

Waste-to-energy education kit for urban flats using sensor-based data visualization

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Abstract. Urban flats generate substantial amounts of organic household waste each day, much of which is commonly disposed of through unsustainable practices such as landfilling or centralized collection without material or energy recovery. These approaches not only contribute to environmental degradation but also overlook the latent energy potential of biodegradable waste streams. Waste-to-Energy (WtE) technologies provide a sustainable alternative by enabling the conversion of organic biomass into useful energy and value-added by-products. This paper presents an interactive, sensor-driven educational dashboard that simulates a seven-day WtE experiment using data obtained from a model composting setup deployed in an urban flat environment. The proposed dashboard visualizes key environmental parameters, including chamber temperature, ambient temperature, humidity, and estimated biogas potential, to illustrate the dynamic processes underlying organic waste decomposition. By transforming raw sensor data into intuitive visual insights, the system aims to enhance public understanding, raise sustainability awareness, and encourage the adoption of decentralized, household-level WtE practices in urban residential settings.

1 Introduction

Organic household waste constitutes a significant fraction of municipal solid waste in urban environments, particularly within high-density residential settings such as flats and apartment complexes. Food scraps, vegetable residues, and other biodegradable materials are generated daily, yet these resources are predominantly managed through conventional disposal pathways, including landfilling and centralized incineration. Such practices contribute to greenhouse gas emissions, leachate formation, and inefficient resource utilization, while simultaneously neglecting the inherent energy potential of organic waste streams [1, 2]. Waste-to-Energy (WtE) technologies, including controlled aerobic composting and anaerobic digestion, provide sustainable and decentralized alternatives by enabling the conversion of biodegradable waste into useful energy carriers such as biogas, in addition to producing nutrient-rich compost by-products [3]. These technologies are particularly well-suited for urban residential applications due to their scalability and compatibility with source-separated

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organic waste. However, the successful adoption of small-scale WtE systems in urban communities is strongly influenced by public awareness, behavioral acceptance, and access to intuitive educational resources [4].

To address this challenge, this project introduces an interactive, dashboard-based educational tool that simulates the Waste-to-Energy process using time-series sensor data obtained from a flat-based composting setup. The system visualizes key environmental parameters such as temperature, humidity, and estimated biogas potential, enabling users to observe the dynamic biological and environmental processes involved in organic waste decomposition. By transforming raw sensor data into intuitive visual representations, the proposed dashboard enhances conceptual understanding of composting dynamics and energy recovery mechanisms, supporting experiential learning and promoting informed participation in decentralized WtE practices [5, 6].

This paper presents a low-cost, sensor-based Waste-to-Energy education kit tailored for urban flats. The proposed system integrates environmental sensing, data-driven simulation, and an interactive Streamlit dashboard to visualize composting and biogas generation processes over a seven-day experimental period. Unlike conventional WtE studies that focus on large-scale systems, this work emphasizes household-level education and sustainability awareness. Experimental results demonstrate measurable waste reduction and energy potential, validating the feasibility of decentralized WtE learning tools for high-density urban environments.

2 Literature Review

Waste-to-Energy (WtE) technologies have increasingly become integral to sustainable solid waste management strategies, especially in urban environments where both land scarcity and waste accumulation are pressing concerns [7, 8]. These technologies enable the transformation of biodegradable waste into valuable energy resources, contributing to circular economy goals. O’Riordan et al. [1] developed a comprehensive model that combines thermal and biological treatment processes for municipal solid waste. Their study highlighted the technical and economic viability of decentralized WtE systems, making them particularly suitable for integration into small-scale, community-level initiatives such as those in urban apartment complexes.

Focusing on the social and behavioral dimensions of waste management, Zhuoya et al. [2] examined composting strategies in densely populated cities and emphasized the importance of engaging local communities. They found that public education campaigns and citizen involvement were essential for the successful adoption of sustainable waste practices. Moreover, they advocated for the use of real-time monitoring and visualization tools to enhance public understanding and foster a sense of ownership, both of which are critical for long-term behavioral change. This aligns closely with the present study’s use of interactive dashboards to support household-level education.

The role of digital technologies in waste management has expanded with the emergence of smart city frameworks. Ali et al. [3] proposed an IoT and machine learning-based system for optimizing municipal waste collection and processing. Their system demonstrated that real-time sensor data could be used to inform predictive models and responsive decision-making. This technological paradigm strongly supports the use of sensor-based systems in educational platforms, where real-world data can simulate dynamic environmental processes such as composting and biogas generation.

From a global policy and perception standpoint, Huang et al. [4] conducted an extensive review of WtE trends and adoption patterns across different regions, while related studies

have examined regional WtE status, incineration evolution, and broader technology assessment issues [9]. These findings suggest that beyond technical implementation, the long-term success of WtE systems depends heavily on public perception, government policy, energy justice, and transparent communication strategies [10]. Tools that make the invisible processes of waste decomposition and energy conversion visible, such as educational dashboards, are vital for demystifying WtE and building community trust.

Rabaey and Verstraete [5] contributed foundational work on microbial fuel cells, focusing on the biological mechanisms that enable energy extraction from organic matter. They emphasized the importance of environmental parameters such as temperature, humidity, and gas emissions in influencing system performance. These variables are also essential for modeling composting dynamics, and thus inform the selection of appropriate sensors and indicators for the proposed dashboard-based system.

Economic and environmental feasibility are particularly important in developing country contexts. Cheng and Hu [6] and Tabasová et al. [11] assessed the lifecycle and environmental performance of various WtE technologies and concluded that small-scale anaerobic digestion and composting were among the most cost-effective and environmentally beneficial options for low-resource urban settings. Their findings support the development of simplified, affordable educational tools that can simulate these processes and be deployed in residential areas without requiring large infrastructure investments.

From a behavioral science perspective, Varela et al. [12] explored the link between environmental awareness and sustainable behavior, while Gauthier et al. [13] demonstrated the value of participatory interactive data visualizations for climate-related learning. Their empirical findings demonstrated that interactive and visually engaging educational interventions significantly improved urban residents' willingness to adopt sustainable waste practices. This reinforces the pedagogical rationale behind the project's dashboard, which aims not only to inform but also to inspire action through visual, data-driven storytelling.

More recently, Cepero et al. [14] explored the application of low-code development platforms for creating sustainability dashboards in smart cities. The present dashboard implementation is supported by Streamlit and Plotly Express documentation for interactive data application development and visualization. They emphasized user-centric design, modular data integration, and real-time feedback as essential elements for engaging urban stakeholders. Their work served as a key technical reference for this project's implementation, particularly in the use of Streamlit for building an intuitive, flexible dashboard interface.

Pignatelli et al. [15] investigated participatory urban environmental monitoring, arguing that the use of interactive data visualizations significantly enhances community engagement and environmental literacy. They observed that participatory tools helped citizens better understand local environmental dynamics and make informed decisions. This community-driven model of learning and awareness is precisely what this project seeks to replicate within the domain of organic waste-to-energy conversion in flats.

In summary, the reviewed literature provides a robust foundation across technical, social, economic, and educational dimensions, including emerging WtE applications linked to AI data centers and resilient energy systems. The current study builds upon this body of work by proposing a novel, sensor-driven, low-cost dashboard system that simulates the composting and biogas generation processes over a seven-day cycle. By combining environmental data collection with interactive visualization, the project aims to promote waste literacy and sustainable practices among residents in high-density urban housing.

3 Methodology

3.1 Waste-to-Energy Education Framework

Fig. 1 presents the proposed Waste-to-Energy (WtE) education framework tailored for high-density urban flats. The framework adopts a layered architecture that connects household waste management practices with community-scale resource recovery and digital learning tools. At the household level, organic waste segregation is emphasized to improve feedstock quality and increase residents’ awareness. The collected waste is processed at the community-level using a shared mini WtE unit, where composting and anaerobic digestion pathways convert organic waste into fertilizer and biogas-equivalent energy. The digital layer integrates Internet of Things (IoT) sensors and cloud-based data storage to enable real-time monitoring and visualization of system performance. Educational indicators, such as estimated energy generation, *CO*₂ emission reduction, and green participation scores, are derived from the collected data to support data-driven sustainability education and community engagement in urban residential environments.

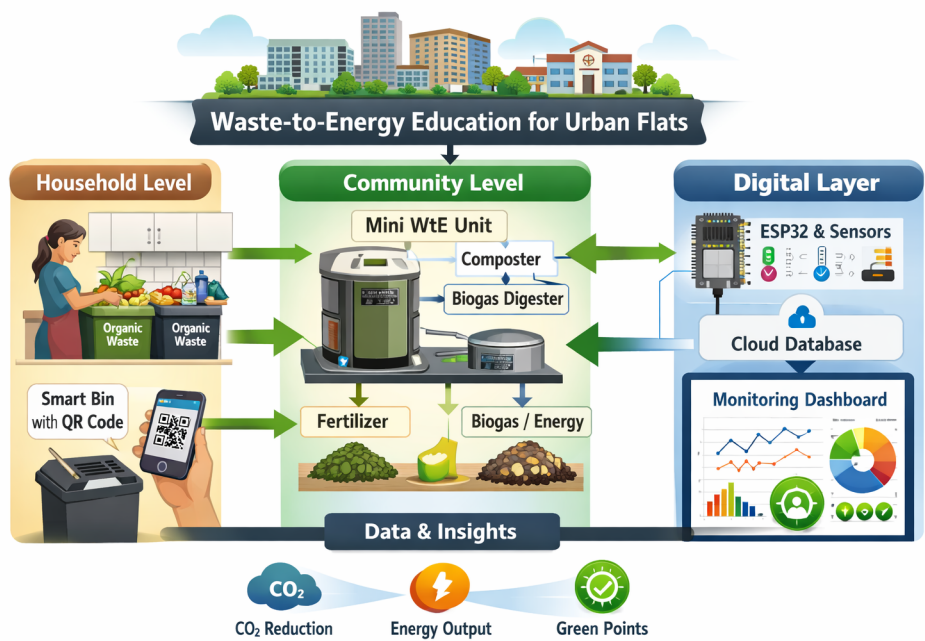


Figure 1. Waste-to-Energy (WtE) education framework for urban flats.

4 Experimental Setup

A small-scale composting system was deployed on the balcony of a high-rise urban flat to emulate typical household organic waste management conditions, as shown in Fig. 2. The experimental setup was designed to reflect realistic environmental exposure, including natural ventilation and ambient temperature variations commonly encountered in urban residential settings.

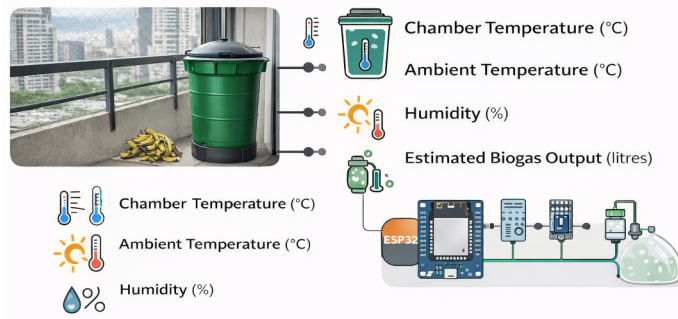


Figure 2. Experimental setup for urban flats.

Data collection was conducted continuously over seven consecutive days. The monitored environmental and process parameters included chamber temperature (°C), ambient temperature (°C), relative humidity (%), and estimated biogas output (litres). Chamber temperature represented the internal thermal conditions of the composting bin, while ambient temperature captured the influence of the surrounding environment. Humidity levels were recorded to assess moisture dynamics, which play a critical role in microbial activity and biogas generation. All sensor measurements were acquired using a microcontroller-based data acquisition platform built around an ESP32 module.

The system enabled real-time sensing and onboard data logging, providing a low-cost and scalable solution for educational and urban household Waste-to-Energy (WtE) experimentation. Data preprocessing was performed using Python to handle anomalies, align time-series measurements, and estimate energy output. A simulated data augmentation technique was applied to model diverse waste input scenarios based on empirical composting behavior [2].

5 Results and Discussion

5.1 Waste-to-Energy Education Kit Dashboard

Fig. 3 illustrates the Waste-to-Energy (WtE) Education Kit Dashboard developed to support the visualization and interpretation of small-scale organic waste-to-energy experiments. The dashboard integrates a raw data table with aggregated performance indicators to facilitate the educational analysis of waste degradation and energy recovery processes. The recorded parameters include chamber temperature, ambient temperature, humidity, waste weight, estimated biogas production, and corresponding energy potential, as shown in Table 1.

For the selected experimental date range, a total waste input of 11.60 kg was processed, yielding an estimated total energy output of 33.50 MJ. The system achieved a waste reduction rate of 32.5%, demonstrating effective biodegradation under the observed operating conditions. In addition, the cumulative biogas volume produced during the experiment reached 1,510 mL. This biogas yield was converted into energy potential using simplified assumptions appropriate for instructional and demonstrative purposes.

The dashboard enables learners to correlate environmental conditions with waste reduction efficiency and energy generation trends through an intuitive visual interface. By combining time-series measurements with summarized performance metrics, the proposed WtE Education Kit serves as an effective pedagogical tool for introducing fundamental concepts of waste-to-energy conversion, sustainability assessment, and data-driven analysis in academic and community-based learning environments.

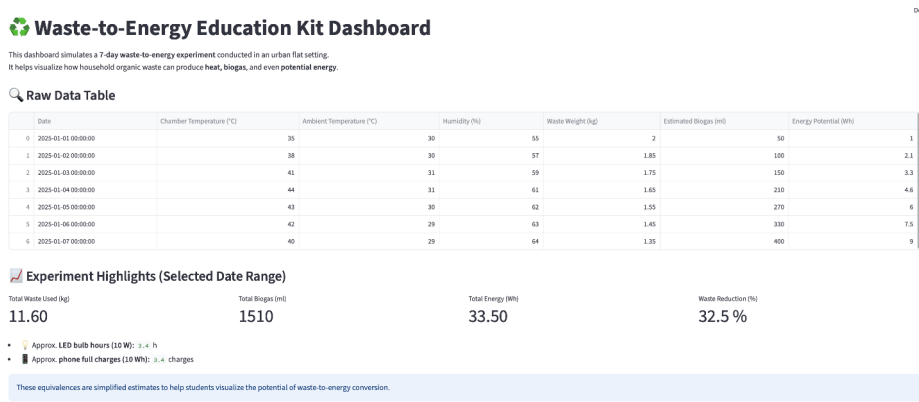


Figure 3. Waste-to-Energy Education Kit Dashboard showing raw experimental data, biogas yield estimation, energy potential, and waste reduction performance.

Table 1. Example of Raw Operational Data of the Waste-to-Energy (WtE) Biogas Chamber.

Date	Chamber Temp. (°C)	Ambient Temp. (°C)	Humidity (%)	Waste (kg)	Biogas (mL)	Energy (Wh)
01-01	35	30	55	2.00	50	1.0
01-02	38	30	57	1.85	100	2.1
01-03	41	31	59	1.75	150	3.3
01-04	44	31	61	1.65	210	4.6
01-05	43	30	62	1.55	270	6.0
01-06	42	29	63	1.45	330	7.5
01-07	40	29	64	1.35	400	9.0

5.2 Environmental and Energy Trend Analysis

Fig. 4 illustrates the environmental and energy-related trends observed during the waste-to-energy experimental period. The dashboard presents four key indicators, namely, chamber and ambient temperature variation, humidity evolution, biogas generation progress, and daily waste weight reduction. Fig. 4(a) shows a comparison of chamber and ambient temperatures over the monitoring period. The chamber temperature consistently remained higher than the ambient temperature throughout the observation period, reaching a peak of approximately 45 °C before gradually declining. This temperature differential indicates active microbial decomposition within the chamber, which is essential for effective organic waste degradation. In contrast, the ambient temperature exhibited relatively minor fluctuations, remaining within the range of typical environmental conditions. Figure 4(b) shows humidity variation during the composting process over the monitoring period. Humidity levels within the composting chamber showed a steady increase over time, rising from approximately 55% to 64%. This trend reflects moisture retention associated with biological activity and supports favorable conditions for anaerobic digestion and biogas production.

Fig. 4(c) illustrates the cumulative biogas production measured during the composting process over the monitoring period. Based on decomposition rates and waste input, the daily biogas potential was estimated at 0.2–0.5 litres. Although small in volume, this output demonstrates the cumulative energy potential of household-scale organic waste. Biogas gen-

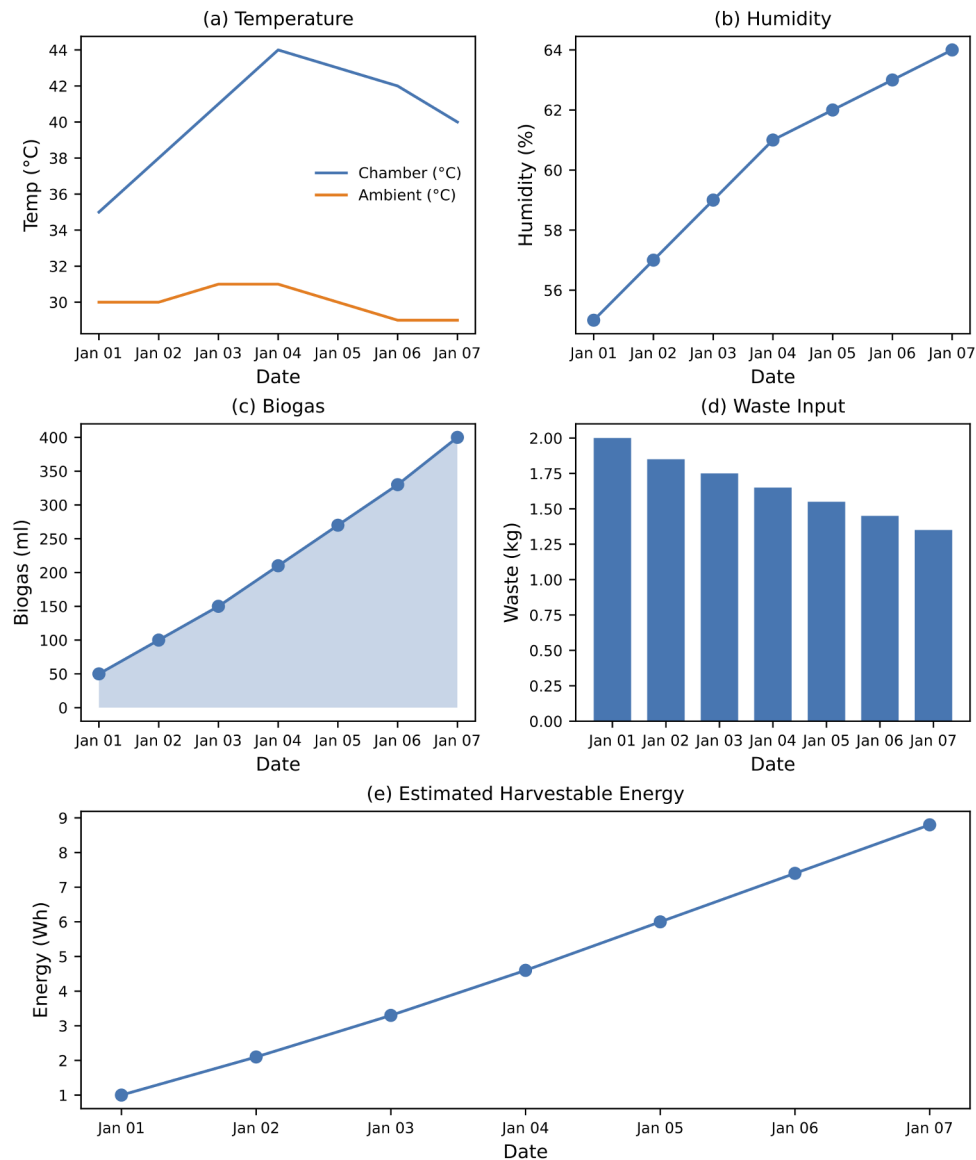


Figure 4. Waste-to-Energy monitoring results: (a) chamber and ambient temperature, (b) humidity, (c) biogas production, (d) waste input per day, and (e) estimated harvestable energy.

eration exhibited a monotonic increase, reaching an accumulated volume of approximately 400 mL by the end of the monitoring period. The progressive rise in biogas output demonstrates a direct relationship between sustained environmental conditions and energy recovery performance.

In addition, the daily waste input exhibited a decreasing trend, declining from approximately 2.0 kg to 1.35 kg over the course of the experiment, as shown in Fig. 4(d). This reduc-

Final Day Summary (Within Selected Range)

-  Final Chamber Temp: 40 °C
-  Ambient Temp: 29 °C
-  Humidity: 64 %
-  Cumulative Biogas (up to this day): 1510 ml
-  Total Waste Used (selected range): 11.60 kg
-  Total Energy Potential: 33.50 Wh

This experiment demonstrates that even small amounts of household waste can yield meaningful energy and environmental value.

Figure 5. Final-day performance summary.

tion confirms effective waste mass conversion and aligns with the observed increase in biogas production. Overall, the integrated visualization enables clear correlations among environmental parameters, waste degradation behavior, and energy generation outcomes, thereby reinforcing the effectiveness of the proposed Waste-to-Energy Education Kit as a learning and experimental platform.

Fig. 4(e) presents the temporal variation in estimated harvestable energy over a one-week period. The energy output exhibits a linear growth pattern, suggesting a proportional relationship between time and accumulated energy. This behavior indicates consistent input conditions and stable system efficiency, with no observable degradation or transient disturbances. Such characteristics are desirable for applications requiring reliable and continuous energy supplies, particularly in low-power IoT and embedded systems.

5.3 Estimated Energy Potential and Final-Day Performance Summary

Fig. 5 illustrates the estimated harvestable energy obtained from the waste-to-energy experiment over the selected observation period. The energy potential was derived from cumulative biogas production using a simplified conversion model suitable for educational demonstration. A steady and near-linear increase in estimated energy output was observed, rising from approximately 1 Wh on the first day to 8.8 Wh by the final day. This trend reflects continuous biogas generation under stable composting conditions and indicates effective conversion of organic waste into usable energy.

In addition, a summary of the key system parameters recorded on the final day of the selected range is presented to provide a consolidated performance overview. The final chamber temperature reached 40 °C, while the ambient temperature remained at 29 °C, confirming sustained thermal activity within the composting chamber. The relative humidity level increased to 64%, supporting favorable conditions for microbial degradation. Cumulative biogas production reached 1,510 mL, corresponding to a total estimated energy potential of 33.50 Wh derived from a total waste input of 11.60 kg.

These results demonstrate that even small quantities of household organic waste can yield measurable energy output and environmental benefits. The combined visualization of energy trends and final-day metrics enhances learners' understanding of the relationships among waste input, biological activity, and energy recovery, thereby reinforcing the effectiveness of the proposed Waste-to-Energy Education Kit as a hands-on instructional and experimental platform. Although the system successfully demonstrates the concept of energy harvesting,

the practical energy yield remains relatively low (33.5 Wh from 11.6 kg of input material). This finding indicates that the current implementation is not intended as a scalable or highly efficient energy solution. Instead, it is better positioned as an educational demonstration platform that provides students and practitioners with a tangible and interactive means of understanding energy conversion processes, system behavior, and sustainability concepts in a controlled environment.

6 Conclusion and Future Work

This project demonstrated a low-cost, educational dashboard for simulating Waste-to-Energy processes in urban flats using environmental sensor data. By offering a visual and interactive experience, the tool fosters greater community participation in sustainable practices. The dashboard allows users to explore key composting indicators, making it a valuable tool for education and community engagement. It illustrates how household waste can be converted into useful outputs and raises awareness of sustainable waste practices. The system can be scaled to multiple units and integrated with real-time IoT platforms such as Firebase. Future work will integrate real-time sensors, AI-based anomaly detection, and multilingual interfaces for broader outreach.

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