Indonesian Journal of Electrical Engineering and Computer Science
Vol. 42, No. 3, June 2026, pp. 729~741
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v42.i3.pp729-741

Development of an IoT-based waste monitoring and notification system for smart environmental management

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Article Info

Article history:

Received Nov 14, 2025
Revised May 4, 2026
Accepted May 26, 2026

Keywords:

Environmental monitoring
Internet of things applications
Real-time notification system
Smart city infrastructure
Wireless sensor network

ABSTRACT

Rapid urban population growth has intensified solid waste generation, while many existing waste management systems still rely on manual inspection and single-parameter monitoring, resulting in delayed responses and inefficient handling. Previous studies have primarily focused on isolated sensing or offline monitoring, highlighting the need for integrated, real-time, and user-oriented waste monitoring solutions. This study used RnD method, proposes a smart garbage level and information hub (SIGALIH), an IoT-based waste monitoring and notification system designed to address these limitations. SIGALIH combines multi-parameter sensing, including waste level, temperature–humidity, gas concentration, and ambient light, with an ESP32 microcontroller, a cloud-based data platform, and a real-time notification service using a messaging bot. System evaluation involved sensor accuracy testing, communication latency analysis, and functional verification. Experimental results indicate an average sensor accuracy of 96.8%, with an average data transmission latency of 1.84 seconds and a notification delay of 2.14 seconds, indicating reliable real-time performance under varying network conditions. Functional testing confirmed stable operation of all system modules. The system was also integrated into an Environmental Education learning module to support environmental literacy and awareness through contextual learning on sustainable waste management. SIGALIH is designed for small- to medium-scale urban and community-based applications. However, performance depends on wireless network availability, which may reduce reliability in low-connectivity areas. Overall, SIGALIH provides a low-cost, scalable, integrated solution supporting smart environmental management and sustainable urban waste initiatives.

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1. INTRODUCTION

The rapid growth of urban areas has significantly increased solid waste generation, posing serious challenges to environmental sustainability and public health. Inefficient waste management practices often result in overflowing landfills, air and water pollution, and disruption of ecological balance. These conditions highlight the need for intelligent waste management systems capable of monitoring waste levels and providing early notifications to support timely and effective waste handling. In this context, the integration of internet of things (IoT) technology offers a promising solution for real-time data collection, monitoring, and communication between distributed sensors and waste management authorities [1], [2].

IoT-based smart waste management systems have been widely explored as a key component of smart city infrastructure and community-based environmental management [3]. Typical implementations utilize ultrasonic or infrared sensors to detect waste bin fill levels, microcontrollers for local data processing, and cloud-based platforms or mobile applications for data visualization and notification services. The availability of real-time waste data allows authorities to optimize collection routes, reduce operational costs, and minimize environmental risks associated with delayed waste handling [4]. However, many existing systems remain limited to single-parameter monitoring and do not incorporate comprehensive environmental sensing or preliminary usability evaluation.

At the local level, Serang City, as the capital of Banten Province, represents a rapidly developing urban area with increasing population density and diverse economic activities. The city faces persistent waste management challenges due to limited landfill capacity, inadequate waste collection infrastructure, and low levels of waste segregation. Local environmental reports indicate that household and commercial waste volumes in Serang continue to increase annually, while unmanaged waste accumulation frequently occurs in residential areas and drainage systems, contributing to flooding and sanitation problems [5], [6]. Moreover, coordination among stakeholders and public awareness initiatives has not yet been supported by integrated digital systems capable of providing real-time waste monitoring and early warning mechanisms. These flooding issues are closely linked to unmanaged solid waste accumulation, highlighting the interdependence between waste management and urban environmental resilience.

At the national scale, waste management remains a major concern in many Indonesian cities. Community-based programs, such as *Kampung Resik Lan Aman*, have demonstrated positive impacts on public awareness and environmental cleanliness [7]. Nevertheless, previous studies emphasize that such initiatives require digital transformation and smart technology integration to ensure long-term effectiveness and scalability [2], [8]. Without real-time monitoring and data-driven decision support, conventional waste management approaches are often reactive rather than preventive.

Recent studies have highlighted that integrating IoT systems with cloud computing and data-driven platforms can enhance transparency, responsiveness, and sustainability in environmental management [9], [10]. Automatic notification mechanisms triggered by predefined threshold conditions enable faster responses from waste management authorities, reducing the risk of waste overflow and associated environmental hazards [11]. In addition, IoT-based environmental monitoring systems contribute to public engagement and environmental education, aligning with sustainability-oriented engineering practices [12]. Despite these advancements, limited research has addressed the combination of multi-parameter waste monitoring, real-time notification, and preliminary usability evaluation within a single integrated system.

Therefore, this study aims to design and develop an IoT-based waste monitoring and notification system capable of collecting real-time waste-related data, visualizing information through a cloud-based platform, and delivering automatic alerts when critical thresholds are reached. The proposed system is expected to support smart environmental management by integrating wireless sensor networks, cloud data processing, and community participation, thereby contributing to sustainable urban waste management practices [13].

The novelty of this study lies in the development of an integrated IoT-based waste monitoring system, namely smart garbage level and information hub (SIGALIH), which combines multi-parameter environmental sensing, real-time cloud visualization, automated messaging-based notifications, and preliminary usability evaluation within a single platform. Unlike most existing systems that emphasize technical sensing performance alone, SIGALIH explicitly addresses operational usability, community-oriented deployment, and accessibility for non-technical users. This integrated perspective positions SIGALIH not only as a technological solution but also as a participatory tool that supports smart environmental management and sustainable urban waste management practice in developing urban contexts. Furthermore, the implementation of SIGALIH is integrated into an Environmental Education learning module, enabling the system to function not only as a monitoring technology but also as a contextual learning resource. Through this integration, students can directly explore real-time environmental data, understand waste management processes, and develop environmental awareness using technology-based learning materials. This educational integration strengthens the practical and pedagogical value of the system, linking smart environmental technology with environmental literacy development and sustainability education.

2. METHOD

In this study, ADDIE is employed as a structured development framework to guide system design and validation, rather than as an instructional evaluation model. This study employed a Research and Development (R&D) approach using the ADDIE model, which consists of five stages: Analysis, Design, Development, Implementation, and Evaluation [14]. The ADDIE model was selected to ensure a systematic and iterative development process suitable for designing and validating an IoT-based prototype. Although all stages were conducted, this research emphasized the development and evaluation stages, as the primary objective was to produce and technically validate a functional system rather than perform large-scale deployment. The overall research workflow based on the ADDIE model is illustrated in Figure 1.

The research was conducted from June to August 2025 at the Faculty of Teacher Training and Education, Universitas Sultan Ageng Tirtayasa (UNTIRTA), and selected waste collection points in Cipare Village, Serang City, Indonesia. Participants consisted of community representatives, sanitation staff, local leaders, and residents selected through purposive sampling. Stakeholder analysis was applied to ensure that participants represented actors directly involved in local waste management activities. A total of 25 respondents participated in the preliminary system usability evaluation.

The analysis stage focused on identifying existing waste management problems and system requirements. Data were collected through field observations, semi-structured interviews with sanitation staff and community leaders, and analysis of local environmental reports. The analysis revealed that waste handling activities were predominantly reactive and relied on manual reporting mechanisms, resulting in delayed responses to waste accumulation. Similar limitations have been reported in other developing urban areas, where insufficient digital infrastructure constrains effective environmental monitoring [9], [15], [16]. These findings confirmed the necessity of a real-time waste monitoring system supported by IoT technology to improve responsiveness and operational efficiency.

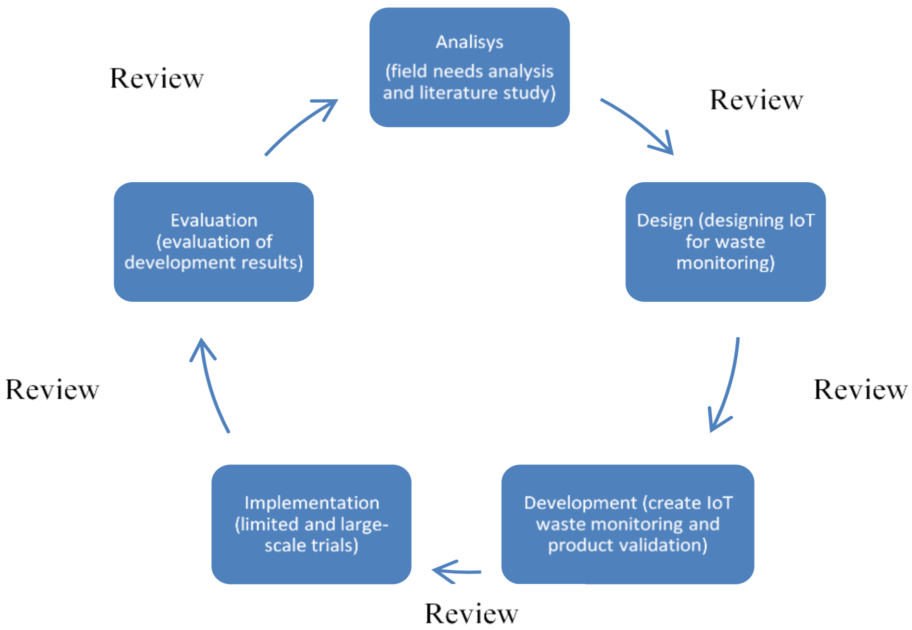

Figure 1. ADDIE model research stages

The overall research workflow based on the ADDIE model is illustrated in Figure 1. During the design stage, the system architecture, hardware configuration, data communication scheme, and user interface were defined. The proposed system adopted an IoT-based architecture consisting of sensor nodes, a microcontroller unit, cloud-based data storage, and a notification interface. The hardware components included an ultrasonic sensor to measure waste bin fill level, a DHT22 sensor to monitor temperature and humidity, MQ-7 and MQ-135 gas sensors for detecting harmful gas concentrations, and an LDR sensor for ambient light detection. An ESP32 microcontroller was used for sensor data acquisition, preprocessing, and wireless data transmission. Sensor data were sampled at predefined time intervals and transmitted via Wi-Fi to a Firebase cloud database for real-time storage and visualization through a web-based dashboard.

Threshold values were defined for each parameter to trigger automatic alerts via an integrated Telegram messaging bot. User interface design principles were applied to ensure accessibility and ease of use for both technical and non-technical users [17], [18].

In the development stage, a functional prototype named SIGALIH was implemented by integrating hardware, software, and network components. The ESP32 microcontroller was programmed using the Arduino IDE to manage sensor data acquisition, preprocessing, and transmission to the cloud server. Sensor calibration was performed to improve measurement accuracy by comparing sensor readings with reference instruments under controlled conditions. For gas sensors (MQ-7 and MQ-135), higher measurement variability was observed due to sensitivity to temperature and humidity. Such behavior has been widely reported in low-cost gas sensors and is generally considered acceptable for indicative environmental monitoring applications. Power consumption was optimized by integrating a solar panel and battery module to support sustainable operation and reduce dependence on grid electricity.

During the implementation phase, the developed SIGALIH prototype was also integrated into an Environmental Education learning module aimed at supporting interactive environmental learning. The web-based interface displayed real-time waste monitoring data, including bin fill level and environmental parameters, which could be utilized in environmental education activities for students and the general public. At the current stage, the implementation was conducted on a limited scale and applied to university students as part of a pilot learning activity. This preliminary deployment allowed students to interact directly with the system while exploring real environmental monitoring data within an educational context. Previous studies indicate that direct interaction with real environmental data enhances learners' problem-solving abilities and critical thinking skills related to sustainability issues [18]. This approach aligns with the broader objective of the present study, which positions the proposed system not only as a technical monitoring tool but also as a pedagogical medium to promote environmental awareness and community engagement [1].

In the evaluation phase, system performance and preliminary usability evaluation were assessed through preliminary observations and structured user feedback involving community members, sanitation staff, and educational stakeholders. The evaluation focused on system functionality, ease of use, clarity of information presented on the dashboard, and the perceived usefulness of real-time notifications. User-centered assessment was conducted to examine the system's potential for broader application in both operational waste management and environmental education contexts. The detailed results of functional testing, performance evaluation, and usability assessment are presented and discussed in Section 3 (Results and Discussion).

3. RESULTS AND DISCUSSION

This section presents and discusses the results obtained from the development and implementation of the SIGALIH system. The discussion is organized to reflect the research workflow, starting from the analysis of existing waste management conditions and stakeholder involvement, followed by system development and implementation, and concluding with system performance evaluation and critical discussion. By structuring the results in this manner, the section highlights how empirical findings address the identified research gaps and demonstrate the effectiveness of the proposed IoT-based waste monitoring and notification system in supporting smart environmental management.

3.1. Needs analysis and existing conditions

The initial stage of this research focused on analyzing community needs and existing waste management conditions in Serang City. Field observations and document analysis indicate that waste handling practices remain predominantly manual and reactive, relying on fixed collection schedules rather than real-time condition-based monitoring. Similar limitations have been reported in other developing urban areas, where the absence of digital monitoring systems reduces operational efficiency and increases environmental pollution risks [16].

In Serang City, waste transportation infrastructure, including garbage trucks, motor carts, and heavy equipment is relatively adequate; however, its utilization remains suboptimal due to manual scheduling, limited inter-agency coordination, and the absence of early-warning mechanisms [5], [17]. Table 1 summarizes the available waste transportation facilities across several districts. These findings suggest that the main challenge lies not in infrastructure availability, but in the lack of data-driven decision-making and real-time monitoring systems capable of identifying critical waste accumulation points.

3.2. Social mapping and stakeholder participation

Stakeholder mapping was conducted to identify key actors involved in environmental management, including local government officials, community leaders, educators, and youth organizations. The results show that village heads, religious leaders, and traditional elders hold significant influence in decision-making processes, while youth groups and educators demonstrate high environmental awareness but limited institutional authority.

This pattern is consistent with previous studies emphasizing the importance of socio-cultural engagement and local leadership in the success of community-based environmental programs [19]. Observations in Cipare Village revealed mixed waste disposal behaviors: while some residents still dump waste into rivers or burn garbage, causing air and water pollution [18]. Others have adopted 3R (Reduce, Reuse, Recycle) practices and actively participate in waste-bank initiatives [20].

Figure 2 illustrates the condition of Cipare RT 03/RW 14, which participates in the *Kampung Resik dan Aman* program. Although this initiative promotes environmental responsibility, periodic flooding and waste accumulation persist, indicating that behavioral change alone is insufficient without technological reinforcement and structured data monitoring [7]. Similar limitations have been reported in other Southeast Asian cities, where conventional community-based programs failed to achieve long-term impact due to the absence of continuous monitoring and accountability mechanisms [17], [21].

Figure 3 presents the distribution of waste banks in Serang District, showing that only four out of nine registered facilities are fully operational. Prior studies indicate that waste-bank sustainability depends heavily on leadership quality, community engagement, and the integration of digital tracking systems [16]. These findings justify the need for IoT-based monitoring to strengthen transparency, coordination, and operational efficiency.

Table 1. Supporting facilities for waste transportation in Serang City

No	Village/Office	Type of vehicle	Quantity
1	Environmental agency of Serang City	Garbage truck	23
		Amrol truck	12
		Excavator	3
		Bulldozer	2
		Shovel	1
2	Serang district	Motor cart (Cator)	1
3	Kaligandu	Cator and handcart	1
4	Cipare	Cator and handcart	2
5	Terondol	Cator	2
6	Unyur	Cator and handcart	2
7	Serang	Cator	1
8	Kagungan	Basket	1
9	Cimuncang	Basket	1
10	Lopang	Cator	2
11	Lontar Baru	Cator	1
12	Kotabaru	Basket	1

Figure 2. Environmental condition of Cipare RT 03/RW 14 participating in the Kampung Resik dan Aman program

3.3. Development of the SIGALIH system

To address the identified needs, an IoT-based prototype named SIGALIH was developed. The system was designed as a low-cost, modular solution capable of monitoring waste volume, environmental conditions, and hazardous gas emissions in real time. Figure 4 illustrates the overall system architecture, including sensor integration, hardware configuration, and data communication flow.

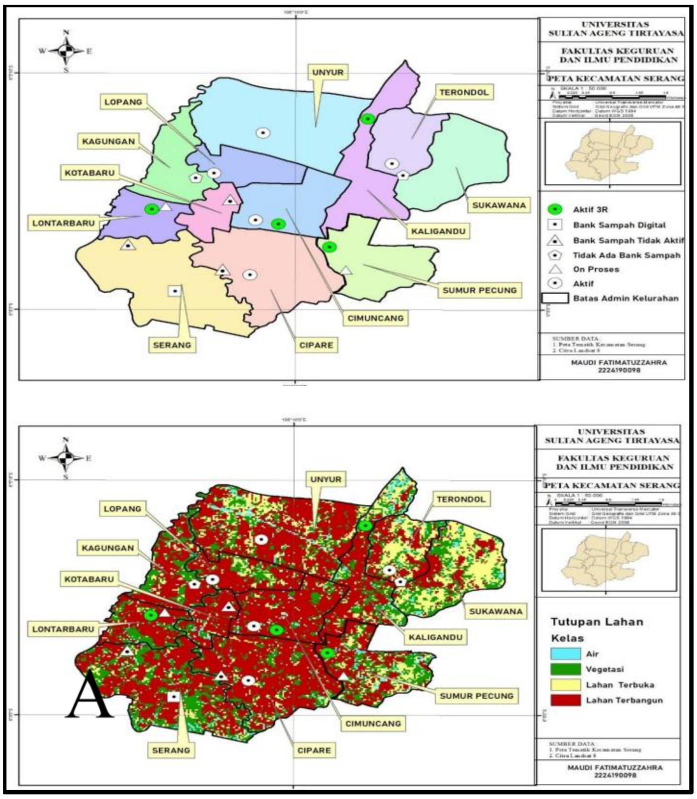

Figure 3. Distribution of waste banks in Serang district

SIGALIH integrates an ultrasonic sensor for waste volume measurement, a DHT22 sensor for temperature and humidity monitoring, and MQ-series gas sensors for detecting hazardous gases. Sensor data are transmitted via an ESP32 microcontroller to a cloud-based Firebase platform for real-time visualization and automated notifications. An alert is triggered when the waste bin reaches 85% of its capacity, functioning as an early-warning mechanism that enables timely waste collection and prevents overflow conditions in residential and educational environments. Furthermore, the system architecture is designed to support future integration of artificial intelligence (AI) algorithms for analyzing waste accumulation patterns and predicting optimal collection schedules. The combination of IoT-based sensing and AI-driven predictive analytics aligns with international smart-city practices that emphasize data-driven resource optimization and proactive environmental management [2], [3].

The overall system architecture and required hardware components of SIGALIH are illustrated in Figure 4, which presents the integration of multi-sensor modules, ESP32 microcontroller, cloud database, and notification services. This modular architecture allows flexible deployment and scalability, making the system suitable for community-based and educational environments.

The physical implementation of the IoT waste monitoring device is shown in Figure 4, where the prototype is integrated with the SIGALIH web platform (http://www.sigalih.site/). The platform, developed collaboratively by the Faculty of Teacher Training and Education, Universitas Sultan Ageng Tirtayasa (UNTIRTA), provides real-time data visualization and supports community-based waste management initiatives. Built using low-cost components and a modular design, the SIGALIH prototype enables local fabrication, maintenance, and future system expansion, thereby fostering community empowerment and sustainability. The real-time monitoring interface displayed on the SIGALIH web dashboard is presented in Figure 5. The dashboard allows users to continuously monitor waste volume, temperature, and gas emissions in an intuitive and accessible manner. Previous studies conducted in Spain and Singapore indicate that public access to real-time environmental dashboards enhances transparency, accountability, and citizen participation in waste reduction programs [22].

To support spatial analysis and decision-making, the deployment distribution of SIGALIH devices across five strategic locations is visualized in Figure 6. These locations include both educational and residential areas, enabling comparative analysis of waste disposal behavior in different social contexts. Geospatial visualization has been shown to improve situational awareness and support evidence-based policymaking in urban environmental management [17].

Figure 4. IoT waste monitoring products

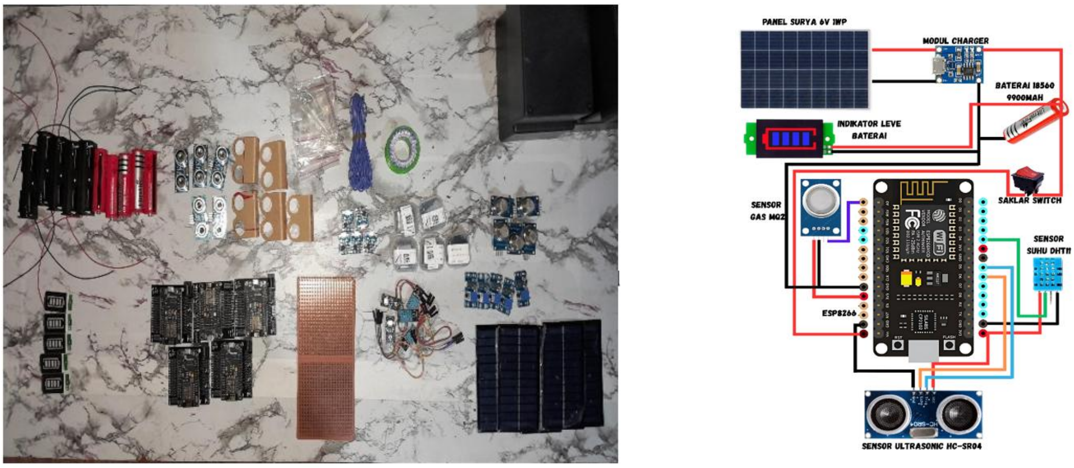

Figure 5. Required components and product design

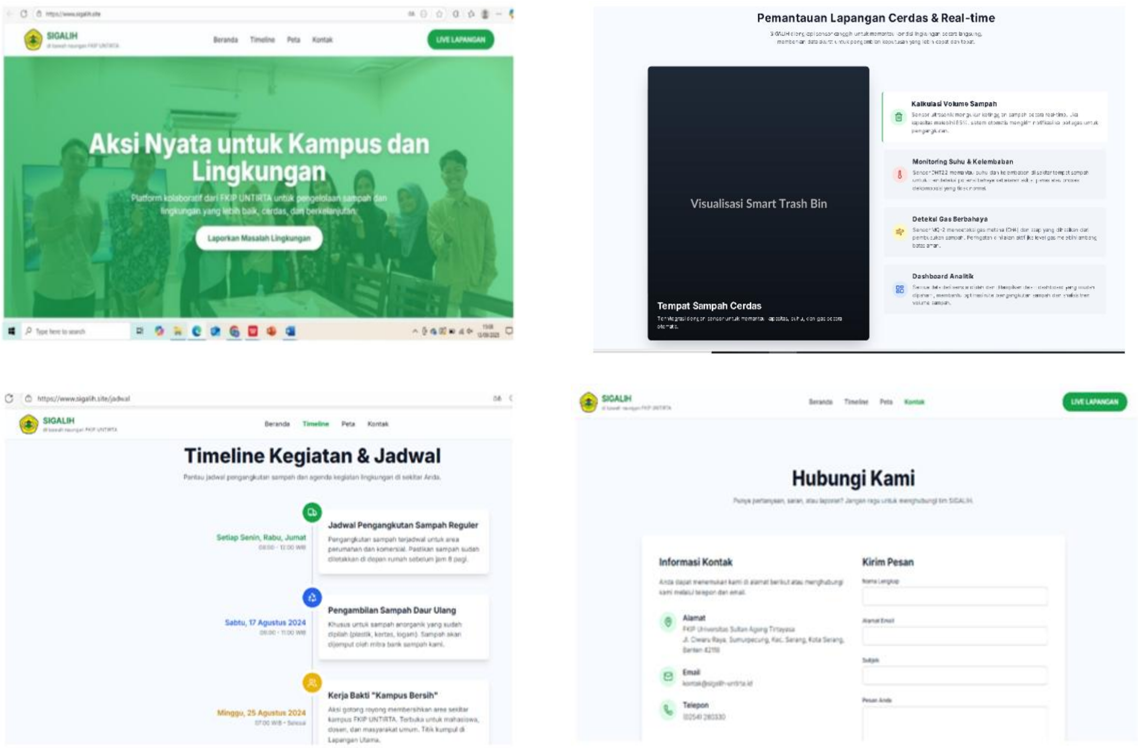

Figure 6. Real-time monitoring dashboard of the SIGALIH system showing waste level and environmental parameters

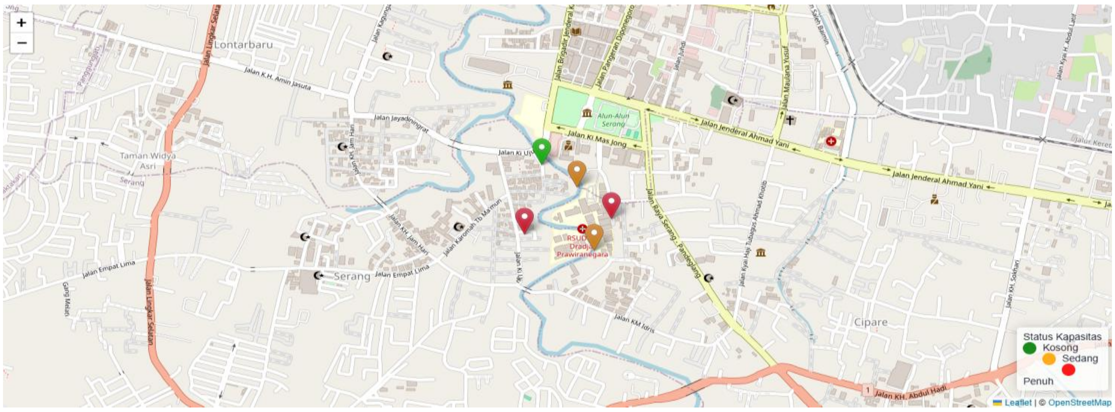

Figure 6. Distribution map of SIGALIH placement locations

An example of the real-time operational status of all installed smart trash can devices is shown in Figure 7. This interface displays each device's fill level and environmental indicators, functioning not only as a monitoring tool but also as a pedagogical instrument. Allowing students and community members to interact directly with live environmental data supports experiential learning, which has been proven to enhance understanding, critical thinking, and engagement in sustainability-related topics [18].

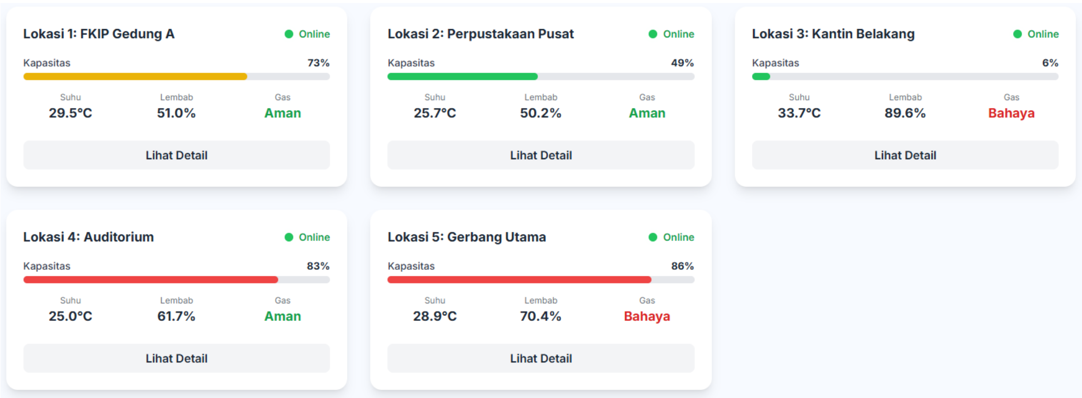

Figure 7. Example of real-time status of all installed smart trash can devices

3.4. System performance evaluation

The SIGALIH prototype underwent a comprehensive performance evaluation to assess sensor accuracy, data transmission latency, network reliability, and functional correctness. Sensor calibration was conducted through repeated field trials by comparing sensor readings with reference measurements. The calibration and accuracy results are summarized in Table 2.

Table 2. Sensor calibration and accuracy results

Sensor type	Measured parameter	True value	Sensor reading	Error (%)	Accuracy (%)
DHT22	Temperature (°C)	30	29.3	2.3	97.7
DHT22	Humidity (%)	65	63.5	2.3	97.7
MQ-135	CO_2 (ppm)	410	395	3.7	96.3
MQ-7	CO (ppm)	8	7.6	5	95
LDR	Light Intensity (lux)	120	118	1.7	98.3
Ultrasonic HC-SR04	Distance (cm)	100	96.8	3.2	96.8
Average Accuracy	—	—	—	—	96.80%

Based on repeated field trials, the system achieved an average accuracy of 96.8%, demonstrating good alignment with standard IoT-based environmental monitoring research [1]. The DHT22 sensor demonstrated stable performance with minimal deviation, confirming its suitability for temperature and humidity monitoring. In contrast, the MQ-135 and MQ-7 gas sensors exhibited slightly higher error rates, which can be attributed to their sensitivity to ambient temperature and humidity fluctuations. Such behavior has been widely reported in low-cost gas sensors and is considered acceptable for indicative air-quality monitoring applications.

Latency testing was conducted to measure the time delay between sensor data acquisition and data visualization on the Firebase cloud dashboard. The results show an average data transmission latency of 1.84 seconds, while the Telegram notification delay averaged 2.14 seconds. These values fall within acceptable thresholds for smart environmental monitoring systems and support near real-time decision-making [23],

Network stress testing under varying Wi-Fi signal conditions demonstrated that the ESP32-Firebase architecture maintained stable communication without permanent disconnection. The system was able to reconnect automatically and synchronize buffered data after temporary network interruptions, indicating robustness for outdoor deployment scenarios.

Functional verification was performed using black-box testing to validate system behavior without examining internal code structures. The test scenarios and outcomes are presented in Table 3. All functional modules achieved a 100% success rate, confirming that SIGALIH reliably performs sensing, data transmission, visualization, and notification tasks, and is technically ready for real-world deployment.

Table 3. SIGALIH black-box testing results

No	Function tested	Expected result	Test result	Status
1	Ultrasonic sensor detects volume >85%	Notification sent	Successful	☑
2	DHT22 sensor reads temperature	Data displayed on dashboard	Successful	☑
3	MQ7&MQ-135 sensor detects hazardous gas	Alarm activated	Successful	☑
4	Web system displays real-time data	Matches sensor readings	Successful	☑
5	System reset button	System restored to normal	Successful	☑

3.5. Discussion

The findings of this study demonstrate that SIGALIH is not merely a functional prototype but a practically relevant IoT-based waste monitoring system that addresses key limitations of existing smart waste management solutions. Unlike many prior studies that focus primarily on single-parameter waste level detection [1], [23], SIGALIH integrates multi-parameter environmental sensing, including waste volume, temperature–humidity, gas concentration, and ambient light, combined with real-time cloud visualization and automated notification services. This integrated approach is particularly relevant for urban stakeholders, educators, and environmental managers who require actionable, real-time information rather than static or manually reported data.

From a performance perspective, the achieved average sensor accuracy of 96.8% places SIGALIH within the upper performance range reported in recent IoT-based environmental monitoring studies, which typically report accuracies between 94% and 97% under comparable field conditions [1], [17], [23]. The stable performance of the DHT22 sensor confirms its suitability for microclimate monitoring, while the slightly higher error margins observed in MQ-series gas sensors are consistent with well-documented cross-sensitivity issues in low-cost gas sensing technologies. Importantly, although these sensors may not provide laboratory-grade precision, their performance is sufficient for early warning and indicative monitoring, which is the primary operational requirement in community-based waste management contexts.

The systems near real-time responsiveness, indicated by an average data transmission latency of 1.84 seconds and notification delay of 2.14 seconds, is a critical contribution to smart environmental management. Compared to conventional waste collection systems that rely on fixed schedules or manual reporting, SIGALIH enables condition-based decision-making, allowing sanitation services to respond proactively to waste accumulation and hazardous environmental conditions. This finding aligns with previous smart-city research emphasizing that responsiveness and timeliness are more impactful for operational efficiency than marginal improvements in sensing precision [2], [3].

In addition to its technical contribution, SIGALIH demonstrates practical relevance for community engagement and environmental education. The public-facing dashboard and real-time data visualization transform environmental monitoring data into a shared resource that can be accessed by residents, students, and local authorities. Prior studies in sustainability education report that direct interaction with real environmental data significantly enhances environmental awareness, systems thinking, and problem-solving skills [12], [18]. Thus, SIGALIH extends the role of IoT systems beyond infrastructure monitoring toward participatory and educational smart-city applications, which remains underexplored in current waste management literature.

Several key experiments were essential in validating the system's feasibility and reliability. These include: (1) sensor calibration and accuracy testing against reference instruments, (2) communication latency measurement under real network conditions, (3) network resilience testing during temporary connectivity loss, and (4) black-box functional verification of all system modules. Together, these experiments confirm that SIGALIH is technically ready for small- to medium-scale deployment in urban and semi-urban environments. However, large-scale longitudinal experiments involving multiple districts and seasonal variations remain necessary to fully evaluate system durability and long-term performance.

Despite its promising results, this study has several limitations that open clear avenues for future research. First, system performance is currently dependent on Wi-Fi availability, which may limit deployment in areas with poor network infrastructure. Future work should explore long-range and low-power communication technologies such as LoRaWAN or NB-IoT to improve coverage and energy efficiency [20]. Second, the inherent instability of low-cost gas sensors suggests the need for adaptive calibration techniques, machine-learning-based sensor drift compensation, or sensor fusion approaches to enhance long-term accuracy. Third, the integration of artificial intelligence and predictive analytics could enable the system to forecast waste accumulation patterns and optimize collection schedules, further supporting data-driven urban waste management.

Overall, the key takeaway from this study is that SIGALIH demonstrates how a low-cost, modular, and integrated IoT system can meaningfully enhance smart environmental management by combining real-time sensing, automated notification, and community participation. By bridging technical performance, operational relevance, and educational value, this research contributes a scalable and context-appropriate solution for sustainable waste management in developing urban environments and provides a solid foundation for future smart-city innovations.

In terms of data security, the SIGALIH system utilizes Firebase cloud services, which support configurable access rules to control read and write permissions, ensuring that only authorized users can modify system data. Data transmission between the ESP32 device and the cloud server is encrypted, reducing the risk of unauthorized access during communication. Regarding long-term reliability, potential challenges include sensor drift, periodic maintenance requirements, and exposure to weather conditions in outdoor deployments. Regular recalibration, scheduled sensor replacement, and protective housing are necessary to maintain system performance over extended periods. These factors should be considered in large-scale and long-term implementations. Future research should focus on integrating artificial intelligence-based prediction models to forecast waste accumulation patterns and optimize collection schedules. The adoption of LoRaWAN or NB-IoT communication technologies is recommended to overcome Wi-Fi dependency and enable wider-area deployment. Additionally, the development of a mobile-based dashboard application and long-term field trials under extreme environmental conditions would further enhance system scalability, reliability, and practical impact.

4. CONCLUSION

This study demonstrates that the proposed IoT-based waste monitoring and notification system, SIGALIH, successfully achieves the research objective of designing, developing, and evaluating a functional system capable of real-time waste monitoring, environmental sensing, and automated notification. The system achieved an average sensor accuracy of 96.8%, with stable data transmission and notification latency below 2.2 seconds, confirming its technical reliability and responsiveness in operational conditions. The integration of multi-parameter sensing, cloud-based visualization, and Telegram-based alerts enables timely decision-making, reduces the risk of waste overflow, and supports community awareness through access to real-time environmental data. Despite these positive results, this study has several limitations. System performance remains dependent on Wi-Fi network availability, which may restrict deployment in areas with limited connectivity. In addition, gas sensor measurements exhibited sensitivity to temperature and humidity variations, affecting measurement stability. The evaluation was conducted over a limited deployment period and focused on technical performance and preliminary usability, without long-term field testing or large-scale implementation. Future research should address these limitations by integrating alternative communication technologies such as LoRaWAN or NB-IoT to improve network resilience, implementing advanced calibration or sensor fusion techniques to enhance gas sensing accuracy, and incorporating predictive analytics or machine learning models for waste generation forecasting. Long-term field trials and broader community deployment are also recommended to assess system durability, scalability, and real-world impact. Overall, SIGALIH represents a low-cost, scalable, and practical solution for smart waste management and environmental education in developing urban contexts, with strong potential for further technological and operational enhancement.

ACKNOWLEDGMENTS

The authors would like to extend their deepest appreciation to the Directorate General of Higher Education, Research, and Technology (Ditjen Dikti Ristek) for the financial support provided through the Fundamental Research scheme. The authors also acknowledge the invaluable facilitation and assistance rendered during the conduct of this study, including the provision of facilities and infrastructure, as well as opportunities to advance scholarly work, which greatly contributed to the successful completion of this research.

FUNDING INFORMATION

This research was funded by the Fundamental Research Grant from the Ministry of Higher Education, Science, and Technology in 2024. The authors would like to express their sincere appreciation to Universitas Sultan Ageng Tirtayasa for institutional support. Special thanks are also extended to the anonymous reviewers for their valuable comments and constructive suggestions that helped improve the quality of this paper.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
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So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

INFORMED CONSENT

Informed consent was obtained from all individuals involved in this study prior to their participation, and all procedures were conducted in accordance with ethical standards to ensure the protection of participants' privacy and personal information.

ETHICAL APPROVAL

This study involving human participants was conducted in accordance with all relevant national regulations and institutional policies and adhered to the principles of the Helsinki Declaration. The research protocol was reviewed and approved by the authors' institutional review board or an equivalent ethics committee as applicable to non-invasive observational and usability studies.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request. The data include sensor measurements, system performance results, and evaluation records generated during system testing and implementation. Some data are not publicly available due to privacy and ethical considerations related to community-based deployment.

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