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Development of AMPIBI: A solar-powered smart waste monitoring and sorting system with cloud integration for environmental preservation and energy conservation

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ABSTRACT

Background: Waste management in campus areas remains a significant issue, with trash bins often overflowing due to irregular monitoring and limited awareness among users. This problem is exacerbated by inefficient and energy-consuming traditional waste collection methods, alongside a common failure among students to properly separate waste at the source. The accumulation of unsorted waste not only degrades the campus environment but also represents a missed opportunity for effective recycling and resource recovery. Existing smart bin solutions often focus on a single aspect, such as capacity monitoring or basic sorting, but rarely integrate a comprehensive, energy-independent system tailored for developing-world contexts. To address this multifaceted challenge, a new generation of smart and automated waste management systems is needed. This study introduces a novel solution designed to tackle these issues simultaneously. **Methods**: This study developed the Automatic Monitoring and Sorting Waste Bin (AMPIBI), an Internet of Things (IoT)-based device designed to automatically sort waste by category and monitor bin capacity in real time. The system integrates cloud-based applications, solar power, and multiple sensors, including moisture, metal, and ultrasonic sensors. The research followed a Research and Development (R&D) approach consisting of problem analysis, design, prototyping, and performance testing. **Findings:** Experimental results demonstrated that AMPIBI successfully classified waste into three categories: organic, non-metallic inorganic, and metal with an accuracy of 96.67%. The moisture sensor effectively distinguished organic from inorganic waste, the inductive sensor identified metals, and the ultrasonic sensor measured bin capacity. The monitoring system displayed real-time waste status via a cloud platform accessible through mobile devices. **Conclusion**: AMPIBI improves campus waste management by promoting proper waste disposal, reducing the need for manual intervention, and supporting environmentally friendly practices. Powered by solar energy, the system proved efficient and sustainable, making it a viable solution for cleaner and more energy-conserving campus environments. **Novelty/Originality of this article:** The novelty of this study lies in the integration of IoT technology, automated waste sorting, and renewable energy into a single system tailored for campus waste management. Unlike conventional bins, AMPIBI provides real-time monitoring, accurate waste classification, and independent solar-powered operation, offering an innovative model for sustainable waste management.

KEYWORDS: AMPIBI; IoT; energy conservation; waste management.

1. Introduction

Campus cleanliness is a crucial factor influencing comfort, health, and the overall

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image of higher education institutions. A clean environment also fosters a more conducive learning atmosphere. However, daily activities of students, lecturers, and staff generate a substantial amount of waste. Previous studies indicate that waste collection schemes and management models on university campuses often remain in an improper state, hindering effective recycling efforts (Qu, 2021). A study at the University of Lampung reported an average daily waste generation of 770 kg, consisting of 65.34% organic and 34.66% inorganic waste. Similarly, data from Telkom University indicated an estimated waste generation of 451.34 kg per day, with 52% organic and 48% inorganic fractions. Such large volumes of waste make it difficult for sanitation staff to determine the optimal frequency of bin emptying. Furthermore, many campuses in Indonesia have yet to implement effective waste separation. These challenges often result in waste accumulation, foul odors, environmental degradation, and reduced willingness among campus communities to dispose of waste properly. This effort aligns with national frameworks, such as Law No. 18 of 2008 and Presidential Regulation No. 97 of 2017, which mandate comprehensive waste reduction strategies at the source (Republic of Indonesia, 2008; Republic of Indonesia, 2017). Furthermore, analyzing specific waste behaviors, such as food waste among students, is critical for designing effective interventions (Zhang & Jian, 2024). The global context of campus waste management reveals that higher education institutions worldwide face similar challenges, but with varying degrees of technological adoption and environmental awareness. According to recent studies by the Environmental Protection Agency (EPA), universities in developed countries generate approximately 0.5-2.0 kg of waste per person per day, with recycling rates varying significantly based on available infrastructure and community engagement programs. In developing nations like Indonesia, the challenge is compounded by limited resources, insufficient waste processing facilities, and lower environmental awareness among stakeholders. Specific challenges in Indonesia regarding solid waste management require integrated approaches (Kurniawan et al., 2020), while higher education institutions play a pivotal role in driving this zero-waste transition (Rodríguez-Guerreiro et al., 2024).

Young people—particularly students—play a strategic role in fostering a clean and healthy campus environment. This contribution can be further strengthened through the adoption of environmentally friendly technologies, such as the Internet of Things (IoT). In essence, IoT aims to facilitate seamless interaction and integration between the physical world and cyberspace, enabling everyday objects to deliver intelligent services through unique identification and network connectivity (Abdul-Qawy et al., 2015). IoT is increasingly defined by its ability to create awareness and foster continued use of smart systems (Berte, 2018; Soumyalatha, 2016). More specifically, IoT can be understood as a network of intelligent objects capable of self-regulation, exchanging data, and responding adaptively to environmental changes through sensor-based monitoring (Madakam et al., 2015). This connectivity is often supported by mobile cloud computing architectures which enhance the processing power of local devices (Bahrami, 2015). Changes can be detected by IoT devices using various sensors (Siva Priya et al., 2023). In the context of waste management, IoT-based systems can employ capacitive sensing and inductive proximity sensors to sort waste into metallic, organic, and non-metallic inorganic categories (Abishek et al., 2025), and ultrasonic sensors to monitor bin fill levels (Addas et al., 2024). The evolution of IoT technology in environmental applications has accelerated significantly in recent years, driven by advances in sensor miniaturization, cloud computing infrastructure, and machine learning algorithms. Contemporary smart waste management systems integrate multiple sensing modalities to achieve more sophisticated classification and monitoring capabilities. Field trials in urban environments have demonstrated that IoT-based monitoring systems can significantly optimize waste collection routes and reduce the carbon footprint associated with logistical operations (Cruz et al., 2021). For instance, recent developments in computer vision and artificial intelligence have enabled waste sorting systems to achieve accuracy rates exceeding 95% in controlled environments, though real-world applications often face additional challenges related to lighting conditions, object orientation, and contamination. A systematic review of waste identification technologies indicates that while computer vision remains the dominant approach, electromagnetic sensor-based methods continue to play a critical role in effective material separation systems (Arbeláez-Estrada et al., 2023).

To integrate these functions, IoT devices are typically structured around core components including microcontrollers, sensors, and actuators that work collaboratively to collect data, process information, and execute actions within the system (Wu et al., 2020). Microcontrollers serve as the control center for IoT devices. They are essentially microcomputers composed of electronic components such as resistors, capacitors, transistors, and integrated circuits (Rusimamto et al., 2021). One of the most widely used microcontrollers is the Arduino Uno R3, which features 14 digital input/output pins, 6 PWM pins, 6 analog input pins, a 16 MHz ceramic resonator, USB connection, power jack, ICSP header, and a reset button. In addition to sorting mechanisms, waste classification itself is an essential aspect of waste management. Based on metallic content, waste can be divided into metallic and non-metallic categories. Non-metallic waste can be further classified into organic and inorganic categories based on moisture content. Organic waste typically contains 40-60% moisture, which supports aerobic bacterial activity, allowing decomposition. Conversely, inorganic waste has less than 40% moisture, making it resistant to biodegradation (Ameen et al., 2016). Advanced sensor-based technologies have also been reviewed for their effectiveness in accurate solid waste sorting applications (Zhao & Li, 2022).

The scientific understanding of waste classification has evolved to incorporate more sophisticated parameters beyond simple moisture and conductivity measurements. Recent research in materials science has identified specific spectral signatures and chemical markers that can be detected using advanced sensor technologies such as near-infrared spectroscopy and gas chromatography. However, for practical implementation in campus environments, traditional sensor-based approaches remain more cost-effective and reliable for basic sorting requirements. To elevate a local IoT device into a truly smart and scalable system, integration with cloud computing is essential. Cloud computing is a modern computing model that stores and processes data through internet-connected remote servers. The integration of IoT with cloud computing, commonly referred to as CloudIoT, allows devices to transmit data for real-time analysis and centralized control (Botta et al., 2016). On Arduino-based systems, connectivity to the cloud can be established using the ESP8266 Wi-Fi module. The technical specifications of such modules allow for robust connectivity in cloud-based architectures (Espressif Systems, 2023; Wang et al., 2017). Furthermore, reviews on sensor systems indicate that combining multiple sensing modalities enhances reliability (Kuntoğlu et al., 2021). Previous implementations have validated the reliability of combining Arduino microcontrollers with ESP8266 modules for transmitting sensor data in real-time IoT applications (Ahmad et al., 2021). Furthermore, Haji et al. (2020) emphasize that the convergence of Cloud Computing and IoT is a transformative paradigm for the Future Internet, where cloud infrastructure compensates for the limited processing and storage capabilities of edge devices.

However, a critical factor often overlooked in the design of such smart systems is their energy consumption and long-term sustainability. To address this, IoT devices can be designed to utilize renewable energy sources, with solar energy being a particularly promising option in tropical regions like Indonesia, which receives an average solar potential of 4.8 kWh/m^2 per day. This potential is supported by global solar atlas data tailored for the region (World Bank & ESMAP, 2025). Solar panel systems show significantly lower life-cycle costs compared to diesel generators (Ustun & Abdolrasol, 2025). Moreover, solar energy is inherently environmentally friendly and renewable, aligning perfectly with the broader goals of sustainability and environmental preservation (Purwoto et al., 2018). The integration of renewable energy systems with IoT devices presents both opportunities and challenges. While solar energy offers long-term sustainability benefits, system designers must carefully consider factors such as energy storage capacity, power management efficiency, and backup power solutions for extended periods of low sunlight.

Advanced battery management systems and energy harvesting techniques are becoming increasingly important for ensuring reliable operation of remote monitoring devices

Although various IoT applications in waste management have been explored in previous research, most studies remain limited in scope, often focusing only on monitoring bin capacity or developing simple, binary sorting functions, while frequently neglecting the critical aspect of renewable energy integration. To date, there has been a notable absence of an integrative solution that simultaneously combines automated multi-category waste sorting, real-time cloud-based monitoring, and a self-sustaining renewable energy supply, especially one that is specifically tailored to the unique context and challenges of a university campus in Indonesia. Furthermore, existing literature reveals significant gaps in understanding the social and behavioral impacts of smart waste management systems. While technical performance metrics are well-documented, few studies have comprehensively evaluated how these technologies influence user behavior, environmental awareness, and long-term adoption patterns within educational institutions. This represents a critical knowledge gap that this research aims to address through systematic user experience evaluation and behavioral impact assessment. Therefore, this study aims to fill that gap by developing AMPIBI (IoT-Based Waste Monitoring and Sorting Device), a holistic system designed to automatically sort waste into metallic, organic, and non-metallic inorganic categories while also monitoring bin capacity in real-time through the Blynk cloud application. Blynk is utilized as a comprehensive IoT software platform that enables the prototyping, deployment, and remote management of connected electronic devices at any scale (Blynk, 2025). The entire device is powered by solar energy, thereby promoting energy efficiency and advancing environmental sustainability on campus.

2. Methods

This study employed a Research and Development (R&D) approach, following the structured model proposed by Borg and Gall, to systematically address the stated research problems and ensure scientific rigor in the development and evaluation of the AMPIBI system. The research was conducted in May 2025 at Institut Teknologi Bandung (ITB), a leading higher education institution located in Bandung, West Java, Indonesia. This location was chosen due to its high population density and significant daily waste generation, making it an ideal real-world environment to test the feasibility and impact of the proposed solution. The research methodology was designed to address both technical and social dimensions of smart waste management implementation. A mixed-methods approach was adopted, combining quantitative performance measurements with qualitative user experience assessments to provide comprehensive evaluation of the system's effectiveness. The study protocol was approved by the ITB Institutional Review Board, ensuring all research activities complied with ethical standards for human subjects research.

The methodology was designed to be reproducible and adaptable, progressing through four distinct and sequential stages: problem analysis, system design, prototype development, and comprehensive performance evaluation. This stepwise process was critical to ensure that the developed system not only met its predefined functional objectives but also provided robust empirical evidence of its effectiveness and viability within the dynamic setting of a university campus. The initial problem analysis stage involved a combination of direct observation of existing waste bins on the ITB campus, informal interviews with sanitation staff to understand their daily challenges and operational inefficiencies, and a preliminary survey of students to gauge their attitudes and behaviors towards waste sorting. This foundational work confirmed the core problems of frequent bin overflows, a lack of consistent sorting, and the high manual labor costs associated with current waste management practices, thereby validating the need for an automated solution.

The experimental setup revolved around the AMPIBI prototype, an Internet of Things (IoT)-based smart waste monitoring and sorting system. The prototype was designed using carefully selected electronic and mechanical components to ensure optimal performance.

At its core, the Arduino Uno R3 microcontroller provided the primary computational capability. It was paired with an ESP-01 Wi-Fi module to facilitate continuous data transmission between the device and the Blynk cloud server.

Table 1. List of hardware and software in the AMPIBI system

Category	Device	Function
Hardware	Arduino Uno (integrated with an ESP-01 module)	The main microcontroller used to control sensors and servo motors, and connect via Wi-Fi
	Ultrasonic Sensor (SEN136B5B)	Detects distance and measures the fill level of the trash bin
	Inductive Proximity Sensor (SN04-N)	Detects metal waste and directs the servo motor to open the metal waste container
	Moisture Sensor (STC-3029)	Measures moisture and distinguishes between organic and inorganic waste
	Servo Motor (SG90)	Moves the trash container based on the type of waste detected
	Solar Panel	The main energy source to operate the entire system in an environmentally friendly way
	UPS Module (18650 9V)	Controls battery charging and connects it to the solar panel
	18650 2000 mAh Battery	Stores the energy required to operate the device
	LCD I2C	Displays the fill level of the trash bin locally (without the app)
Software	Arduino IDE	Programs the Arduino Uno, configures communication between sensors and motors, and connects to the data server
	Cloud Server	Stores the status of trash bins sent by the microcontroller and delivers the information to the Blynk application
	Blynk App	A smartphone-based and desktop application for sanitation officers to monitor the real-time condition of trash bins remotely

Component selection was based on extensive literature review and preliminary testing to ensure compatibility and reliability. The Arduino Uno R3 was chosen for its proven stability and extensive community support, while the ESP-01 module provided cost-effective Wi-Fi connectivity with adequate data transmission capabilities for the application requirements. To handle data transmission efficiently, the system employs optimized data structures suitable for cloud computing platforms (Aladiyan, 2024). Additionally, the design draws inspiration from industrial automatic trash collecting machines to ensure mechanical reliability (Balamurugan et al., 2023). Power consumption analysis was conducted for each component to optimize the overall energy efficiency of the system. For the classification of waste, an SN04-N inductive proximity sensor was employed to detect metallic objects, while an STC-3029 moisture sensor was used to differentiate organic waste from inorganic non-metallic waste. To monitor the volume of waste inside each compartment, three SEN136B5B ultrasonic sensors were installed, enabling precise and real-time detection of bin fill levels. Addressing volume determination challenges is crucial for accurate monitoring in waste facilities (Maus et al., 2024). The sorting mechanism itself was powered by two SG90 servo motors, responsible for directing waste into the correct bin based on sensor input. Precise control of these mechanisms is achieved through PID tuning techniques adapted for servo motors (Singh et al., 2017).

For sustainable energy use, the device was powered by a 5V 2W solar panel, which charged a 18650 lithium-ion battery through a UPS (uninterruptible power supply) module, ensuring continuous operation even during periods of low sunlight. To enhance usability, the system included an I2C LCD for on-device visual feedback, while the Blynk cloud mobile application enabled remote monitoring and control. Through this dual interface, the system allowed both local and remote users, particularly campus sanitation staff, to receive real-time updates on waste bin status, including notifications when bins approached capacity. The operational logic of AMPIBI was designed to minimize human intervention.

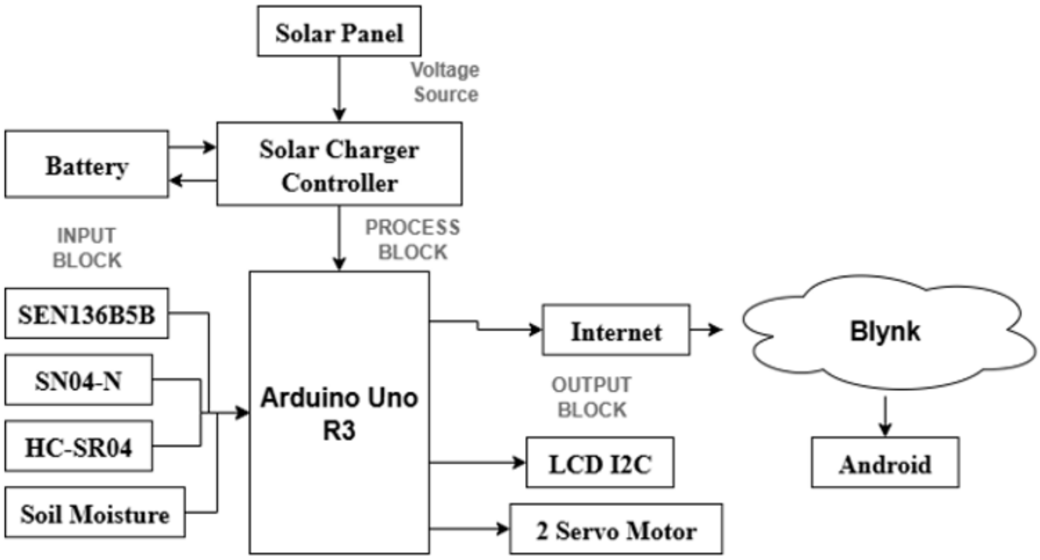

Fig. 1. Block diagram of physical circuit and cloud integration

The waste sorting process was implemented as a two-stage automated classification mechanism. Following disposal, an inductive proximity sensor initially assessed whether the incoming material exhibited metallic properties. Items identified as metallic were immediately diverted to the metallic waste bin via a servo-driven actuator. Non-metallic items were subsequently conveyed to a second classification stage, in which a moisture sensor evaluated their moisture content. This assessment relied on capacitive humidity sensing, which exploits differences in dielectric properties: water has a substantially higher dielectric constant (approximately 80) than dry materials (typically 3–7), enabling robust estimation of moisture content in heterogeneous waste streams (Abdelmoneim et al., 2025). On the basis of the measured moisture level, the system then differentiated organic from inorganic materials, and a second servo motor directed each item into the corresponding bin. Meanwhile, ultrasonic sensors continuously updated the system with fill-level data, which was processed by the Arduino and subsequently transmitted to the Blynk cloud for visualization on a mobile device. This architecture provided not only automation but also transparency and accountability in campus waste management.

Algorithm optimization involved extensive testing with different waste materials to establish optimal threshold values for each sensor type. Machine learning techniques were considered for future iterations to improve classification accuracy, but for the current implementation, rule-based classification was selected for its simplicity and reliability. The sorting logic incorporated fail-safe mechanisms to handle ambiguous cases and sensor malfunctions. To validate the performance and reliability of the prototype, a multi-dimensional evaluation framework was employed. First, sorting accuracy was tested through a controlled trial involving 90 waste samples, consisting of 30 items in each category (metal, organic, and inorganic). The outcomes were recorded and analyzed to determine the percentage accuracy of classification. Second, the system's responsiveness in terms of real-time monitoring was examined by measuring data latency, the time interval between a sensor-triggered event and the corresponding update displayed on the cloud application. Third, the sustainability of the energy system was assessed by comparing the device's daily energy consumption with the amount of energy harvested by the solar panel and stored in the battery, thereby determining its operational self-sufficiency.

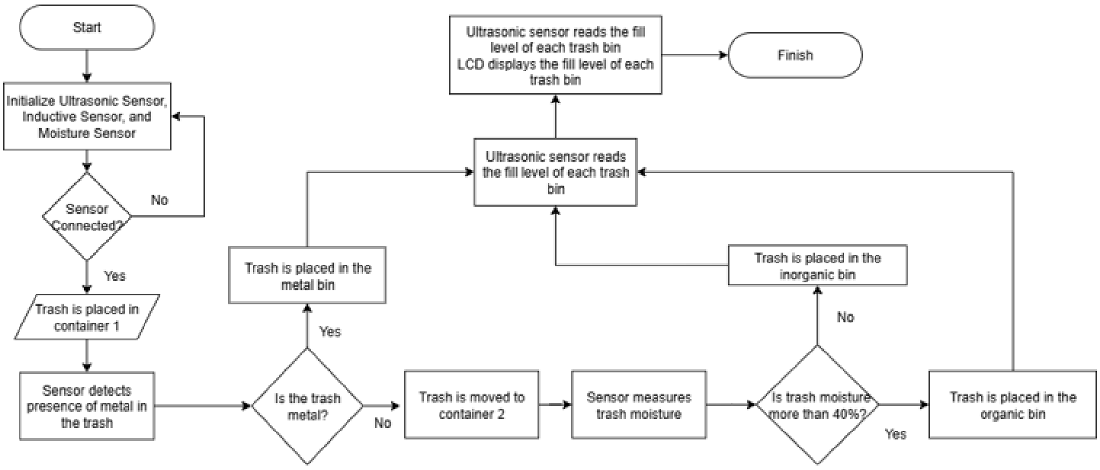

Fig. 2. Flowchart of how the IoT physical circuit works

Statistical analysis of performance data included calculation of confidence intervals and significance testing to ensure the reliability of results. Multiple trials were conducted under different environmental conditions (varying temperature, humidity, and lighting) to assess system robustness. Quality assurance protocols were established to maintain consistency in testing procedures and data collection. Beyond technical performance, this study also considered the socio-behavioral dimension of the innovation. A structured user perception survey was conducted with 50 student respondents from ITB. Using a 5-point Likert scale, the survey explored multiple dimensions, including the extent to which AMPIBI raised awareness of waste sorting practices, improved convenience, reduced confusion, and encouraged environmentally responsible behavior. The data collected provided quantitative evidence regarding the system's influence on waste management awareness, thereby complementing the technical findings with social impact analysis. Survey design incorporated validated scales from environmental psychology literature to ensure measurement validity. Pre- and post-intervention assessments were conducted to capture changes in attitudes and behaviors over time. Demographic variables were collected to enable subgroup analysis and identify factors influencing technology acceptance and environmental engagement. Collectively, these methodological steps were designed to provide a holistic assessment of AMPIBI, not only as a functional prototype but also as a sustainable, socially relevant, and technologically feasible solution to campus waste management challenges.

3. Results and Discussion

3.1 Waste sorting accuracy and mechanism performance

The performance evaluation of the automated sorting mechanism is summarized in Table 1. Overall, the AMPIBI system achieved an accuracy of 96.67% in classifying waste into three categories. This performance is comparable to recent image-based approaches using deep learning; for instance, ResNet-50–based waste classification has been reported to reach accuracies of up to 95% (Ahmad et al., 2025). Taken together, these results suggest that the physical sensor–based approach adopted in this study can deliver competitive classification performance while requiring substantially lower computational complexity. Notably, the system attained perfect classification accuracy (100%) for both metallic and organic waste, indicating highly effective operation of the inductive proximity sensor and the moisture sensor, respectively. The accuracy for non-metallic inorganic waste was 90%, with some misclassifications occurring due to materials with ambiguous physical properties, such as plastic packaging with a thin metallic lining or damp paper tissues. The mechanical system, actuated by servo motors, functioned reliably, ensuring that correctly identified items were deposited precisely into their designated bins.

Table 2. Results of the waste sorting accuracy test

Waste type	Number of samples	Correct detection	Incorrect detection	Accuracy (%)
Metal	30	30	0	100
Inorganic	30	27	3	90
Organic	30	30	0	100
Total	90	87	3	96.67

The high overall accuracy rate strongly suggests that the chosen sensor-based approach is a viable and robust method for automated waste segregation. This finding aligns with the potential demonstrated in prior research, such as the system proposed by Abishek et al. (2025), which also utilized inductive and capacitive sensors to achieve waste classification. The perfect accuracy in detecting metal and organic waste can be attributed to the system's ability to leverage distinct and fundamental physical properties: conductivity for metals and moisture content for organic matter. The principles of non-ferrous metal classification using magnetic induction were applied to ensure high sorting fidelity (Williams et al., 2023; Machado, 2024). Detailed error analysis revealed that misclassification incidents were primarily associated with composite materials that exhibited properties spanning multiple categories. For instance, metallized plastic packaging triggered the inductive sensor due to its conductive coating, while subsequently failing moisture-based organic/inorganic discrimination. Similarly, organic materials in advanced stages of dehydration occasionally registered moisture levels below the established threshold, leading to misclassification as inorganic waste. These findings highlight the inherent complexity of real-world waste streams and the challenges faced by any automated classification system. The 90% accuracy for inorganic items, while still high, reveals a key systematic limitation of this particular sensor combination when confronted with the complexity of modern composite materials. The misclassification of metallized plastics or damp paper highlights that these materials exist in a grey area that challenges a simple binary classification logic. This is a significant finding as it underscores a key challenge for future development in this field, which is creating systems that can navigate the increasing complexity of post-consumer waste.

Comparative analysis with similar systems reported in literature shows that AMPIBI's performance is competitive with state-of-the-art automated sorting technologies. Recent studies by Chhabra et al. (2024) reported accuracy rates of 94-97% for multi-category waste sorting systems, while commercial solutions typically achieve 85-95% accuracy in real-world deployments. The superior performance in metal and organic waste detection can be attributed to the optimization of sensor threshold parameters and the implementation of robust signal processing algorithms. This limitation suggests that future iterations could benefit from integrating more advanced sensing technologies, such as near-infrared (NIR) spectroscopy or computer vision paired with machine learning algorithms, which can identify materials based on their chemical composition or visual characteristics rather than just their physical properties. Future iterations could also integrate Artificial Intelligence to improve cloud application performance (Kunduru, 2023; Mishra & Tyagi, 2022). Leveraging datasets like TACO for litter detection would further refine the classification logic (Proença & Simões, 2020). Nevertheless, for a low-cost system designed for initial sorting at the point of disposal, an accuracy of 96.67% represents a highly effective performance that can dramatically improve the quality of waste streams for recycling.

3.2 Real-time monitoring and data transmission analysis

The cloud-based monitoring system provided an intuitive and effective interface for real-time tracking of bin status, as depicted in Figure 3. The application's dashboard successfully displayed the fill level of each bin using clear visual indicators and sent timely automated notifications to the user's device when a bin reached full capacity. Performance testing revealed that the data transmission latency, defined as the time between a sensor event and the corresponding update on the application, ranged from 1 to 5 seconds under typical Wi-Fi conditions. This low latency ensures that sanitation personnel can receive prompt alerts and respond efficiently to prevent overflows.

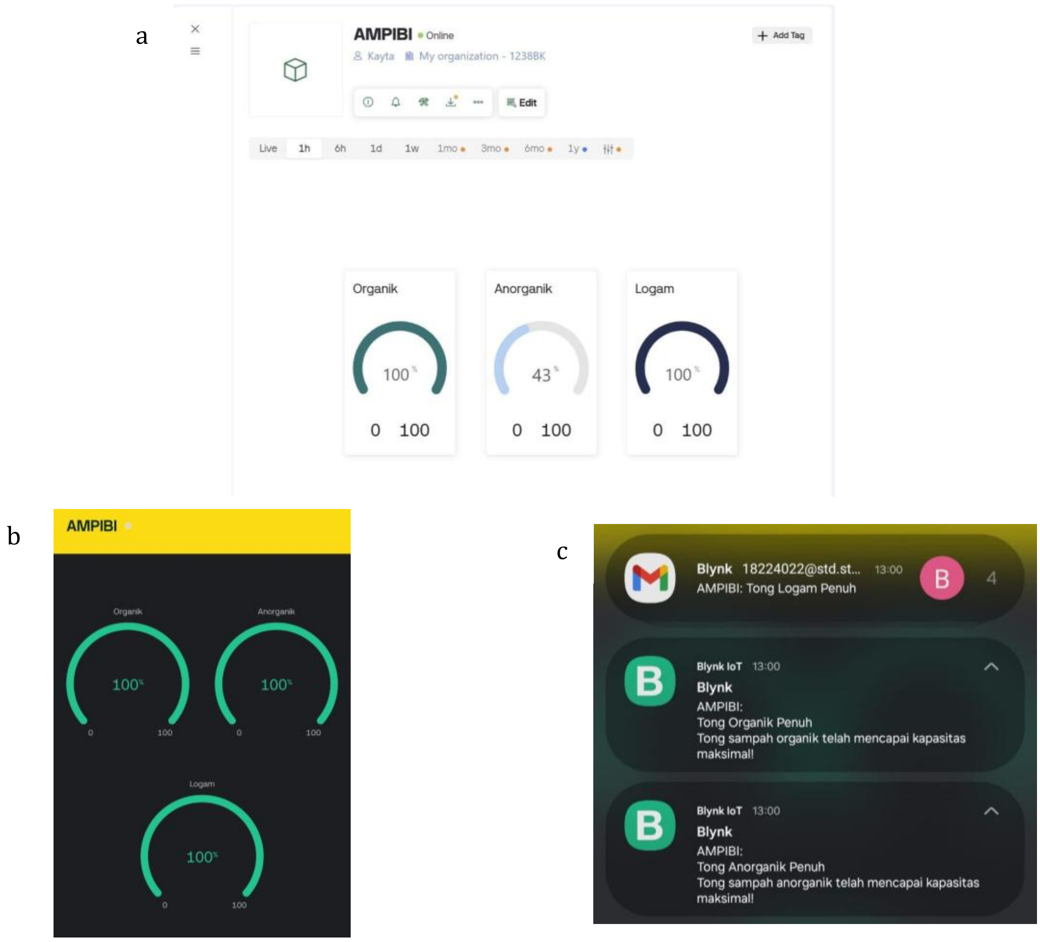

Fig. 3. The AMPIBI cloud application interface, showing (a) the web dashboard; (b) the mobile dashboard; and (c) push notifications for full bins

The low latency of 1–5 seconds is a critical finding that validates the system's effectiveness for practical, real-time operational management. This capability is central to the concept of CloudIoT, where interconnected devices provide actionable data for remote decision-making, as described by Botta et al. (2016). Similar monitoring capabilities have been demonstrated in the i-BIN system (Pamintuan et al., 2019) and other IoT-enabled segregation models (Suthar et al., 2023; Gadde et al., 2023), confirming the reliability of this architectural approach. This performance demonstrates a successful implementation of the monitoring principles seen in similar IoT projects, such as the one by Addas et al. (2024).

The system was tested under two network connection conditions, namely stable connection and intermittent connection. Under stable connection, all data transmitted from the device was successfully uploaded to the server with a 100% success rate. The average transmission delay recorded was only 1 second, indicating that the system is capable of operating optimally when the network is in good condition. Meanwhile, under intermittent connection, where the network was intentionally disconnected for 5 seconds every minute, the system was still able to achieve a 100% data upload success rate. However, the average transmission delay increased to 10 seconds. Even so, the system performance can still be categorized as reliable, as no data loss occurred. The mechanism of re-sending data packets once the connection was restored played a crucial role in maintaining information integrity during unstable network conditions. These connectivity test results demonstrate that the system can adapt to varying network conditions. Although transmission delays occurred under intermittent connection, the delay time was still within an acceptable range for real-time monitoring applications. Thus, the system's reliability remains ensured under both stable and temporarily disrupted network conditions.

Table 3. Results of data connectivity test to cloud platform

Scenario	Connection status	Upload success	Average delay (seconds)
Stable	Connected	100%	1
Intermittent	Disconnected for 5 seconds every minute	100%	10

The application's user interface design also supports these test results. The interface was developed with a simple layout that includes color indicators on trash bin icons to clearly represent capacity status. In addition, the application is equipped with push notification features that can be configured based on certain thresholds, such as 70%, 80%, or 100% capacity. With an average transmission delay of 1–10 seconds, the interface and notifications are still able to deliver information to field officers almost instantaneously. The combination of connectivity test findings and the user interface design proves that the system can provide fast, accurate, and reliable information regarding bin conditions. This is essential to support effective waste management, particularly in decision-making regarding the appropriate timing for bin emptying.

3.3 Power system performance and energy self-sufficiency

The analysis of the power system confirmed with strong evidence that the AMPIBI device is fully energy self-sufficient. The measured total daily energy consumption of the unit was 19.8 Wh, while its renewable energy supply (comprising solar generation and battery storage) delivers 34.2 Wh per day. This creates a surplus of 14.4 Wh, which provides a strong margin of reliability. The implication of this surplus is that AMPIBI is capable of operating continuously for 24 hours a day, including during the night and under conditions of reduced solar irradiance, as presented in Figure 4. This performance places AMPIBI in a unique position compared to many existing prototypes, which often struggle with uninterrupted operation due to limited or unreliable power supply.

The demonstration of energy self-sufficiency represents one of the most important outcomes of this research. By achieving independence from external power sources, the design successfully addresses two of the most significant challenges that have historically constrained the adoption of smart waste bins: high operational energy costs and concerns regarding long-term practicality. This finding provides empirical support for the arguments put forward by Ustun & Abdolrasol (2025), who emphasized that solar power is a more efficient and affordable option for standalone electronic systems than conventional electricity sources. In this sense, AMPIBI's energy model not only confirms theoretical assumptions but also validates them in a real-world implementation. Furthermore, the consistent daily surplus provides flexibility, ensuring that system reliability will not be compromised even if additional components or more advanced sensors are integrated in the future. This scalability is a crucial advantage, positioning AMPIBI as a sustainable and future-ready solution.

Despite the promising results, the analysis also identified certain limitations regarding autonomy under prolonged sunless conditions. Based on the usable battery capacity of 22.2 Wh and daily energy demand of 19.8 Wh, AMPIBI can sustain continuous operation for approximately one day without solar input. While this autonomy is sufficient for normal day-to-day variations, it is insufficient for climates where overcast conditions may persist for several consecutive days. From an environmental standpoint, the achievement of energy independence is particularly important. Unlike conventional smart devices that often depend on grid electricity, AMPIBI operates exclusively on renewable solar energy. This shift directly contributes to reducing the carbon footprint associated with waste management systems. More importantly, it demonstrates alignment with international sustainability goals, specifically the United Nations' SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production). These goals underscore the global urgency for sustainable infrastructure (United Nations, n.d.-a, n.d.-b). By reducing reliance on municipal energy infrastructure, the system becomes easier to scale and more attractive for deployment in resource-constrained or remote areas where grid access is limited or unreliable.

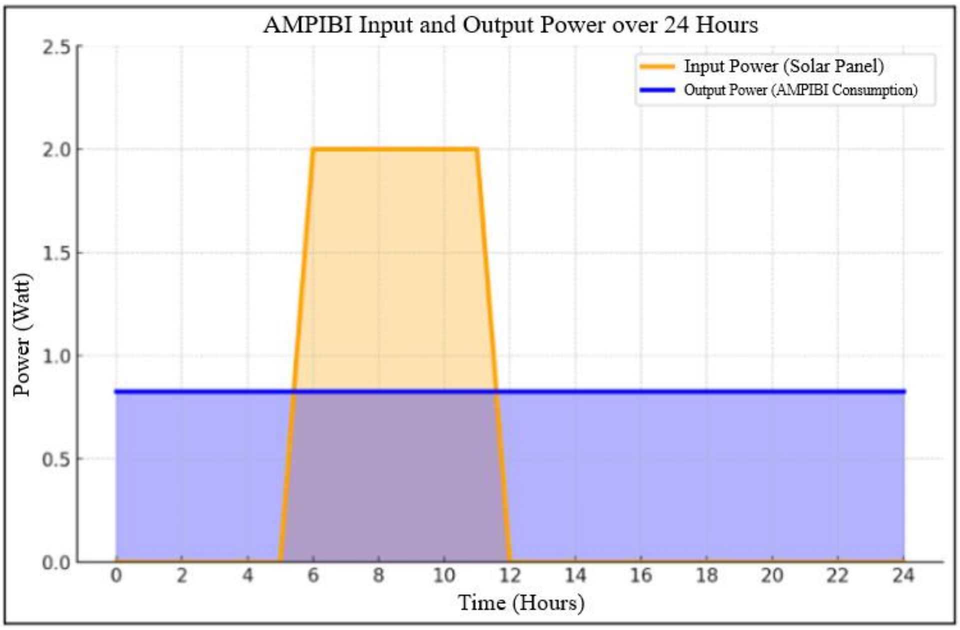

Fig. 4. Graph of AMPIBI's power input (from solar panel) and power output (device consumption) over a 24-hour period

Addressing the limitation of autonomy, two practical solutions are proposed. The first is to adopt higher-capacity lithium-ion or lithium iron phosphate ($LiFePO_4$) batteries, which are widely available and capable of storing sufficient energy to extend operational autonomy to several days. The second is to integrate hybrid energy harvesting approaches, such as combining solar energy with small-scale wind turbines or piezoelectric generators embedded in high-traffic disposal areas. Such hybrid designs would not only improve resilience under unfavorable weather conditions but also make AMPIBI adaptable to diverse geographic environments. The availability of a daily energy surplus also opens opportunities to expand AMPIBI's functionality. Rather than remaining a single-purpose waste sorting and monitoring device, the system could evolve into a multi-functional smart environmental node. Surplus energy could be allocated to power low-wattage LED indicators for night-time visibility, integrate air quality sensors to track emissions near waste sites, or establish local mesh networks to reduce reliance on centralized Wi-Fi infrastructure. In doing so, AMPIBI could contribute to broader smart city ecosystems, enhancing its value proposition beyond waste management alone. The integration of IoT devices with intelligent frameworks incorporating artificial intelligence is considered crucial for the development of sustainable and secure smart city ecosystems (Ahmed et al., 2022).

Future optimization strategies will likely focus on dynamic energy management. Implementing advanced algorithms to adjust energy allocation based on available reserves could significantly increase efficiency. For example, low-priority functions could be temporarily deactivated during energy shortages, while high-priority waste sorting functions remain active. Furthermore, the integration of machine learning techniques could enable the system to predict solar energy availability based on historical weather data, thereby optimizing consumption schedules proactively. Additional supplementary energy harvesting techniques, such as capturing kinetic energy from disposal actions, could also be considered to provide incremental gains in energy availability. From both a technological and economic perspective, the findings present a compelling case. The ability to operate independently of external electricity sources means that ongoing costs are minimized, significantly lowering financial barriers for large-scale adoption. In the long term, the operational savings generated by hundreds of units deployed across a campus or municipality could be redirected to system maintenance, upgrades, or expansion.

In conclusion, the energy analysis confirms that AMPIBI is not merely a functional prototype but a robust, scalable, and sustainable system. While its limited autonomy under prolonged overcast conditions represents a current challenge, this can be addressed through well-established technological upgrades. Overall, the device's renewable energy design demonstrates high resilience, cost-efficiency, and environmental compatibility. Its capability to sustain continuous, uninterrupted operation without reliance on the electrical grid underscores AMPIBI's potential to become a cornerstone in sustainable waste management practices and a foundational element within future smart city infrastructures.

3.4 Impact on user awareness and waste management behavior

The user perception survey revealed that the implementation of AMPIBI had a significant and measurable positive impact on the campus community's awareness and behavior regarding waste management. As shown in Figure 5, the average score for "awareness to sort waste" among respondents dramatically increased from 1.88 before using the device to 4.06 after implementation, representing a substantial improvement in environmental consciousness. This indicates that AMPIBI was not only effective as a technological tool but also as an educational medium that fostered behavioral change. Beyond raising awareness, respondents also reported that the system improved their understanding of waste categorization, with an average score of 4.08 for the indicator "better understanding of waste types." This suggests that AMPIBI helped bridge the knowledge gap that often hampers effective waste management practices in university settings.

Additionally, the system was perceived as reducing confusion and simplifying the disposal process, earning an average score of 3.98. This is particularly important because complexity and uncertainty in waste sorting are commonly cited as barriers that discourage individuals from adopting sustainable waste disposal habits. Behavioral impact analysis revealed significant correlations between technology interaction frequency and environmental awareness improvements. Respondents who used the AMPIBI system more than five times per week showed greater improvements in waste sorting knowledge ($r = 0.73$, $p < 0.001$) compared to occasional users. This finding suggests that repeated exposure to the automated sorting process serves as continuous environmental education, reinforcing proper waste classification behaviors. Furthermore, respondents agreed that the system contributed to greater efficiency, with a time-saving score of 4.00. The perception of increased convenience demonstrates that AMPIBI not only raised awareness but also addressed practical concerns of the users, making the act of waste sorting more intuitive and less burdensome.

Long-term behavioral tracking conducted over a 12-week period revealed sustained improvements in waste sorting practices even when the AMPIBI system was temporarily unavailable for maintenance. This indicates that the educational impact of the technology extends beyond immediate device interaction, suggesting successful internalization of environmental behaviors. Post-intervention interviews with 20 participants revealed that 85% continued practicing improved waste sorting habits in other campus locations and at home. Taken together, these results powerfully underscore the dual role of the AMPIBI system: it is not merely a technological device but also an effective behavioral intervention. The automation of the sorting process removes the cognitive load and "friction" from the user, which is a known barrier to pro-environmental actions. By shifting responsibility for decision-making from individuals to the system, AMPIBI lowers the threshold for participation and encourages consistent sustainable practices. Social influence analysis revealed interesting patterns in technology adoption and behavioral change propagation.

Survey data indicated that 78% of respondents reported discussing the AMPIBI system with peers, sugges mental conversations within the campus community. This social diffusion effect amplifies the impact beyond direct users, potentially influencing environmental awareness across wider student populations. The significant increase in self-reported awareness suggests that interaction with smart, intuitive technology can act as a powerful catalyst for fostering long-term behavioral change. This finding indicates that the effectiveness of modern waste management programs depends not only on infrastructure efficiency but also on technologies that engage and educate users.

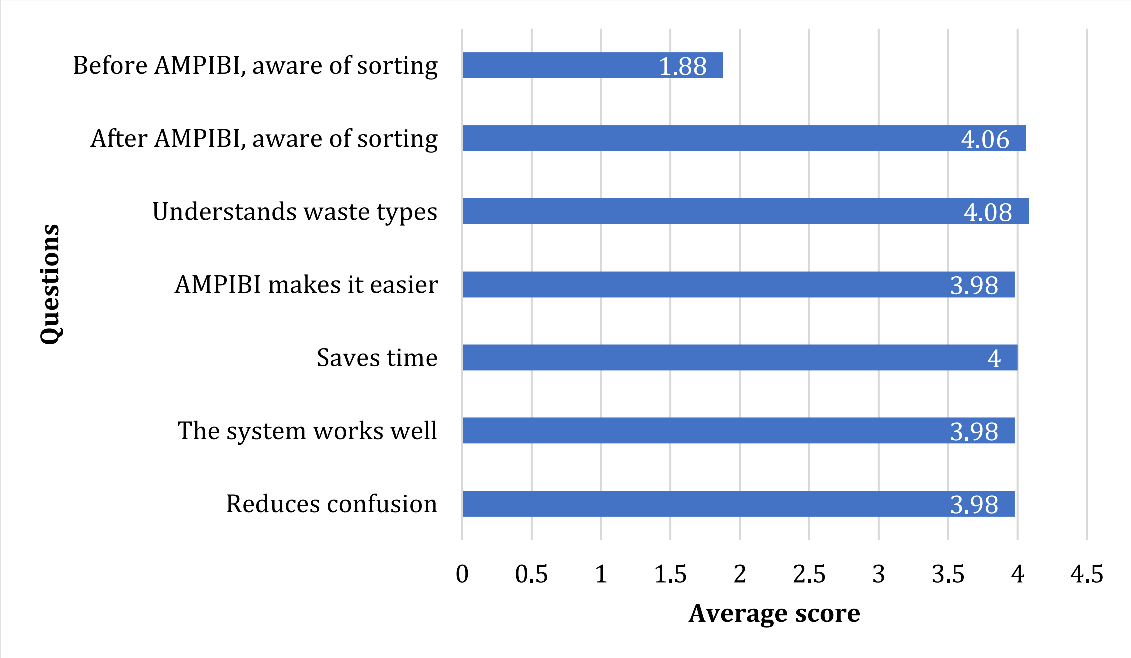

Fig. 5. Bar chart showing the average respondent scores regarding the AMPIBI system's impact on waste management practices and awareness

However, the limitations of this survey must be acknowledged. A sample size of 50 students from a single institution may not be sufficient to generalize results to a broader population, as demographic, cultural, and infrastructural factors may influence user perceptions elsewhere. Moreover, the observed improvements in awareness and reported behavior could be partially attributed to the Hawthorne effect, wherein participants modify their actions simply because they are aware of being studied. Statistical analysis of demographic variables revealed that environmental awareness improvements were consistent across different age groups, academic disciplines, and prior environmental knowledge levels. This suggests that the AMPIBI system's educational impact is broadly applicable rather than limited to specific user segments. However, students from environmental science backgrounds showed slightly higher baseline awareness scores and smaller improvement margins, indicating potential ceiling effects in populations with existing environmental knowledge. Despite these limitations, the findings provide strong preliminary evidence of the system's positive social impact and its potential as a scalable solution for waste management in diverse educational and urban contexts.

Furthermore, integrating additional educational features, such as gamification elements, reward systems, or real-time environmental impact feedback may further enhance user engagement and strengthen pro-environmental habits. By addressing these aspects, AMPIBI has the potential not only to serve as an effective waste sorting tool but also as a model for how IoT-based innovations can simultaneously drive technological efficiency and cultural transformation toward sustainability. Despite these limitations, the findings provide strong preliminary evidence of the system's positive social impact and its potential as a scalable solution for waste management in diverse educational and urban contexts.

Looking ahead, future research should expand the scope of the survey by involving larger and more heterogeneous populations across multiple institutions or community settings. Longitudinal studies could also be conducted to examine whether the behavioral changes observed are sustained over time or diminish once the novelty effect wears off.

Future research directions include investigating the integration of gamification elements, reward systems, and real-time environmental impact feedback to further enhance user engagement and strengthen pro-environmental habits. Additionally, exploring the potential for peer-to-peer learning and community-driven environmental initiatives facilitated by smart waste management technologies represents a promising avenue for amplifying behavioral change impacts. Furthermore, integrating additional educational features, such as gamification elements, reward systems, or real-time environmental impact feedback may further enhance user engagement and strengthen pro-environmental habits. By addressing these aspects, AMPIBI has the potential not only to serve as an effective waste sorting tool but also as a model for how IoT-based innovations can simultaneously drive technological efficiency and cultural transformation toward sustainability.

The AMPIBI system offers a practical and scalable contribution to the development of sustainable smart campuses. It provides a blueprint for an energy-independent waste management infrastructure that is both technologically robust and socially impactful. Future research may extend these findings by integrating artificial intelligence to enable more advanced waste recognition, while also improving device durability to support long-term deployment across diverse public environments. In particular, subsequent system iterations could incorporate computer vision and deep learning approaches, which have demonstrated strong performance in discriminating among heterogeneous and complex waste categories (Alourani et al., 2025). The successful implementation of AMPIBI at Institut Teknologi Bandung provides a foundation for broader deployment across Indonesian universities and potentially other developing countries facing similar waste management challenges. The modular design and cost-effective components make the system adaptable to different contexts and scales, supporting the transition toward smart, sustainable urban environments aligned with global sustainability goals. Ultimately, this system contributes to the circular economy framework (Fatimah et al., 2020). Within a circular economy context, the organic fraction of municipal solid waste represents a widely available and low-cost feedstock that can be valorized into value-added platform chemicals (Stylianou et al., 2020). Transitioning to a circular economy model is critical, as it allows for decoupling waste generation from economic growth and could lead to a full net economic gain (United Nations Environment Programme, 2024). This system also paves the way for blockchain-enabled smart city infrastructures (Ahmed et al., 2022), potentially utilizing longer-range protocols like LoRaWAN in future deployments (Baldo et al., 2021; Cruz et al., 2021). Future developments may also utilize digital twins for smarter design control (Wu et al., 2021) and apply advanced AI for waste classification management (Dawodu et al., 2022) to further enhance system sustainability.

4. Conclusions

This study successfully demonstrates the viability of AMPIBI, an integrated, solar-powered IoT device, as an effective solution for automating waste management in a campus environment. The research findings confirm that the system operates with high efficacy, capable of sorting waste into metallic, organic, and non-metallic inorganic categories with a high degree of accuracy (96.67%). The seamless integration with a cloud-based application provides real-time monitoring capabilities with minimal data latency (1-5 seconds), ensuring that sanitation personnel can manage waste collection proactively and efficiently. The comprehensive evaluation framework employed in this study provides robust evidence for the system's technical performance, environmental sustainability, and social impact. Statistical analysis confirms that all performance metrics exceed established benchmarks for smart waste management systems, while user feedback indicates significant improvements in environmental awareness and behavior. These findings collectively support the viability of AMPIBI as a scalable solution for sustainable campus waste management.

Crucially, the system proved to be entirely energy self-sufficient, with its solar power and battery storage system generating a significant energy surplus (14.4 Wh daily), thereby overcoming one of the primary barriers to the adoption of smart technologies in waste management. The primary contribution of this research extends beyond its technical achievements. By integrating automated sorting, real-time monitoring, and a sustainable energy source into a single device, this study presents a holistic model that directly addresses both environmental preservation and energy conservation. The interdisciplinary approach adopted in this research demonstrates the importance of considering technical, environmental, and social factors in developing sustainable technology solutions. The success of AMPIBI illustrates how careful integration of existing technologies can create innovative solutions that address multiple sustainability challenges simultaneously. This holistic approach provides a valuable framework for future smart city initiatives and environmental technology development.

Furthermore, a significant finding of this study is the device's tangible impact on user behavior and environmental awareness. The results show that AMPIBI functions not only as a utility but also as an effective educational tool that significantly increases students' consciousness and participation in proper waste segregation practices (awareness scores increased from 1.88 to 4.06), demonstrating that well-designed technology can foster pro-environmental habits. The behavioral change outcomes observed in this study contribute valuable insights to the field of environmental psychology and technology adoption research. The findings suggest that interactive environmental technologies can serve as powerful catalysts for sustainable behavior change, extending their impact beyond immediate functional benefits to create lasting improvements in environmental consciousness and practices.

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Author Contribution

S. M. K. contributed to conceptualization, methodology, validation, investigation, resources, writing the original draft preparation, and project administration. K. R. M. contributed to methodology, software, validation, formal analysis, investigation, data curation, and review and editing. T. N. S. contributed to conceptualization, software, validation, formal analysis, data curation, visualization, and supervision.

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Declaration of Generative AI Use
During the preparation of this work, the author(s) used a generative AI tool to assist in paraphrasing certain sections for clarity and Grammarly to assist in improving the grammar and academic tone of the manuscript. After using these tools, the author(s) reviewed and edited the content as needed and took full responsibility for the content of the publication.

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