e-ISSN: 2745-9535
No. 105/E/KPT/2022
Jurnal Pengabdian Masyarakat
Member of: ALJEBI
Editorial Office: Jl. Soekarno-Hatta, Rembuksari No. 1A, Malang, East Java, Indonesia, 65113
Contact: Phone: +62 (341) 478494 e-mail: jpm@asia.ac.id
The journal is published by Institut Teknologi dan Bisnis Asia Malang
Website: https://jurnal.stie.asia.ac.id/index.php/jpm
Indexed in: Google Crossref neliti GARUDA Journal Dimensions

Technology-Driven Community Waste Management Model: Transforming Organic Waste into Renewable Energy

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Volume
6
Issue
2
Edition
November
Page
800-807
Year
2025

Article History

Submission: 01-09-2025
Review: 08-10-2025
Accepted: 13-11-2025

Keyword

Biogas;
IoT;
Waste Management;
Automatic Sorting System;

How to cite

Junus, M., Mustain, A., Putra, I. L., Afrizal, D., Bintang, Z., Rizky, M. A., Akbar, F., & Herdiana. (2025). Technology-driven community waste management model: Transforming organic waste into renewable energy. Jurnal Pengabdian Masyarakat, Volume 6(2), 800-807 https://doi.org/10.32815/jpm.v6i2.2834

Abstract

Purpose: This study addresses the challenge of ineffective organic waste management in Indonesia by developing a technology-driven, community-based model.

Method: An integrated system was implemented at an Integrated Waste Processing Facility (TPST), featuring an automatic sorter using color, infrared, and weight sensors, combined with an anaerobic bioreactor for biogas production. The process was monitored through an IoT platform for real-time control.

Practical Applications: The system improved sorting efficiency and reduced processing time, while community training increased household waste segregation participation from 15% to 48%.

Conclusion: The model achieved 92% sorting accuracy and produced an average of 22 m³ of biogas per ton of waste, demonstrating that combining automation with social empowerment creates an effective and replicable solution for sustainable waste management and renewable energy transition.

Introduction

The global energy crisis and environmental degradation have intensified the need for renewable energy solutions. Fossil fuels remain the dominant energy source, yet they are finite and responsible for significant greenhouse gas emissions, accelerating climate change (Nguyen & Le, 2023; Sarkar & Seo, 2023). This situation has prompted governments and researchers worldwide to explore sustainable alternatives that reduce dependency on non-renewable resources while mitigating environmental impacts.

Indonesia, with a population exceeding 270 million, faces a dual challenge: meeting its growing energy demands and managing escalating volumes of domestic waste (Kementerian Lingkungan Hidup dan Kehutanan [KLHK], 2023). In 2022, national waste generation reached approximately 67.8 million tons annually, with organic waste accounting for nearly 57% of the total, primarily originating from households and traditional markets (KLHK, 2023). The improper handling of this waste contributes to severe environmental issues, including leachate contamination, unpleasant odors, and methane emissions—methane being 25 times more potent than carbon dioxide in its greenhouse effect (Jameel et al., 2024).

Organic waste, however, presents an opportunity for renewable energy production through anaerobic fermentation, which generates biogas and organic fertilizer (Lizundia et al., 2022; Rohmadi et al., 2022). Despite its potential, most biogas systems in Indonesia remain industrial-scale, inaccessible to local communities due to high costs, technical complexity, and socio-economic limitations (Gupta et al., 2022; Santos, 2024). This gap underscores the need for community-based solutions that integrate technology with local participation.

Another critical barrier lies in waste sorting. Effective bioconversion requires accurate segregation of organic and inorganic materials, yet sorting practices at the household level are often inefficient or nonexistent (Pučnik et al., 2024). While automated sorting technologies using sensors have been explored, few studies combine these systems with biogas production and real-time monitoring to ensure process optimization (Prasetya et al., 2022; Subekti et al., 2023). Without such integration, the efficiency and scalability of waste-to-energy initiatives remain limited.

To address these challenges, this study proposes a technology-driven community waste management model that integrates automatic sorting, anaerobic biogas conversion, and Internet of Things (IoT)-based monitoring. The system was implemented at TPST 3R Mulyoagung in Malang Regency, East Java, a facility that processes approximately five tons of organic waste daily but faces operational constraints due to limited technology and community engagement (Junus et al., 2025; Mardiana et al., 2023). By combining technical innovation with participatory approaches, the model aims to enhance sorting accuracy, optimize biogas production, and foster behavioral change at the grassroots level.

This community services contributes to both theory and practice by demonstrating that sustainable waste management requires more than technological advancement—it demands social transformation. Through community empowerment initiatives such as training and mentoring, the project seeks to increase household-level waste segregation and promote local ownership of environmental solutions. The findings are expected to inform future policies and replication strategies for community-based waste-to-energy systems in developing regions, supporting broader goals of circular economy and renewable energy transition (Santos, 2024; Kumar et al., 2021).

Method

This study was conducted at the Integrated Waste Processing Facility (TPST 3R Mulyoagung Bersatu) in Malang Regency, East Java, Indonesia. The facility serves five hamlets (RW 1–RW 5) and processes approximately five tons of organic waste daily, although only 3.5 tons are optimally treated due to technical and operational constraints (Junus et al., 2025). The research design combined technological innovation with community empowerment to ensure both technical efficiency and social sustainability.

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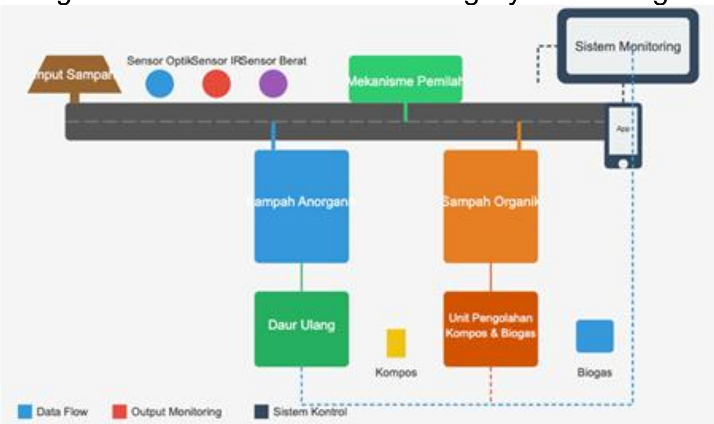
Figure 1. Automatic Waste Sorting System Design

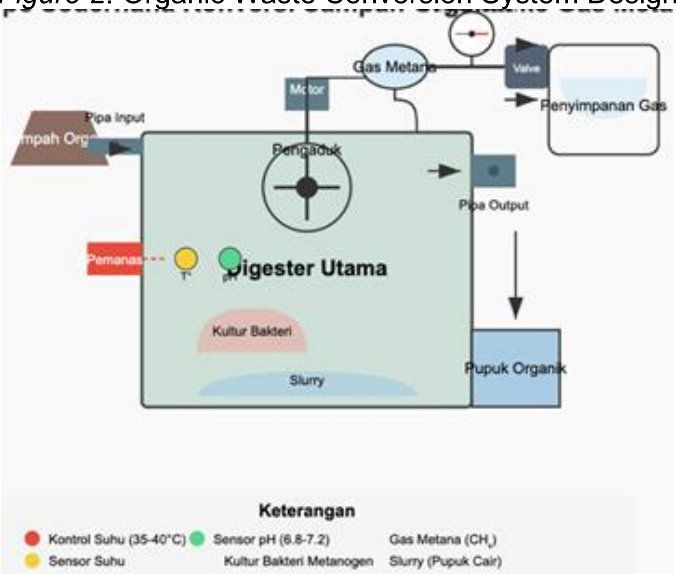


Source: Author's Work, 2025.

The participatory approach began with socialization sessions involving TPST management, local leaders, and residents. These sessions introduced project objectives, benefits, and operational stages through visual presentations and group discussions (Nguyen & Le, 2023). Training programs were then conducted for TPST operators and selected volunteers, covering waste classification, anaerobic digester operation, safety protocols, and IoT-based monitoring. Hands-on workshops at the TPST site allowed participants to practice system assembly and maintenance under expert supervision. Instructional modules and demonstration videos were provided to support post-training implementation.

The developed system integrates three core components: an automatic sorting unit, an anaerobic biogas digester, and an IoT-based monitoring platform. The sorting unit employs optical sensors for color detection, infrared sensors for moisture measurement, and load sensors for weight assessment, enabling accurate segregation of organic and inorganic waste streams (Pučnik et al., 2024; Prasetya et al., 2022). Sorted organic waste is directed to a sealed anaerobic digester equipped with a mixing motor, temperature and pH sensors, and an automatic heating element to maintain optimal conditions (35–40°C, pH 6.8–7.2). Methane produced during fermentation is stored in a gas tank via a controlled pipeline system, while residual slurry is collected for organic fertilizer production (Jameel et al., 2024).

Figure 2. Organic Waste Conversion System Design



Source: Author's Work, 2025.

To ensure process stability, an IoT platform was integrated with the bioreactor. Sensors transmit real-time data on temperature, gas pressure, and pH to a dashboard via an ESP32 microcontroller and Wi-Fi connection. The dashboard provides alerts when parameters deviate from predefined thresholds, allowing operators to take corrective actions promptly (Subekti et al., 2023). The interface was designed for ease of use, enabling operators with minimal technical training to monitor and manage the system effectively.

The evaluation employed both technical and social indicators. Technical performance was assessed through sorting accuracy, biogas yield (m³ per ton of organic waste), and compost production (kg per week). Social impact was measured using pre- and post-training surveys, attendance records, and focus group discussions to evaluate knowledge improvement and behavioral change (Gupta et al., 2022; Santos, 2024). Monthly follow-up meetings ensured continuous feedback and adaptation of strategies to enhance community participation.

Result

The implementation of the technology-driven waste management system at TPST 3R Mulyoagung produced significant technical and social outcomes. Daily waste composition data indicated that the facility processes approximately five tons of waste per day, consisting of 60% organic, 30% inorganic, and 10% residual materials. After deploying the automatic sorting system, classification accuracy improved to 92%, compared to 65–70% achieved through manual methods (Pučnik et al., 2024). This improvement reduced contamination in organic waste streams, ensuring higher efficiency in biogas production.

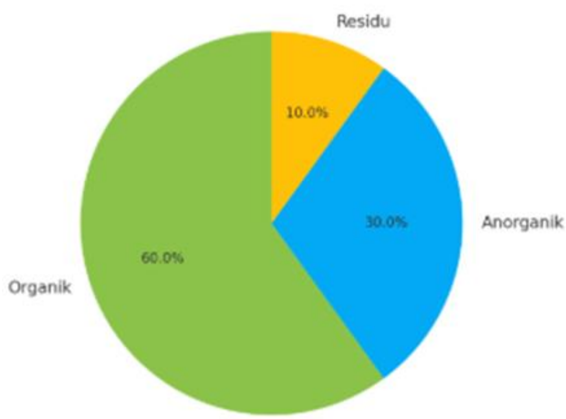
Table 1. Total of Vehicles for Each Entrance

Waste Type	Percentage	Daily Volume (Tons)
Organic	60%	3.0
Inorganic	30%	1.5
Residual	100%	0.5

Source: Author's Work, 2025.

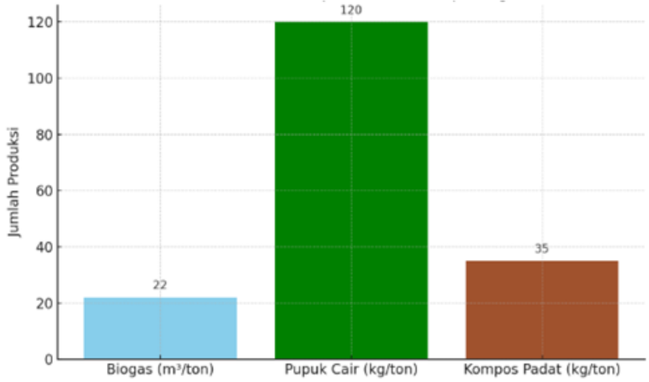
Biogas generation was a key performance indicator. The anaerobic digester produced an average of 20–25 m³ of biogas per ton of fresh organic waste, with methane content suitable for household-scale cooking and small commercial applications (Jameel et al., 2024). In addition to biogas, the system yielded approximately 100–150 kg of organic fertilizer per ton of processed waste. These outputs demonstrate the potential for creating a circular economy model that converts waste into valuable energy and agricultural inputs.

Figure 3. Daily Waste Composition at The Facility



Source: Author's Work, 2025.

Figure 4. Average Output per Ton of Organic Waste



Source: Author's Work, 2025.

The IoT-based monitoring system functioned reliably throughout the operational period. Real-time data on temperature, pH, and gas pressure were transmitted to a mobile dashboard, enabling operators to maintain optimal fermentation conditions (Subekti et al., 2023). Alerts were triggered when parameters deviated from predefined thresholds, allowing timely corrective actions. This feature minimized downtime and improved overall process stability.

From a social perspective, community participation increased substantially. Household-level waste segregation rose from 15% before the intervention to 48% within two months of training and mentoring programs (Nguyen & Le, 2023; Santos, 2024). This behavioral change was supported by continuous engagement activities, including home visits, peer learning, and demonstration sessions. Local champions—such as youth leaders and neighborhood coordinators—played a critical role in sustaining participation and promoting environmental awareness.

Economic benefits also emerged during the project. The sale of organic fertilizer and potential commercialization of biogas created new income streams for TPST operators and community members. These tangible outcomes strengthened local support for the program and encouraged broader adoption of sustainable waste management practices (Gupta et al., 2022; Mardiana et al., 2023).

Overall, the results confirm that integrating automated sorting, biogas conversion, and IoT-based monitoring with community empowerment can significantly enhance waste management efficiency while fostering social transformation. This synergy between technology and participation provides a replicable model for other regions seeking sustainable solutions to waste and energy challenges.

Discussion

The findings of this study demonstrate that integrating automated sorting, biogas conversion, and IoT-based monitoring significantly improves the efficiency of community-scale waste management systems. The sorting accuracy of 92% achieved by the developed system represents a substantial improvement over manual methods, which typically range between 65% and 70% (Pučnik et al., 2024). This enhancement not only reduces contamination in organic waste streams but also optimizes biogas production, confirming the technical viability of sensor-based sorting technologies in low-resource settings (Prasetya et al., 2022).

The biogas yield of 20–25 m³ per ton of organic waste aligns with previous studies on anaerobic digestion performance, indicating that community-scale systems can achieve outputs comparable to industrial models when properly managed (Jameel et al., 2024; Rohmadi et al., 2022). Furthermore, the production of organic fertilizer as a by-product reinforces the circular economy approach, providing additional economic and environmental benefits. These results validate the hypothesis that technological innovation, when combined with participatory strategies, can create sustainable waste-to-energy solutions for developing regions (Lizundia et al., 2022; Sarkar & Seo, 2023).

From a social perspective, the increase in household-level waste segregation from 15% to 48% within two months underscores the effectiveness of community empowerment initiatives. This behavioral transformation was facilitated by continuous mentoring, peer learning, and the emergence of local champions, which are consistent with findings from similar programs in Vietnam and the Philippines (Nguyen & Le, 2023; Santos, 2024). The participatory approach not only improved technical outcomes but also strengthened social cohesion and local leadership, which are critical for sustaining long-term environmental practices (Gupta et al., 2022; Mardiana et al., 2023).

Despite these successes, several challenges were encountered. Initial skepticism toward the technology and inconsistent sorting behavior required repeated engagement and demonstration activities. These barriers mirror those reported in other developing countries, where sustained mentoring and institutional support are essential for adoption (Kumar et al., 2021). Additionally, the system's reliance on stable electricity and internet connectivity poses limitations for replication in remote areas, highlighting the need for adaptive designs and offline monitoring capabilities in future iterations.

The integration of IoT-based monitoring proved particularly valuable for maintaining process stability. Real-time alerts enabled operators to respond promptly to deviations in temperature, pH, and gas pressure, reducing downtime and improving biogas yield (Subekti et al., 2023). This feature demonstrates how digital technologies can enhance operational efficiency even in community-scale settings, provided that user-friendly interfaces and adequate training are in place.

Overall, this study contributes to the theoretical discourse on community-driven development by illustrating that technological adoption alone is insufficient without social ownership. The synergy between technical innovation and participatory engagement offers a replicable model for other regions seeking to implement sustainable waste-to-energy systems. Future research should focus on scaling this model through policy support, financial incentives, and standardized training frameworks to ensure long-term sustainability and broader impact.

Conclusion

This study successfully designed and implemented a technology-driven community waste management model that integrates automated sorting, anaerobic biogas conversion, and IoT-based monitoring. The system achieved notable technical outcomes, including a sorting accuracy of 92%, biogas production averaging 20–25 m^3 per ton of organic waste, and a 40% reduction in processing time compared to conventional methods (Pučnik et al., 2024; Jameel et al., 2024). These results confirm that combining sensor-based automation with real-time monitoring can significantly enhance operational efficiency in community-scale waste management systems.

Beyond technical performance, the project demonstrated the critical role of social empowerment in sustaining environmental initiatives. Community participation in household-level waste segregation increased from 15% to 48% within two months, driven by structured training, mentoring, and the emergence of local champions (Nguyen & Le, 2023; Santos, 2024). This behavioral transformation underscores the importance of participatory approaches in complementing technological innovation, ensuring long-term adoption and resilience.

The findings contribute to both theory and practice by illustrating that sustainable waste-to-energy solutions require a synergy between technology and social engagement. This integrated model offers a replicable framework for other regions seeking to implement circular economy principles and renewable energy strategies at the grassroots level (Gupta et al., 2022; Mardiana et al., 2023).

However, several limitations remain, including dependence on stable electricity and internet connectivity, which may hinder replication in remote areas. Future research should focus on adaptive designs, offline monitoring capabilities, and policy frameworks that support scaling through financial incentives and standardized training modules (Kumar et al., 2021).

In summary, this initiative demonstrates that technological advancement alone is insufficient without active community involvement. By fostering local ownership and institutional collaboration, the proposed model not only addresses waste management challenges but also contributes to broader environmental sustainability and energy transition goals.

Acknowledgements

The author would like to express sincere gratitude to the entire management team of TPST 3R Mulyoagung Bersatu for their support, cooperation, and openness throughout the implementation of this research. Appreciation is also extended to the residents of Mulyoagung Village for their active participation in educational activities, training sessions, and technology system testing. Furthermore, the author acknowledges the support from academic institutions and related stakeholders who provided facilities, technical guidance, and logistical assistance during the study. It is hoped that the results of this research will contribute meaningfully to community-based waste management and the advancement of renewable energy development in Indonesia.

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