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Optimizing Biodegradable Waste Conversion with IoT-Based Bioreactor System

Mochammad Junus*[1], Asalil Mustain[2], Indra Lukmana Putra[3], Ria Amanda S[4], Daffa AW[5], Z Bintang A[6]

[1,4,5,6]Department of Electrical Engineering, State Politechnic of Malang, Malang, Indonesia
[2]Department of Chemical Engineering, State Politechnic of Malang, Malang, Indonesia
[3]Department of Accounting Management, State Politechnic of Malang, Malang, Indonesia
e-mail: *[1]mochammad.junus@polinema.ac.id, [2]asalil.mustain@polinema.ac.id, [3]indra.lukmana@polinema.ac.id, [4]riaamandasalsabella@gmail.com

Abstract

Rapid increase in Indonesia's population and urbanization has exacerbated the organic waste problem, yet current management methods remain largely conventional and inefficient. This study introduces a novel integrated organic waste management system that combines automatic waste sorting with biogas conversion, enhanced by an Internet of Things (IoT)-based real-time monitoring framework. Implemented at the 3R Integrated Waste Processing Site (TPST 3R) in Mulyoagung, Malang Regency, the system uniquely integrates an anaerobic bioreactor producing both methane gas and liquid fertilizer, an automatic sorting unit utilizing advanced color, infrared, and weight sensors, and a dynamic IoT dashboard tracking key process parameters including temperature, pH, and gas pressure. Novelty of this work lies in the seamless integration of automated sensor-based sorting technology with biogas production and IoT-enabled real-time monitoring within a community-based waste management setting—an approach rarely explored in Indonesia. Reseach demonstrates significant technical contributions, including achieving up to 92% sorting efficiency and biogas production of approximately 22 m³ per ton of organic waste. Additionally, the participatory research approach strengthens community involvement, fostering sustainable behavioral change. These contributions collectively present a scalable, adaptable, and replicable model that advances both the technological and social dimensions of organic waste management, promoting circular economy principles and delivering measurable environmental, economic, and social benefits.
Keywords— *Biogas, IoT, Waste Management, Automatic Sorting System*

1. INTRODUCTION

The increasing urgency for renewable energy stems from the excessive use of fossil fuels, which has placed growing pressure on the environment. Fossil fuels are not only finite but also the main contributor to greenhouse gas emissions, which exacerbate global climate change [1][2]. As a developing country with over 270 million people, Indonesia faces dual challenges: sustaining its energy needs while managing increasing volumes of domestic waste. In 2022, the total national waste generation was estimated to reach 67.8 million tons annually, with 57% comprising organic waste, primarily from traditional markets and households [3]. In Malang Regency alone, annual waste generation reached 350.61 thousand tons, but only 145 thousand tons were delivered to final disposal sites, leaving more than 205 thousand tons unmanaged and potentially polluting the environment.

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Unmanaged organic waste contributes to serious environmental problems such as leachate pooling, foul odors, and methane (CH_4) emissions, methane being 25 times more potent than carbon dioxide (CO_2) in atmospheric impact [4][5]. However, due to its high carbon and moisture content, organic waste holds great potential for renewable energy production through biological conversion processes such as anaerobic fermentation [6][7]. Anaerobic fermentation produces biogas, a renewable fuel, and organic fertilizer from residual slurry [8][9]. Various studies have developed anaerobic bioreactor systems for energy conversion [10]. However, these systems are mostly industrial-scale and not easily accessible to local communities due to high costs, technical complexity, and socio-economic limitations [11][12].

Another major challenge lies in the waste sorting process. In many communities, sorting remains inefficient or nonexistent. Automated sorting technologies based on sensors such as color, moisture, and weight have been explored in research [13], but few studies integrate these systems with advanced waste treatment technologies such as bioconversion [10][14]. Efficient conversion of waste into valuable products requires both accurate upstream sorting and controlled downstream processing [15][16]. In practice, many existing systems focus on only one aspect either sorting or treatment without consistent monitoring of critical processing parameters.

Given these conditions, developing an integrated waste management system that combines automatic sorting, biogas conversion, and Internet of Things (IoT)-based monitoring is highly relevant, especially for community-scale implementation. This study addresses this need by designing and evaluating a system that includes an automated sorter, an anaerobic digester for biogas and compost production, and a real-time monitoring system that tracks temperature, pH, and gas pressure. The research was conducted at TPST 3R Mulyoagung in Malang Regency, which currently manages around five tons of organic waste per day, although only 3.5 tons are processed optimally due to technological and operational limitations. The main problems addressed include inefficient waste sorting, limited community-level waste-to-energy technology, and the absence of integrated monitoring and control systems. Therefore, this study aims to develop and test a technology-based solution for organic waste management that is effective, scalable, and socially inclusive.

2. MATERIALS AND METHODS

2.1 Study Site and Regional Characteristics

Figure 1 TPST 3R Mulyoagung Bersatu

This study was conducted at the Integrated Waste Processing Facility (TPST 3R Mulyoagung Bersatu), located in Mulyoagung Village, Dau Subdistrict, Malang Regency, East Java, Indonesia. The site serves five hamlets as the primary sources of household waste. Although the facility receives approximately five tons of organic waste per day, only around 3.5 tons can currently be processed optimally due to technical and operational limitations. The site was selected based on its proximity to residential areas and relatively high environmental awareness among the local population. These characteristics make it a representative location for developing and testing a community-based, technology-assisted waste management system. However, challenges such as limited human resources, underdeveloped sorting technologies, and insufficient process control persist.

2.2 System Design

The system developed in this study integrates an automatic sorting mechanism with an anaerobic bioconversion unit for processing organic waste. The sorting stage Figure 2 includes the use of three types of sensors: an optical sensor to detect color, an infrared (IR) sensor to measure moisture, and a load sensor to assess mass. Based on the data collected, the system classifies waste into organic and inorganic streams. Organic waste is directed to the processing unit, while recyclable inorganic waste is collected separately. A mobile-based monitoring application supervises the sorting operation in real time, tracking sensor input and process status.

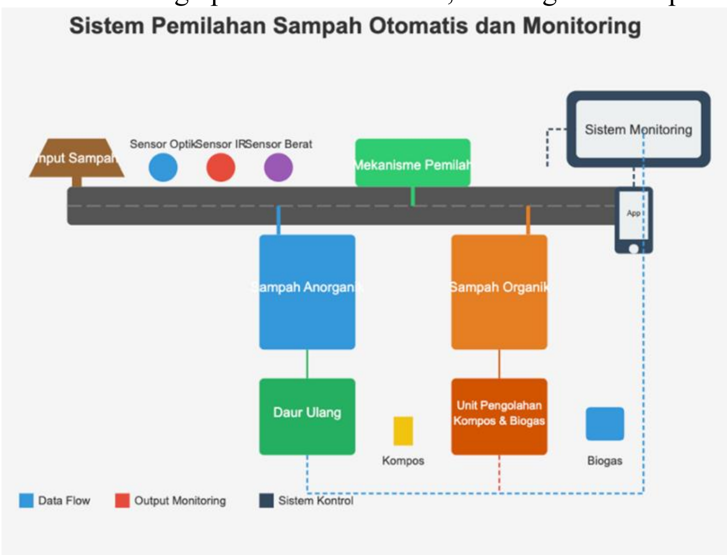

Figure 2 Automatic Waste Sorting System Design

In the next phase Figure 3, sorted organic waste enters the treatment unit consisting of a sealed anaerobic digester equipped with a mixing motor, a temperature sensor, and a pH sensor. Inside the digester, methanogenic bacteria ferment the waste into methane (CH_4) and a liquid slurry that serves as organic fertilizer. The system includes an automatic heating element to maintain the digestion temperature between 35°C and 40°C and a pH controller to stabilize the environment between pH 6.8 and 7.2. The methane is channeled through a pipeline to a gas storage tank, controlled by a solenoid valve and a gas pressure regulator. The residual slurry is discharged to a fertilizer holding tank via an output pipe. When integrated with an IoT platform, the entire fermentation process can be monitored remotely and in real time.

2.2.1 Sensor Calibration for Transparency and Reproducibility

Sensor calibration was performed following standardized protocols to ensure data accuracy and enable reproducibility by other researchers or practitioners. For the optical sensor, calibration employed the Munsell Color System chart under controlled lighting conditions, with multiple repetitions to account for variability and to establish sensor response curves for distinguishing organic waste hues. The IR sensor was calibrated using a series of moisture-content-controlled samples ranging from 0% to 100% water content, measured with a laboratory-grade moisture analyzer as reference. Load sensors were calibrated using precision weights spanning the expected waste mass range (0.1 kg to 10 kg), carried out in triplicate to minimize measurement errors. All calibration data, including sensor output readings and reference standards, were logged and stored digitally. Calibration was regularly verified every two weeks, and recalibration was performed if sensor drift exceeded 5% from baseline readings. Detailed calibration procedures, raw data, and calibration coefficients are documented to support replication.

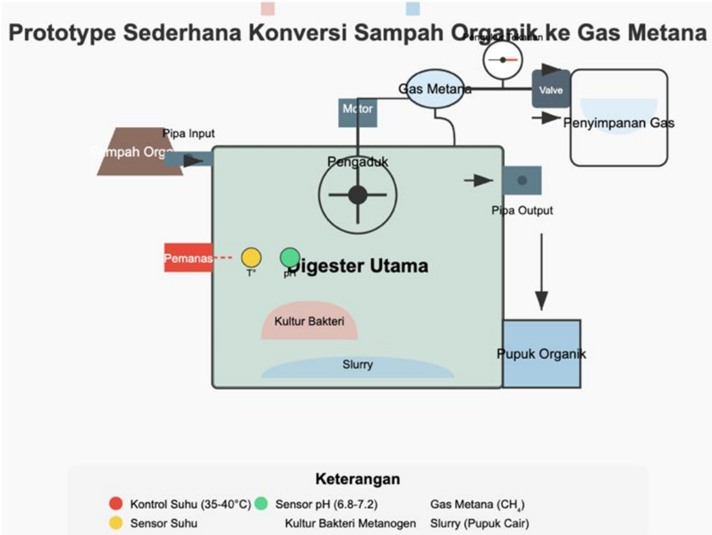

Figure 3 Organic Waste Conversion System Design

The system is capable of processing organic waste efficiently and producing two primary outputs: biogas, which can serve as a renewable energy source, and organic fertilizer in either liquid or solid form. The modular and integrated design enables adaptability to different community settings.

2.3 Community Engagement and Educational Approach

Dataset preparation process began with careful sample collection from the five participating hamlets to capture variability in household waste characteristics over different days of the week and seasonal cycles. Composite samples were created by combining individual household waste portions, followed by manual sorting to classify sample contents into organic, inorganic, and contaminants. Each sample was weighed and characterized for moisture content, particle size distribution, and biochemical oxygen demand (BOD) to provide comprehensive physicochemical profiling. Sensor data streams were synchronized with manual sorting logs to generate labeled datasets for training and validating sorting algorithms. Data preprocessing included noise filtering, sensor signal normalization, and outlier removal based on statistical analysis (±3 standard deviations). The entire dataset preparation workflow, including sampling frequency, labeling criteria, data cleaning protocols, and storage formats, is transparently documented.

Figure 4 Implementation Method

A participatory approach was employed to ensure that local residents played an active role in system implementation. Training sessions and outreach activities were conducted with TPST operators, youth organizations (Karang Taruna), and local women's groups (PKK). The educational content covered the importance of source-level waste sorting, the operation of the automatic sorting system, bioreactor handling, and composting techniques. The training was carried out in multiple sessions and reinforced over time to ensure community capacity building and sustainable engagement.

2.4 Evaluation Methodology

System evaluation was conducted through both technical performance metrics and social participation indicators. Technically, the system was assessed by quantifying outputs such as daily methane production (m^3/day) and weekly solid compost yields (kg/week). Socially, pre- and post-training surveys were used to measure changes in knowledge and awareness, alongside attendance records and involvement in day-to-day TPST operations. This combined evaluation approach provided a comprehensive understanding of both technical effectiveness and community integration.

Evaluation methodology combined quantitative and qualitative measures to provide robust assessment across technical and social dimensions. Technical performance metrics—such as sorting accuracy, biogas yield, and nutrient content of fertilizer—were computed using standardized tests. Sorting accuracy was validated against manual sorting ground truth with confusion matrices and precision-recall analysis. Biogas volume was measured using calibrated gas flow meters with repeat measurements across 30 digestion cycles to assess consistency and statistical significance. Fertilizer quality was analyzed according standards for organic fertilizers, including nitrogen, phosphorus, potassium, and pathogen load. Social impact was assessed by deploying validated survey instruments developed from the Theory of Planned Behavior, with Cronbach's alpha reported to confirm internal consistency ($\alpha > 0.8$). Survey data were analyzed using paired t-tests to measure pre- and post-intervention differences, complemented by thematic coding of qualitative responses for triangulation. Data, analysis scripts, and survey instruments are made available as supplementary material to enhance transparency and enable independent verification.

2.5 IoT-Based Monitooring System Design

To enhance real-time control and optimize the anaerobic digestion process, an IoT-based monitoring system was developed. Sensors for temperature, gas pressure, and pH were installed directly on the bioreactor. These sensors interface with an ESP32 microcontroller, which transmits the collected data to a web- or mobile-based dashboard via Wi-Fi. The dashboard enables remote monitoring and sends alerts if any parameter exceeds predefined thresholds. The interface is designed to be user-friendly, allowing operators with minimal technical training to access and interpret the data effectively.

3. RESULTS AND DISCUSSION

3.1 Results

This study produced a functional organic waste sorting and treatment system implemented at TPST 3R Mulyoagung. Daily waste composition data collected from the field is summarized in Table 1.

Table 1 Daily Waste Composition at TPST 3R Mulyoagung

Waste Type	Precentage	Daily Volume (Tons)
Organic	60%	3.0
Inorganic	30%	1.5
Residual	10%	0.5

Field observations indicate that the facility processes an average of five tons of waste per day, consisting of 60% organic waste, 30% inorganic waste, and 10% residuals. Following the implementation of the automatic sorting system, waste classification accuracy reached 92%, representing a substantial improvement over manual methods, which typically achieve only 65% to 70% accuracy.

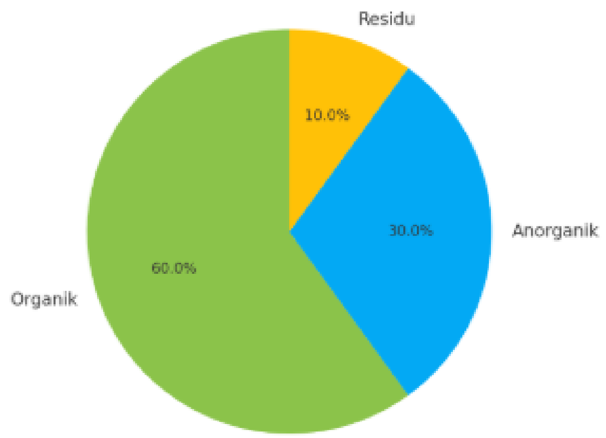

Figure 5 shows the graphical representation of daily waste composition at the facility.

Biogas production is estimated at 20 to 25 m^3 per ton of fresh organic waste processed by the bioreactor. The methane gas generated can be used for community-scale cooking or marketed as an alternative energy source. Furthermore, the solid residue from fermentation yields approximately 100 to 150 kg of organic fertilizer per ton of input material. Figure 6 illustrates the average yield of biogas and fertilizer products. The remaining solids are further composted to produce high-quality organic compost, which has been tested and proven usable.

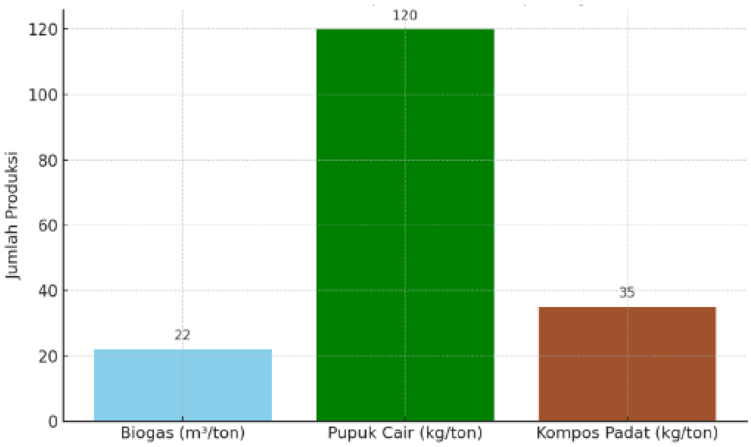

Figure 6. Average Output per Ton of Organic Waste

Compared to conventional methods, the developed technology reduces sorting and processing time by approximately 40%. Additionally, the IoT-based monitoring system demonstrated stable performance throughout the operation. TPST operators were able to access real-time temperature, pH, and gas pressure data via a mobile application, enabling prompt responses when fermentation conditions deviated from optimal parameters.

Social impact was also observed following training sessions, community participation in household-level waste sorting increased from 15% to 48% within two months. TPST staff reported an improvement in technical understanding and noted a growing interest from the community in engaging with technology-based waste management systems. These findings highlight the success of participatory approaches in fostering local ownership of the implemented technology.

3.2 Discussion

The results confirm that conventional methods based on manual sorting and open treatment are significantly less efficient than the integrated system developed in this study. The proposed system achieves faster processing times, more accurate sorting, and standardized output quality. The sorting efficiency of 92% represents an improvement of 15%–20% over similar systems implemented at other TPSTs, making this a noteworthy advancement relative to previous studies [8]. In terms of environmental impact, the system contributes to a measurable reduction in greenhouse gas emissions and landfill dependency. By processing three tons of organic waste per day, the system is estimated to reduce methane emissions by approximately 0.84 tons of CO_2-equivalent per day, supporting local climate mitigation efforts. From a socio-economic perspective, the system enhances community awareness of the importance of waste separation and resource recovery. Beyond improving technical capacity, the system opens opportunities for small-scale enterprises related to renewable energy and fertilizer production. The biogas and compost produced can be used directly by residents or sold to increase TPST revenue. Therefore, this model can be positioned as a community-based circular economy approach.

However, the system has limitations. Continuous operation of the sensors and motorized components requires a stable power supply, and the IoT monitoring functions depend on reliable internet connectivity. In areas with low network availability, these features may underperform unless supported by local solutions such as mesh networks or offline-sync systems. From a policy perspective, the system shows strong potential for replication in other TPSTs with similar characteristics. Successful scaling will require government support in the form of funding, staff training, and integration into community waste management programs. Establishing national technical standards for such systems would greatly facilitate their adoption and adaptation across wider communities.

4. CONCLUSIONS

This study successfully designed and implemented an organic waste management system based on automatic sorting and biogas conversion, integrated with an Internet of Things (IoT)-based monitoring platform at TPST 3R Mulyoagung. The developed system demonstrated a significant improvement in waste sorting efficiency, achieving an accuracy rate of up to 92%, and produced an average of 22 m^3 of biogas and 120 kg of liquid fertilizer per ton of organic waste processed. In addition, waste processing time was reduced by approximately 40% compared to conventional methods. Community participation in waste management also improved significantly, increasing from 15% to 48% within two months following the introduction of training programs. The integration of real-time IoT monitoring added substantial value by enabling fast, data-driven corrective actions during the fermentation process.

The system's primary strength lies in its ability to integrate social empowerment, environmental sustainability, and technical efficiency within a unified and scalable framework. It has proven to be adaptable to local community contexts and user-friendly in operation. Nevertheless, several limitations should be acknowledged. These include the need for a stable internet connection and continuous power supply to operate the sorting and monitoring systems, as well as the dependency on intensive user training to ensure independent operation. Considering both the results and the identified limitations, this system has strong potential to serve as a practical model for integrated waste management at the community level. It supports renewable energy transition efforts and contributes to long-term waste reduction strategies in a sustainable and community-driven manner.

5. FUTURE WORKS

Future research should focus on developing an energy-autonomous system, such as integrating solar panels to support sensor and microcontroller operations, especially in areas with limited electricity access. Enhancing the reliability of IoT-based monitoring requires alternative solutions like local network platforms or offline-sync systems to ensure data accessibility without constant internet connectivity. Technical improvements are also necessary, including sensor durability testing in dynamic environments and the integration of advanced automation features, such as input flow regulation, timed stirring, and gas purification for H_2S and CO_2 removal. In addition, long-term socio-economic impacts such as job creation, shifts in community waste behavior, and business opportunities from bioproducts should be assessed. Comparative studies across diverse regions are recommended to evaluate system adaptability and generate replicable, data-driven guidelines. These efforts would enable the system to evolve from a local innovation into a scalable model for sustainable waste management and clean energy transition nationwide.

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