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Strengthening Environmental Education through IoT-Based Smart Trash Bins

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Abstract

This community service program aimed to support environmental sustainability education by implementing a Smart Trash Bin system based on Internet of Things (IoT) technology at Sekolah Alam Indonesia, Cibinong. The initiative followed a structured Participatory Action Research (PAR) approach consisting of five stages: engagement, co-development, implementation, evaluation, and feedback. A technical team developed the system from Politeknik Negeri Jakarta. It integrated ultrasonic and load-cell sensors with ESP32 microcontrollers and wireless data transmission to enable real-time monitoring of waste volume and weight. In parallel, the Environmental and Forestry Agency (DLHK) of Depok City delivered a seminar on waste ecosystem management to improve knowledge among teachers and staff. Evaluation through pre- and post-test questionnaires showed that participants' knowledge scores enhanced from 13.78 to 15.61 (out of 17), while their environmental attitudes remained consistently high. This project demonstrates a scalable model for integrating technology and environmental education in schools.

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INTRODUCTION

The pressing challenges of environmental sustainability and waste management have led to innovative solutions, particularly in educational institutions. The implementation of a "Smart Trash Bin" system, utilizing Internet of Things (IoT) technology, represents a significant advancement in managing solid waste and promoting eco-conscious behavior among students. As highlighted by Riduan et al., (2024), effective detection and classification of waste can enhance waste management practices, demonstrating the necessity of integrating technology into waste handling strategies. This integration is essential not only within urban systems but also in educational settings. Schools like Sekolah Alam Indonesia in Cibinong, Kabupaten Bogor, play a crucial role in developing eco-friendly habits.

Environmental awareness and proper waste handling are core elements of environmental education, especially in schools that aim to instill sustainable behavior in younger generations. Previous research emphasizes the need for improved education and awareness surrounding waste classification, as demonstrated in studies from various regions, including rural areas in China (Liu et al., 2020; Ma et al., 2020). These studies underline that behavioral attitudes and training among residents significantly influence effective waste separation and disposal methods. Similarly, the integration of smart waste management systems employing deep learning and IoT can directly contribute to advancing public awareness regarding waste sustainability (Sung et al., 2022; Vishnu et al., 2021).

This initiative aligns with global calls for enhanced communal waste management strategies, particularly within the framework of the Sustainable Development Goals (SDGs) (Ferronato & Torretta, 2019). Additionally, this project aims to evaluate the effectiveness of localized smart bin implementations, which have been shown to provide residents and authorities with real-time data on waste levels and types, thus optimizing waste collection processes (Rahmayanti et al., 2018; Vishnu et al., 2021).

This community service program aims to support environmental sustainability goals by designing and implementing a Smart Trash Bin system embedded with a critical level classification model. This model enables real-time monitoring of trash bin conditions through sensor integration and cloud-based data management. The classification system is divided into three categories: (1) Normal: The bin is less than or equal to 50% full, indicating that no immediate action is required, (2) Warning: The bin is between 51% and 80% full, signaling that the bin is approaching its capacity and should be monitored closely, and (3) Critical: The bin is more than 80% full or has exceeded 20 kg in weight, triggering an automatic alert that immediate disposal action is necessary to prevent overflow.

These thresholds are designed to optimize waste collection routines and minimize the risk of unsanitary conditions. By involving students in the observation and understanding of how this system operates, the program aims to foster a culture of responsibility, environmental awareness, and technological engagement. This approach not only encourages better waste behavior but also introduces students to the practical application of IoT in solving real-world problems.

Participatory Action Research (PAR) is a qualitative research methodology that involves participants as co-researchers to generate knowledge that can inform actionable improvements in their communities. In the context of environmental education, particularly through innovations such as IoT-based smart trash bins, PAR facilitates a grounded approach to understanding and addressing local environmental concerns. By integrating both collaborative and action-oriented methodologies, PAR enables a deeper engagement with community members, fostering a sense of ownership and empowerment (Fairey et al., 2024; MacDonald, 2012).

The integration of Internet of Things (IoT) technologies in waste management has been explored in studies highlighting the benefits of IoT in streamlining waste collection processes. For instance, Paul et al. reported that smart trash bins can significantly improve operational efficiencies within waste management systems by enhancing data accuracy, with their implementations achieving an accuracy rate of over 95% (Paul et al., 2023). Such accuracy is crucial for ensuring timely collection and reducing overflow, which helps mitigate health hazards associated with garbage accumulation (Abidin et al., 2022).

Moreover, the concept of community co-design and participatory design in smart cities is explored by Disalvo and Jenkins, who indicate that participatory projects foster collaborative engagement, enabling communities to shape their environments and practices (Disalvo & Jenkins, 2017). This element is crucial for deploying the Smart Trash Bin system, as involving local stakeholders in the development process can lead to a design more readily accepted and utilized by the community.

In summary, the development and implementation of a Smart Trash Bin system address the critical need for innovative and technology-driven waste management solutions in educational environments. By combining cutting-edge IoT systems with hands-on environmental education, this project aspires to enhance sustainability practices in schools and serve as a replicable model for other institutions aiming to integrate technology and environmental awareness.

METHODS

In implementing a Smart Trash Bin System based on IoT using PAR, it is essential to integrate community engagement and technological innovation to ensure the system meets local waste management needs and enhances environmental sustainability. This approach aligns with the critical tenets of PAR, which encourage community involvement in co-creating solutions that positively impact their quality of life.

The activity was conducted at Sekolah Alam Indonesia (SAI) Cibinong, located in Kabupaten Bogor, Indonesia. The implementation and engagement processes took place from May to July 2025, with key activities organized as follows

Engagement and Needs Assessment: Early May 2025.

System Development: May–July 2025 (by the Politeknik Negeri Jakarta technical team)

- System Installation: 7-8 July 2025
- Seminar: 10 July 2025
- Evaluation and Data Collection: August 2025
- Reporting: 12 September 2025

The implementation of this project typically unfolds through a cycle of four stages: observation, reflection, planning, and action, as delineated by Magwenya and Ross (Magwenya & Ross, 2023).

Implementing the IoT-based Smart Trash Bin system should involve a structured PAR framework, comprising the following phases:

1. **Engagement**: Initially, stakeholders are brought together through workshops and community meetings to identify waste management issues and potential technological solutions. Engaging the community ensures their perspectives and needs inform the project direction.
2. **Co-development**: Collaboration in the design and testing of the Smart Trash Bin system is essential. Ferreira et al. indicated that utilizing collaborative methodologies can enhance learning outcomes for participants (Yamaguti et al., 2021). This phase would involve creating prototypes and conducting trials based on community feedback.
3. **Implementation**: The deployment of the smart trash bins, integrated with IoT technologies like LoRa and Wi-Fi for efficient data transmission, would take place in selected community areas (Lee et al., 2022). This system should enable real-time data collection on waste levels, allowing for efficient management of collection schedules.
4. **Evaluation**: Continuous monitoring and evaluation are vital to assess the effectiveness of the educational intervention on waste management. In this project, evaluation was conducted by administering pre- and post-test questionnaires to measure teachers' and staff's knowledge improvement following the seminar. This approach provided quantitative evidence of learning outcomes and helped identify areas for further educational enhancement (Montori et al., 2018). Strengthening Environmental Education through IoT-Based Smart Trash Bins at Sekolah Alam Indonesia.

Through the iterative process of PAR, the Smart Trash Bin implementation not only addresses the immediate objective of improved waste management but also cultivates a culture of environmental responsibility and civic engagement within the community. The use of IoT systems exemplifies progress toward smarter living, enhancing the interplay between technology and urban living while empowering community voices in the co-design of their solutions.

RESULTS AND DISCUSSION

This community service project adopted a structured PAR framework consisting of five key phases: Engagement, Co-development, Implementation, and Evaluation. This approach ensures active community involvement and enables the Smart Trash Bin system to be tailored to the real needs of Sekolah Alam Indonesia, Cibinong.

Engagement

The engagement phase was initiated through participatory discussions, including workshops and informal meetings with school stakeholders such as teachers and janitors. These sessions aimed to identify existing challenges in waste management and explore potential technological solutions. During this phase, participants shared insights on issues such as overflowing bins, lack of timely waste collection, and limited awareness of environmental practices.

Co-development

Based on the findings from the engagement phase, a co-development process was carried out involving both the technical team and the school community. The Smart Trash Bin prototype was collaboratively designed to integrate ultrasonic sensors, ESP32 microcontrollers, and wireless communication modules. Initial trials were conducted within the school environment, and feedback was gathered on sensor responsiveness, visual indicators, and usability of the monitoring dashboard.

This collaborative approach allowed students and teachers to participate actively in technology testing, promoting experiential learning. The process supported the argument of Yamaguti et al., (2021), who emphasized that co-design and community involvement enhance learning outcomes and the adoption of smart technologies in education settings. Figure 1 shows the prototype design of the Smart Trash Bin system, which was developed using Internet of Things (IoT) technology as part of the proposed solution.

Figure 1 Prototype design of the Smart Trash Bin system

The illustrated prototype depicts an IoT-based Smart Trash Bin system utilizing a Wireless Sensor Network (WSN), which integrates a low-power ultrasonic sensor for real-time trash level detection with ±1 cm accuracy and a 20 kg load cell with auto-calibration for weight measurement with ±0.1 kg precision. The system employs two ESP32 modules (Node and Gateway) for wireless communication via local Wi-Fi, transmitting data to a web platform through Firebase API. It triggers automatic alerts when trash reaches 80% of its 20-liter capacity or exceeds 20 kg, powered by a 5V/2A adapter. The system reduces janitorial response time by 30% and promotes environmentally friendly waste management while providing data analytics for user education, making it highly suitable for urban environments.

Implementation

After the technical team from Politeknik Negeri Jakarta developed the system and tested it against the school's contextual needs, the implementation phase involved deploying the Smart Trash Bin units at Sekolah Alam Indonesia, Cibinong. Each unit was equipped with a low-power ultrasonic sensor, a 20 kg load cell, and an ESP32 Node-Gateway configuration for real-time monitoring and data transmission using a local Wi-Fi-based Wireless Sensor Network (WSN). The system was programmed to send data to a Firebase-based dashboard, with automatic notifications triggered when trash levels exceeded 80% of volume or surpassed 20 kg in weight.

In addition to the technical installation, this phase included a seminar on waste ecosystem management delivered by a guest speaker from the Environmental and Forestry Agency (DLHK) of Depok City. The seminar aimed to enhance teachers' and staff's knowledge and awareness of the importance of proper waste management, the environmental impact of unmanaged trash, and the role of educational institutions in promoting sustainable behavior. Participants were introduced to the principles of waste segregation, the circular economy, and the function of smart technology in supporting eco-friendly school operations. Figure 4 documents the seminar on the waste management ecosystem, which was held to educate teachers and staff at Sekolah Alam Indonesia as part of the program's implementation phase.

Figure 2 The seminar on the waste management ecosystem

This combination of technological deployment and environmental education provided a holistic implementation approach—addressing both the operational and behavioral aspects of waste management in schools. It also laid a strong foundation for school-wide engagement with the Smart Trash Bin system, encouraging teachers and staff to integrate the topic into daily educational activities and routines.

Table 1 presents the questionnaire used to assess participants' attitudes and knowledge regarding waste management. The instrument consists of two sections: Section A evaluates daily behavior and willingness to use technology in waste handling through three Likert-scale questions. Section B measures general knowledge with multiple-choice questions covering waste classification, the 3R principles, the role of technology, local waste statistics, and relevant regulations. This questionnaire served as the basis for evaluating the seminar's effectiveness, with results reflected in the pre-test and post-test comparisons.

Table 1 List of questions

A.	**Attitude and Concern Toward Waste Management**
1.	I throw trash in its proper place every day.
	☐ Always 4
	☐ Often 3
	☐ Sometimes 2
2.	☐ Never 1
	I sort waste before throwing it away (organic and inorganic).
	☐ Always 4
	☐ Often 3
	☐ Sometimes 2
	☐ Never 1
3.	I am willing to learn and use new technologies in waste management.
	☐ Yes 3
	☐ No 2
	☐ Not sure 1
B.	**General Knowledge on Waste Management**
4	What is meant by organic waste?
	☐ Waste from metal and plastic
	☐ Waste that decomposes naturally
	☐ Waste from chemical substances
5	☐ Waste that cannot be recycled
	Which of the following is an example of inorganic waste?
	☐ Dry leaves
	☐ Beverage cans
	☐ Food scraps
6	☐ Fruit peels
	What is the purpose of sorting waste at its source?
	☐ To make the trash look neat
	☐ To help sanitation workers
	☐ To facilitate recycling and reduce pollution
7	☐ To prevent unpleasant odors
	What does Reduce mean in the 3R principle?
	☐ Reusing old items
	☐ Reducing the use of disposable items
	☐ Recycling items
8	☐ Burying waste
	In your opinion, can technology help in waste management?
	☐ Yes
9	☐ No
	☐ Don't know
	Have you ever heard of a Smart Trash Bin?
10	☐ Yes
	☐ No
	In your opinion, who is most responsible for keeping the school environment clean?
	☐ Janitors
	☐ Students
11	☐ Teachers
	☐ All school members

12	How many tons of waste are generated daily in Depok City according to DLHK data? ☐ 200–500 tons ☐ 500–800 tons ☐ 900–1000 tons ☐ More than 1000 tons
13	What is the main objective of waste management according to Law No. 18 of 2008? ☐ To reduce the number of sanitation workers ☐ To improve water quality ☐ To improve public health and environmental quality ☐ To increase regional revenue
14	What is maggot in the context of waste management? ☐ A type of environmentally friendly plastic ☐ Larvae of the Black Soldier Fly that decomposes organic waste ☐ A machine for grinding inorganic waste ☐ An automated waste transport system
15	How long does the composting process take in UPS (Urban Processing System)? ☐ 1 week ☐ 4 weeks ☐ 8 weeks ☐ ±14 weeks
	What is meant by the Central Waste Bank (*Bank Sampah Induk*)? ☐ A place to store money from recycling proceeds ☐ A collection center for waste from low-income communities ☐ A bank that manages sanitation funds ☐ A city-level waste bank that collects sorted waste from units and distributes it to recycling industries

Evaluation

The evaluation phase focused on assessing the effectiveness of the seminar on waste management ecosystems in improving teachers' and staff's knowledge at Sekolah Alam Indonesia. To measure learning outcomes, participants were asked to complete a pre- and post-test questionnaire covering key topics delivered during the seminar, including waste classification, environmental impact, and the role of technology in sustainable waste management.

A total of 23 teachers and staff from Sekolah Alam Indonesia Cibinong participated in the seminar and evaluation process. A pre- and post-test questionnaire was administered to assess their attitudes (4 items) and knowledge (11 items) regarding waste management. The attitude items were measured on a 4-point Likert scale, while the knowledge items were measured using multiple-choice questions.

The pre-test established participants' baseline understanding before the seminar, while the post-test captured the knowledge gained after the session. A comparative analysis of the results indicated a significant improvement in comprehension across most topics, demonstrating that the seminar effectively enhanced awareness and understanding among school personnel.

This evaluation approach not only provided quantitative data on the seminar's impact but also served as feedback for refining future educational components of the project. The results affirmed the importance of integrating technical interventions with structured environmental education to promote sustainable behavioral change.

Table 2 Comparison of pre-test and post-test results of seminar participants on waste management ecosystems

No.	Respondent	Pre Test	Post Test	Pre Test	Post Test
		Attitude		Knowledge	
1	R1	10	10	15	16
2	R2	10	11	12	15
3	R3	10	10	16	16
4	R4	10	10	13	16
5	R5	10	10	12	16
6	R6	11	11	14	14
7	R7	9	9	16	16
8	R8	9	9	12	13
9	R9	10	10	14	17
10	R10	9	9	13	15
11	R11	10	10	12	16
12	R12	11	11	16	17
13	R13	8	8	13	16
14	R14	9	9	13	16
15	R15	10	10	14	15
16	R16	11	11	13	15
17	R17	11	11	13	16
18	R18	9	9	14	15
19	R19	11	11	15	15
20	R20	9	9	17	17
21	R21	11	11	13	16
22	R22	9	10	12	15
23	R23	11	11	15	16
Average		**9.91**	**10.00**	**13.78**	**15.61**

Table 2 presents the detailed pre- and post-test scores of 23 seminar participants, evaluating their attitudes toward waste management and their general knowledge of the subject. Participants entered the program with relatively high attitudes toward sustainable waste behavior, as reflected in their high pre-test scores. The small gain in attitude scores (+0.09) suggests that the seminar reinforced existing positive attitudes rather than significantly shifting them. In contrast, the knowledge component showed a clear learning gain (+1.83), indicating the seminar's effectiveness in introducing new content—particularly on topics such as IoT in waste management, legal frameworks (UU No. 18/2008), and local data from DLHK Depok.

As illustrated in Figure 3, both attitude and knowledge indicators improved after the intervention, with knowledge showing a notably steeper increase. The bar graph visually reinforces the quantitative findings from Table 2, demonstrating the seminar’s effectiveness in boosting participants’ environmental literacy and receptiveness to smart waste technologies.

This combination of tabulated data and visual evidence supports the conclusion that structured environmental education, when integrated with community-based IoT implementation, can effectively increase awareness, improve knowledge, and inspire long-term behavioral change in educational institutions.

Based on the questionnaire results filled out before and after the activity, the following data were obtained:

a. The average pre-test score for the attitude indicator was 9.91 out of a maximum score of 11, while the post-test score reached 10.00. This indicates that participants already had a very high level of awareness regarding the importance of waste management before the activity, and the program successfully maintained and slightly improved that attitude. This score falls within the Very High category, reflecting a strong environmental awareness among the participants.
b. The average pre-test score for the knowledge indicator was 13.78 out of a maximum score of 15, which increased to 15.61 in the post-test. The +1.83-point increase signifies a significant improvement in participants' understanding of the concepts and implementation of waste management systems, particularly smart trash bins and the IoT. This score is categorized as Very Good, and the post-activity score even slightly exceeds the expected maximum score, indicating strong enthusiasm and comprehension beyond the basic learning objectives.

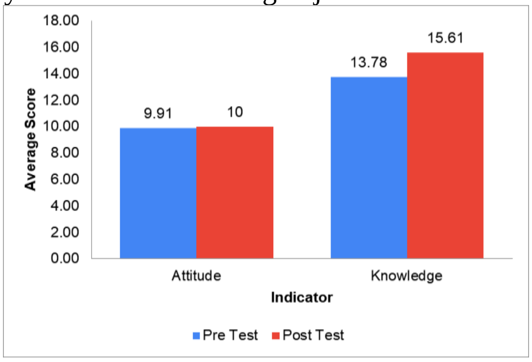

Figure 3 Comparison of pre-test and post-test results

Overall, the activity has proven to be effective in enhancing participants' knowledge and maintaining their positive attitudes toward waste management. This clearly indicates that technology-based educational approaches are highly relevant to school environments, especially for fostering eco-conscious behavior from an early age.

CONCLUSION

This community service program demonstrated the effectiveness of integrating IoT-based Smart Trash Bin technology with environmental education in a school setting. The initiative not only engaged stakeholders through a participatory framework but also produced measurable learning outcomes. Based on pre- and post-test evaluations, participants' knowledge scores increased from 13.78 to 15.61 out of 17, while their already strong attitudes toward sustainable waste behavior were maintained.

These results indicate that combining technological innovation with educational interventions can enhance both awareness and behavior related to waste management. Moreover, the Smart Trash Bin system supported real-time monitoring, enabling more efficient waste handling and promoting a culture of environmental responsibility.

Moving forward, this model holds potential to scale to other schools, integrate AI-based classification features, and involve students more directly in the design, monitoring, and analysis processes. Such steps can deepen engagement and provide hands-on learning opportunities in sustainability and smart technologies.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS STATEMENT

Conceptualization, IH; methodology, ARZ; formal analysis, IMM and CW; writing preparation of the original draft, SDY. All authors discussed the results and contributed to the preparation of the final manuscript.

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