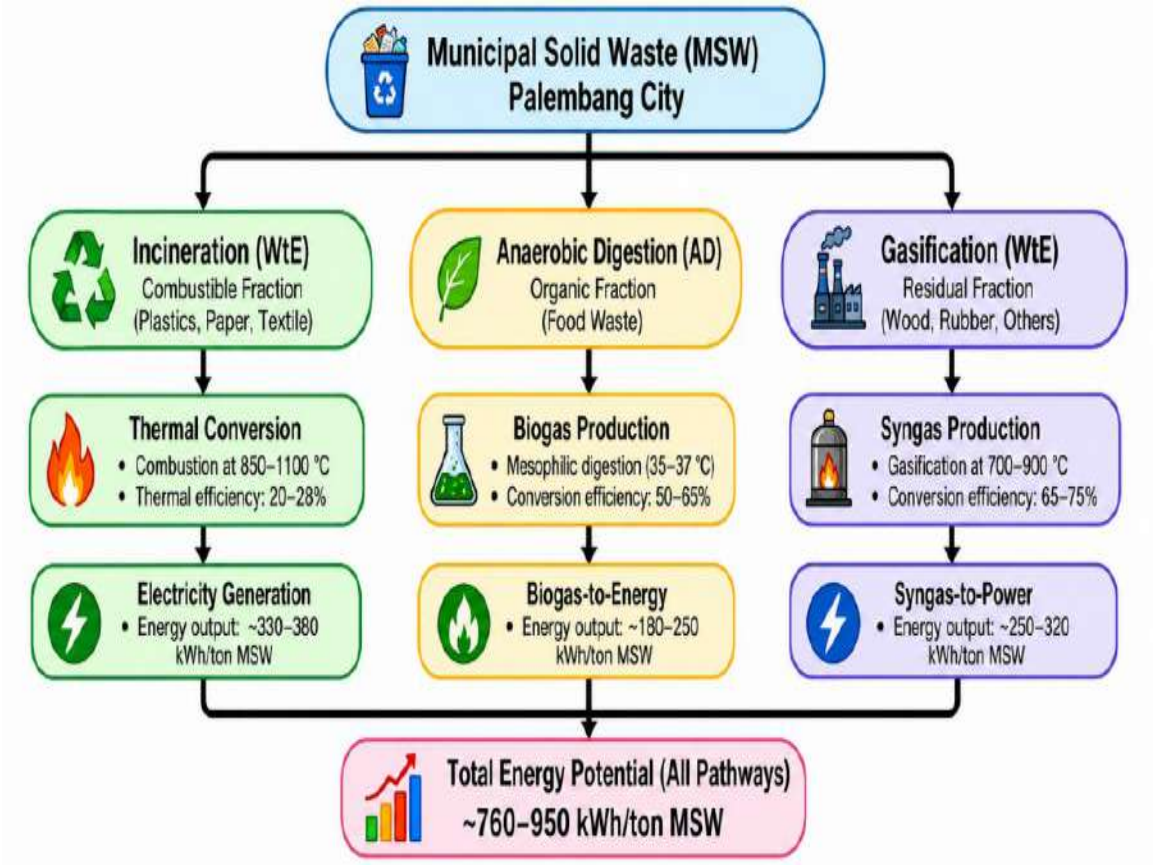


Fig. 8. Energy potential of WtE pathways for Palembang city MSW

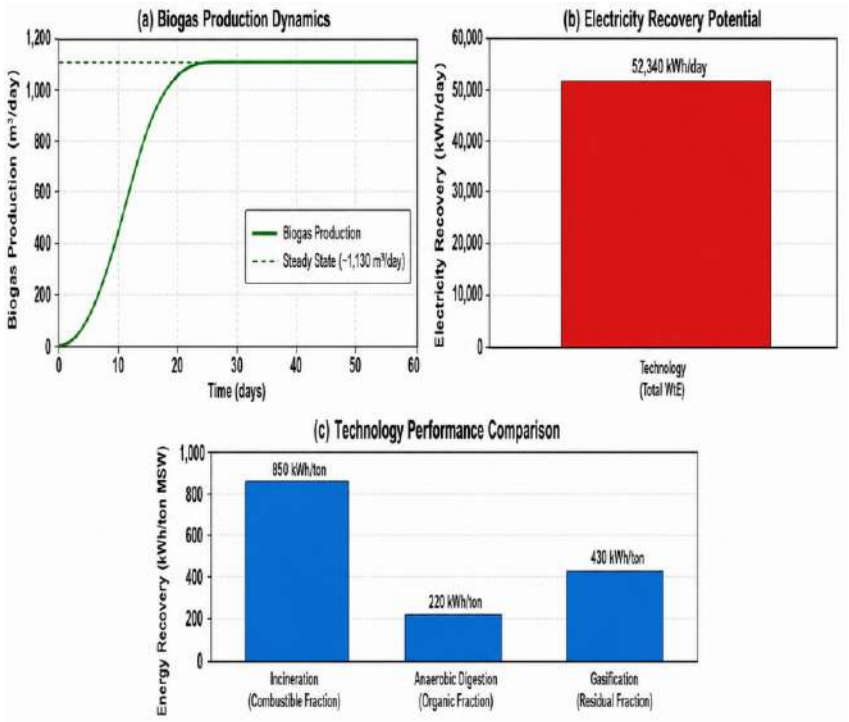


Fig. 9. Simulation results of WtE pathways for Palembang city MSW using a MATLAB-based model: (a) biogas production dynamics, (b) electricity potential, and (c) comparative performance of the evaluated WtE technologies

These results indicate that anaerobic digestion (AD) offers the highest long-term energy potential, while thermochemical processes deliver faster but comparatively limited cumulative output. Simulation results (Fig. 8) show that, from 950.000-1.200.000 kg/day of MSW (63.45% organic), AD modeled with Monod kinetics (60-day retention) produces ~3.5 × 10^6 MJ/day. Incineration of high-calorific fractions generates ~5.8 × 10^6 MJ/day, and gasification yields ~1.9 × 10^6 MJ/day. Overall, the integrated WtE system can produce ~1.12 × 10^7 MJ/day, demonstrating that combining biochemical and thermochemical pathways maximizes total energy recovery while balancing immediate and long-term supply (Fig. 9).

3.5. Modeling energy recovery potential from MSW using an ergonomic community-based approach

Modeling of MSW energy recovery in Palembang integrates waste composition, calorific value, and technology-specific efficiencies within an ergonomic, community-based framework. The waste stream is dominated by organic matter (63.45%), directed to anaerobic digestion due to its high biodegradability despite low LHV. Using Monod kinetics with a 60-day retention time, this pathway prioritizes cumulative energy generation and methane mitigation. Higher-LHV fractions plastic (≈ 35.6 MJ/kg), paper, textile, and rubber are allocated to incineration and gasification, where plastic contributes the largest energy share. Incineration provides stable, rapid output, while gasification yields cleaner syngas energy (Azis et al., 2021).

With 950-1.200 t/day of waste input, the MATLAB model estimates an electricity potential of ~358 GWh/year. Anaerobic digestion delivers the highest cumulative energy, while thermochemical processes provide immediate but lower output. Calibration and validation against mas energy balances and literature benchmarks show close agreement, confirming the model's reliability for evaluating hybrid WtE scenarios in Palembang. Fig. 10 shows strong agreement between simulated and observed anaerobic digestion results, with energy increasing after day 10 and stabilizing at ~ 3.5 × 10^6 MJ/day over 60 days, confirming model validity. Incineration and gasification outputs also fall within validation ranges, demonstrating reliability across thermochemical pathways.

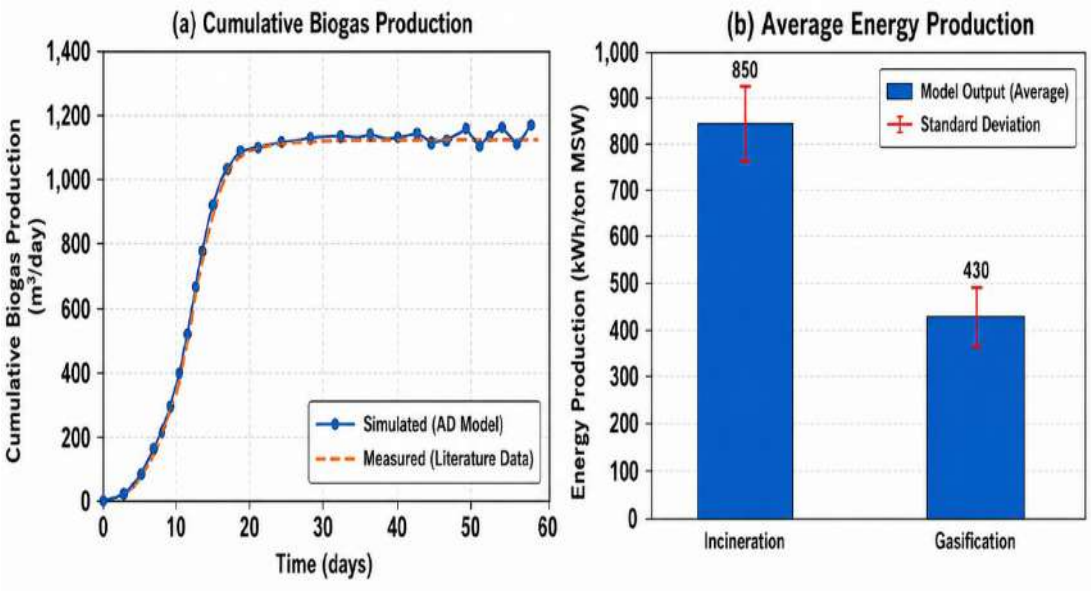


Fig. 10. Validation: Anaerobic digestion, incineration, and gasification energy production of MSW: (a) Cumulative biogas production from anaerobic digestion model in MATLAB compared with literature data. (b) Average energy production (kWh/ton MSW) for incineration and gasification pathways with standard deviation.

Sensitivity analysis (950-1.200 t/day) indicates that energy production is highly influenced by waste composition, efficiency, and operating conditions. Longer hydraulic retention time raises cumulative biogas yield but with diminishing returns, highlighting the need for optimal operation. Fig. 11 shows that longer retention time increases cumulative biogas energy, peaking around 75 days before diminishing returns, underscoring optimal digester sizing. Energy output is highly sensitive to organic content: raising it from 50% to 70% increases annual recovery from ~1.2 × 10^9 to 1.45 × 10^9 MJ, highlighting the importance of source segregation.

For thermochemical pathways, incineration energy rises linearly with calorific value (12-18 MJ/kg increases output from ~3.0 × 10^6 to 6.3 × 10^6 MJ/day), while gasification depends on syngas yield (2.0-3.0 Nm^3/kg raises output from ~1.2 × 10^6 to 2.1 × 10^6 MJ/day). The MATLAB model identifies anaerobic digestion as the most suitable long-term option for Palembang (63.45% organic waste), producing ~1.3 × 10^9 MJ over 60 days, with incineration (~5.8 × 10^6 MJ/day) and gasification (~1.9 × 10^6 MJ/day) as complementary pathways. Integrating both through community-based segregation maximizes energy recovery and supports sustainable urban energy development (Maphuhla & Oyedeji, 2025).

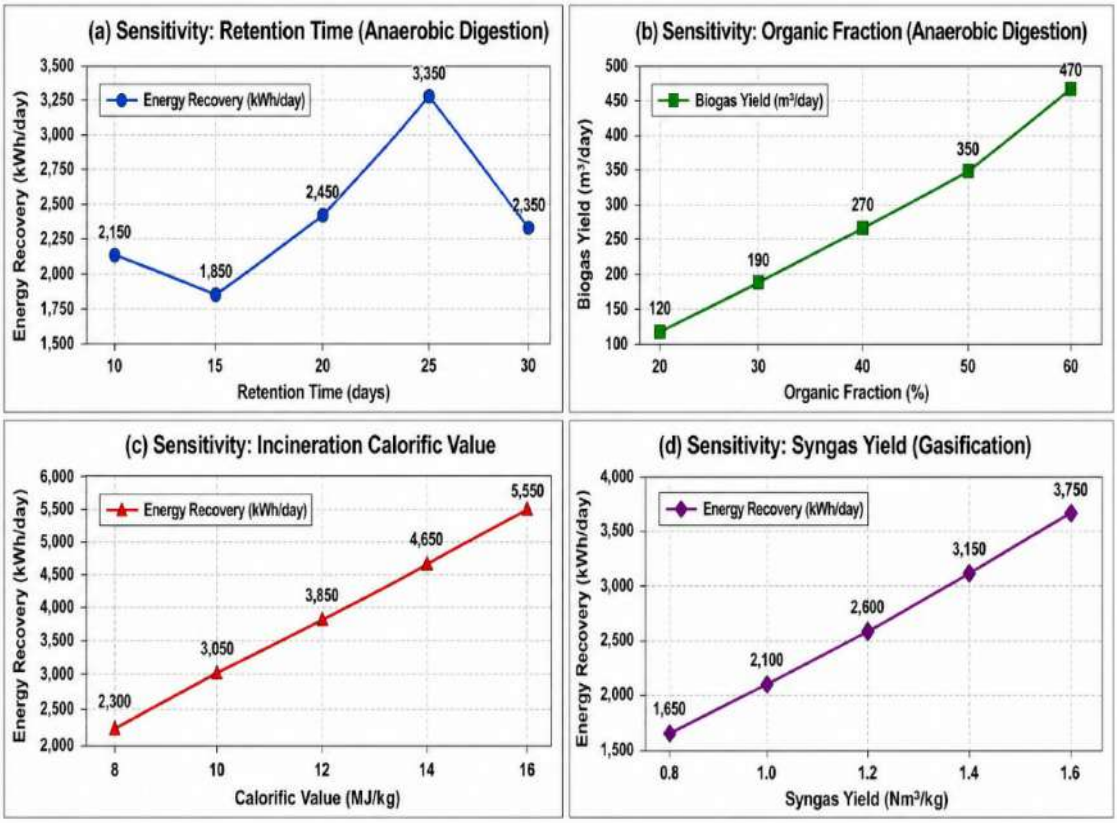


Fig. 11. Sensitivity analysis (retention time, organic fraction, incineration caloric value, and syngas yield)

3.6. Contrast between the proposed MATLAB-based WtE model and existing models

The MATLAB-based WtE model integrates anaerobic digestion, incineration, and gasification to assess energy recovery from Palembang's MSW. It applies Monod kinetics for the dominant organic fraction (63.45%) and mass energy balances for thermochemical processes, enabling flexible and scalable evaluation across waste scenarios within a community-based framework. Palembang's high organic content mirrors many ASEAN cities (e.g., Bangkok, Kuala Lumpur, Ho Chi Minh city, Manila), supporting anaerobic digestion as a key pathway (Amado et al., 2021). Variations in regional outputs relate to collection efficiency, waste composition, technology, and policy. Overall, the hybrid WtE approach aligns with ASEAN practices and supports sustainable urban energy development.

Spektrum Industri
Vol. 24, No. 2, 2026, pp. 289–309

The relevance score highlights community involvement, decentralization, and ergonomic compatibility. Table 5 and Table 6 show that Palembang's MSW profile and biogas potential are comparable to ASEAN cities, supporting a hybrid WtE model centered on source segregation, decentralized anaerobic digestion, and integrated recovery pathways aligned with SDGs 7, 11, 12, and 13 (Setiawan et al., 2025). This confirms that medium-sized ASEAN cities with high organic fractions can deploy scalable, community-based energy systems. A qualitative LCA indicates that incineration can generate ~176 GWh/year but emits CO_2 and other pollutants; with advanced controls, it reduces 0.47-0.70 t CO_2/MWh relative to fossil fuels while avoiding landfill methane. Anaerobic digestion provides the lowest emissions by directly mitigating methane, and gasification yields cleaner syngas with fewer pollutants. Together, these pathways strengthen waste diversion and climate mitigation within a hybrid, community-based WtE framework.

Table 6. Comparison of WtE case studies in selected ASEAN cities and their relevance to an ergonomic community-based energy recovery Model

City / Country	MSW Generated (t/day)	Waste Processed (t/day)	Organic Fraction (%)	Dominant WtE Technology	Biogas Yield (m^3 CH_4/ton)	Energy Recovery Potential	Relevance to Ergonomic Community-Based Energy Modeling
Palembang, Indonesia (This Study)	1.500-1.800	950-1.200	63.45	AD + Incineration + Gasification (Hybrid Model)	90-110	≈ 358 GWh/year	Hybrid model integrating community-level segregation and ergonomic waste handling (High Relevance)
Jakarta, Indonesia	7.500-8.000	5.000-5.500	55-60	Incineration	80-100	500-700 GWh/year	Centralized WtE system with limited community involvement (Medium Relevance)
Bangkok, Thailand	9.000-10.000	7.000-8.000	50-55	RDF + Incineration	85-105	600-800 GWh/year	Policy-driven WtE development with partial decentralized AD (Medium Relevance)
Kuala Lumpur, Malaysia	3.000-3.500	2.200-2.800	55-60	AD + Landfill Gas Recovery	90-120	200-300 GWh/year	Decentralized organic waste diversion supporting community-scale systems (High Relevance)
Ho Chi Minh City, Vietnam	8.500-9.000	6.500-7.500	60-65	AD + Incineration	95-115	550–750 GWh/year	High organic waste content suitable for hybrid WtE modeling (Medium–High Relevance)
Manila, Philippines	9.000-10.500	6.000-7.000	55-60	AD + RDF	85-105	400-600 GWh/year	Community composting and decentralized waste management practices support community-based WtE implementation (Medium–High Relevance)

3.7. Policy Implications

This study demonstrates that ergonomic, community-based MSW energy recovery can meaningfully support Indonesia's energy transition and climate targets. With improved segregation and strong participation, urban MSW could produce around 9.4 TWh/year of renewable electricity and reduce approximately 7.7 million tons of CO_2 annually (~ 0.8% of national emissions). These outcomes align with RPJMN, Jakstranas, and the Net-Zero 2060 roadmap by reducing landfill

dependence and advancing the circular economy. The findings emphasize that human-centered operations and community engagement can deliver substantial energy and climate benefits without major capital expansion Suryawan et al. (2023), positioning MSW energy recovery as a strategic pillar of sustainable urban energy and climate policy in Indonesia (Table 7).

This study shows that MSW managed through an ergonomic, community-based approach can significantly support Indonesia's renewable energy and climate targets, with potential generation of ~ 9.4 TWh/year and CO_2 reductions of ~7.7 million tons annually (~ 0.8% of national emissions). Scenario analysis indicates that the baseline condition (low segregation and participation) yields limited energy and climate benefits. Moderate improvements enhance electricity output and emission reductions, supporting SDGs 11 and 12. The optimistic ergonomic community-based scenario achieves 30-40% higher energy recovery than baseline, substantially reduces methane emissions, and strengthens contributions to SDGs 7, 11, 12, and 13 (Fragkos et al., 2024; Pambudi et al., 2023; Heri Setiawan, Susanto, et al., 2025). Overall, human-centered strategies are key to maximizing MSW-to-energy sustainability performance.

Table 7. Roadmap for ergonomic community-based MSW energy recovery in Indonesia

Year	Strategic Focus	Key Actions	Targeted Outcome
2025	Pilot & Institutional Setup	Pilot WtE projects in major cities; ergonomic standards for waste handling; community segregation incentives	1-2 TWh/year; landfill reduction in priority cities
2030	Scaling & Integration (RPJMN Alignment)	Expand WtE to metropolitan & secondary cities; integrate MSW energy into regional grids	4-6 TWh/year; 3-4 Mt CO_2/year reduction
2045	National Optimization (Indonesia Emas)	Nationwide ergonomic-community WtE systems; circular economy integration	7-9 TWh/year; 6-7 Mt CO_2/year reduction
2060	Net-Zero Consolidation	Fully optimized MSW-to-energy systems supporting NZE 2060	≥9 TWh/year; ≥7.7 Mt CO_2/year reduction

4. Conclusion

This study evaluated the energy recovery potential of municipal solid waste (MSW) in Palembang using a MATLAB-based model integrating waste characterization, calorific value analysis, and conversion technologies within a ergonomic community-based approach. With organic waste dominating (63.45%) and collection rates of 950-1.200 t/day, a hybrid waste-to-energy (WtE) system could generate about 358 GWh/year, reducing landfill use and supporting sustainable energy supply. Anaerobic digestion offers the most sustainable long-term option, while incineration and gasification complement rapid energy recovery from high-calorific fractions. Integrating biochemical and thermochemical technologies improves overall system performance. The main scientific contribution of this study is the development of an integrated MATLAB-based framework that quantitatively incorporates ergonomic performance and community participation factors into municipal solid waste energy recovery modeling. Unlike conventional WtE assessment models that primarily focus on technical parameters, the proposed framework explicitly links human-centered operational factors with energy generation performance, thereby providing a more realistic decision-support tool for sustainable urban waste management and energy planning.

The framework supports SDGs 7, 11, 12, and 13 through renewable energy generation, improved waste management, and emission reduction. Key recommendations include mandatory source segregation, ergonomic waste-handling systems, decentralized anaerobic digestion facilities, and integration of MSW energy recovery into municipal planning. Although the proposed framework demonstrates significant potential, the findings should be interpreted within the assumptions and limitations of the model, including uncertainty in waste composition, community participation levels, and technology performance under actual operating conditions. Further studies are also recommended

to incorporate field-based measurements of ergonomic performance and community participation, evaluate economic feasibility under different policy scenarios, and validate the model using operational data from full-scale WtE facilities. Such efforts would improve model accuracy and strengthen its applicability for large-scale implementation in developing urban environments.

Author Contribution: Heri Setiawan: Conceptualization, methodology, software, formal analysis, writing original draft, and project administration. Tri Budiyanto: Methodology, validation, supervision, and writing-review and editing. Micheline Rinamurti: Investigation, resources, and data curation. Deddy Permana: Investigation, resources, and data curation. Bonifasius Ferdinandus Bangun: Investigation, resources, and data curation. Dominikus Budiarto: Formal analysis, validation, visualization, and writing-review and editing. Yohanes Dicka Pratama: Software, data curation, and visualization. Achmad Alfian: Formal analysis, validation, and visualization. Theresia Sunarni: Investigation, data curation, and writing-review and editing. Evelyn Agustin: Data curation, visualization, and writing-review and editing. All authors read and approved the final manuscript.

Funding: No Funding.

Acknowledgment: This research is collaborative research between the Innovation System Center Laboratory (ISC Lab) of the Industrial Engineering Study Program with Komunitas Hutan Kita Institute (HaKI) South Sumatera Province, Indonesia. We would like to express our gratitude to Komunitas Hutan Kita Institute (HaKI) South Sumatera Province, Indonesia who have permitted and funded this research. We would also like to express our gratitude to the members of the research team and parties who supported this research.

Conflicts of Interest: The authors declare no conflict of interest.

Declaration of AI-Tool Usage: AI-assisted tools were used to support manuscript proofreading, verify the consistency of variables and mathematical notation, and check reference formatting. All outputs were reviewed and verified by the authors, who take full responsibility for the accuracy and integrity of the final manuscript.

References

Abubakar, I. R., Maniruzzaman, K. M., Dano, U. L., AlShihri, F. S., AlShammari, M. S., Ahmed, S. M. S., Al-Gehlani, W. A. G., & Alrawaf, T. I. (2022). Environmental Sustainability Impacts of Solid Waste Management Practices in the Global South. *International Journal of Environmental Research and Public Health*, *19*(19), 12717. https://doi.org/10.3390/ijerph191912717

Agaton, C. B., & Santos, M. J. A. (2025). Social Acceptability of Waste-to-Energy: Research Hotspots, Technologies, and Factors. *Clean Technologies*, *7*(3), 63. https://doi.org/10.3390/cleantechnol7030063

Amado, M., Barca, C., Hernández, M. A., & Ferrasse, J.-H. (2021). Evaluation of Energy Recovery Potential by Anaerobic Digestion and Dark Fermentation of Residual Biomass in Colombia. *Frontiers in Energy Research*, *9*. https://doi.org/10.3389/fenrg.2021.690161

Aristizabal C. J. A., Puerto-Rojas, E., Correa-Galindo, S. N., & Sierra Puentes, M. C. (2025). A Community-Based Intervention Proposal for Municipal Solid Waste Management: Analyzing Willingness, Barriers and Spatial Strategies. *Sustainability*, *17*(13), 6206. https://doi.org/10.3390/su17136206

Azis, M. M., Kristanto, J., & Purnomo, C. W. (2021). A Techno-Economic Evaluation of Municipal Solid Waste (MSW) Conversion to Energy in Indonesia. *Sustainability*, *13*(13), 7232. https://doi.org/10.3390/su13137232

Bangura, A. M., & Kanty, P. F. (2024). The Impact of Solid Waste Generation, Storage and Separation Practices among Households on the Environment in Freetown. *Journal of Geoscience and Environment Protection*, *12*(08), 219–238. https://doi.org/10.4236/gep.2024.128012

Baziar, M., Yousefi, M., Oskoei, V., Makhdoomi, A., Abdollahzadeh, R., & Dehghan, A. (2025). Machine learning-based prediction of heating values in municipal solid waste. *Scientific Reports*, *15*(1), 14589. https://doi.org/10.1038/s41598-025-99432-8

Bongomin, O., Mwape, M. C., Mpofu, N. S., Bahunde, B. K., Kidega, R., Mpungu, I. L., Tumusiime, G., Owino, C. A., Goussongtogue, Y. M., Yemane, A., Kyokunzire, P., Malanda, C., Komakech, J., Tigalana, D., Gumisiriza, O., & Ngulube, G. (2025). Digital twin technology advancing industry 4.0 and industry 5.0 across sectors. *Results in Engineering*, *26*, 105583. https://doi.org/10.1016/j.rineng.2025.105583

Cui, W., Wei, Y., & Ji, N. (2024). Global trends of waste-to-energy (WtE) technologies in carbon neutral perspective: Bibliometric analysis. *Ecotoxicology and Environmental Safety*, *270*, 115913. https://doi.org/10.1016/j.ecoenv.2023.115913

Darmey, J., Ahiekpor, J. C., Narra, S., Achaw, O.-W., & Ansah, H. F. (2023). Municipal Solid Waste Generation Trend and Bioenergy Recovery Potential: A Review. *Energies*, *16*(23), 7753. https://doi.org/10.3390/en16237753

Elroi, H., Zbigniew, G., Agnieszka, W.C., & Piotr, S. (2023). Enhancing waste resource efficiency: circular economy for sustainability and energy conversion. *Frontiers in Environmental Science*, *11*. https://doi.org/10.3389/fenvs.2023.1303792

Elsha, W., & Budiarto, R. (2023). Comparative Study of Waste to Energy (WtE) Technology in Municipal Solid Waste Management (MSWM) in Yogyakarta. *Journal of Industrial Engineering and Education*. https://jiee.bksti.org/index.php/iee/article/view/19

Fragkos, P., Zisarou, E., & Andreou, A. (2024). Exploring the Impacts of Lifestyle Changes in the Global Energy Transition: Insights from a Model-Based Analysis Using PROMETHEUS. *Climate*, *12*(12), 193. https://doi.org/10.3390/cli12120193

Gerassimidou, S., Velis, C. A., Williams, P. T., & Komilis, D. (2020). Characterisation and composition identification of waste-derived fuels obtained from municipal solid waste using thermogravimetry: A review. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, *38*(9), 942–965. https://doi.org/10.1177/0734242X20941085

Hartono, D. M. (2015). Potential reduction of solid waste generated from traditional and modern markets. In *International Journal of Technology*. academia.edu. https://www.academia.edu/download/89363177/448.pdf

Hoang, Q. N., Vanierschot, M., Blondeau, J., Croymans, T., Pittoors, R., & Van Caneghem, J. (2021). Review of numerical studies on thermal treatment of municipal solid waste in packed bed combustion. *Fuel Communications*, *7*, 100013. https://doi.org/10.1016/j.jfueco.2021.100013

Islam, N. F., Gogoi, B., Saikia, R., Yousaf, B., Narayan, M., & Sarma, H. (2024). Encouraging circular economy and sustainable environmental practices by addressing waste management and biomass energy production. *Regional Sustainability*, *5*(4), 100174. https://doi.org/10.1016/j.regsus.2024.100174

Maphuhla, N. G., & Oyedeji, O. O. (2025). From Trash to Treasure: Systematic Evaluation of Potential and Efficiency of Waste-to-Energy Incineration for Electricity Generation. *Waste*, *3*(4), 39. https://doi.org/10.3390/waste3040039

Markova, P., Vreckova, D., Mikva, M., Szabo, P., & Cambal, M. (2025). The Impact of Ergonomic Rationalisation on the Efficiency and Productivity of the Production Process. *Administrative Sciences*, *15*(2), 62. https://doi.org/10.3390/admsci15020062

Nanda, M. A., Sugandi, W., Wijayanto, A. K., Imantho, H., Sutawijaya, A., Nelwan, L. O., Budiastra, I. W., & Seminar, K. B. (2023). The Waste-to-Energy (WtE) Technology to Support Alternative Fuels for Agriculture in the Context of Effective Solid Waste Management in the Jabodetabek Area, Indonesia. *Energies*, *16*(24), 7980. https://doi.org/10.3390/en16247980

Pambudi, N. A., Firdaus, R. A., Rizkiana, R., Ulfa, D. K., Salsabila, M. S., Suharno, & Sukatiman. (2023). Renewable Energy in Indonesia: Current Status, Potential, and Future Development. *Sustainability*, *15*(3), 2342. https://doi.org/10.3390/su15032342

Primasari, I. A., & Budiyanto, T. (2025). Lean Ergonomic Approach to Ergonomic Risk Analysis for Workplace Assessment. *LOGIC : Jurnal Rancang Bangun Dan Teknologi*, *25*(1), 35–44. https://doi.org/10.31940/logic.v25i1.35-44

Salem, K. S., Clayson, K., Salas, M., Haque, N., Rao, R., Agate, S., Singh, A., Levis, J. W., Mittal, A., Yarbrough, J. M., Venditti, R., Jameel, H., Lucia, L., & Pal, L. (2023). A critical review of existing and emerging technologies and systems to optimize solid waste management for feedstocks and energy conversion. *Matter*, *6*(10), 3348–3377. https://doi.org/10.1016/j.matt.2023.08.003

Seah, C. C., Habib, S. H., Hafriz, R. S. R. M., Shamsuddin, A. H., Razali, N. M., & Salmiaton, A. (2024). Prospective energy content assessment of waste biomass and polymer via preliminary analysis. *Results in Engineering*, *22*, 102301. https://doi.org/10.1016/j.rineng.2024.102301

Setiawan, H, Budiyanto, T., Rinamurti, M., & Alfian, A. (2025). Prototype Design of Ergo-Flexibility Wheelchair Based on Stakeholder Technical Requirements, Zachman Framework Approach, and Nigel Cross Method Integration. *Spektrum Industri*. https://doi.org/10.12928/si.v23i2.356

Setiawan, Heri, Bangun, F., Budiarto, D., & Pratama, Y. D. (2025). Assessing Waste Potential and Greenhouse Gas Emissions from Existing Waste Management Systems: A Case Study of Palembang City South Sumatera of Indonesia. *Jurnal Improsci*, *3*(3), 156–171. https://doi.org/10.62885/improsci.v3i3.965

Setiawan, Heri, Susanto, S., Rinamurti, M., Alfian, A., Pratama, Y. D., & Budiarto, D. (2025). Work System Improvement in the Production Process Station Area PT SMS Using Macro Ergonomics and Design (MEAD) to Increase Productivity. *Jurnal Improsci*, *3*(2), 80–94. https://doi.org/10.62885/improsci.v3i2.939

Shekari, A., Shishebori, D., Sadegheih, A., & Alidoosti, Z. (2025). Integrating energy justice principles in waste-to-energy conversion: A multi-criteria decision framework for sustainable urban waste management. *Sustainable Futures*, *10*, 101175. https://doi.org/10.1016/j.sftr.2025.101175

Shovon, S. M., Akash, F. A., Rahman, W., Rahman, M. A., Chakraborty, P., Hossain, H. M. Z., & Monir, M. U. (2024). Strategies of managing solid waste and energy recovery for a developing country – A review. *Heliyon*, *10*(2), e24736. https://doi.org/10.1016/j.heliyon.2024.e24736

Siahaan, G., Junianto, P., Pada, A. T., Sembiring, C. F., & Regina, D. (2023). Zero Waste Business Model: Building A Regenerative Business Model Through Innovation and Collaboration. *International Journal of Science and Society*, *5*(4), 404–415. https://doi.org/10.54783/ijsoc.v5i4.795

Sohrabi, M. S., Khotanlou, H., Heidarimoghadam, R., Mohammadfam, I., Babamiri, M., & Soltanian, A. R. (2024). Modeling the Impact of Ergonomic Interventions and Occupational Factors on Work-Related Musculoskeletal Disorders in the Neck of Office Workers with Machine Learning Methods. *Journal of Research in Health Sciences*, *24*(3), e00623. https://doi.org/10.34172/jrhs.2024.158

Suryawan, I. W. K., Septiariva, I. Y., Sari, M. M., Ramadan, B. S., Suhardono, S., Sianipar, I. M. J., Tehupeiory, A., Prayogo, W., & Lim, J.-W. (2023). Acceptance of Waste to Energy Technology by Local Residents of Jakarta City, Indonesia to Achieve Sustainable Clean and Environmentally Friendly Energy. *Journal of Sustainable Development of Energy, Water and Environment Systems*, *11*(2), 1–17. https://doi.org/10.13044/j.sdewes.d11.0443

Taghipour, A., Foukolaei, P. Z., Ghaedi, M., & Khazaei, M. (2023). Sustainable Multi-Objective Models for Waste-to-Energy and Waste Separation Site Selection. *Sustainability*, *15*(22), 15764. https://doi.org/10.3390/su152215764

Traven, L. (2023). Sustainable energy generation from municipal solid waste: A brief overview of existing technologies. *Case Studies in Chemical and Environmental Engineering*, *8*, 100491. https://doi.org/10.1016/j.cscee.2023.100491

Utami, R., Khair, H., & Rachman, I. (2024). Waste-to-Energy Potential in Medan City, Indonesia: Challenges and Opportunities for Sustainable Urban Development. *International Journal Of Scientific Advances*, *5*(6). https://doi.org/10.51542/ijscia.v5i6.41

Walczyk, G., & Ozadowicz, A. (2026). Digital Twin-Based Simulation of Smart Building Energy Performance: BIM-Integrated MATLAB/Simulink Framework for BACS and SRI Evaluation. *Energies*, *19*(2), 543. https://doi.org/10.3390/en19020543

Zahrah, Y., Yu, J., & Liu, X. (2024). How Indonesia's Cities Are Grappling with Plastic Waste: An Integrated Approach towards Sustainable Plastic Waste Management. *Sustainability*, *16*(10), 3921. https://doi.org/10.3390/su16103921

Zhang, M., Nieuwenhuys, A., & Zhang, Y. (2025). Posture prediction models in digital human modeling for ergonomic design: A systematic review. *Medical Engineering & Physics*, *143*(1), 104391. https://doi.org/10.1016/j.medengphy.2025.104391

Zhang, Z., Chen, Z., Zhang, J., Liu, Y., Chen, L., Yang, M., Osman, A. I., Farghali, M., Liu, E., Hassan, D., Ihara, I., Lu, K., Rooney, D. W., & Yap, P.-S. (2024). Municipal solid waste management challenges in developing regions: A comprehensive review and future perspectives for Asia and Africa. *Science of The Total Environment*, *930*, 172794. https://doi.org/10.1016/j.scitotenv.2024.172794