Formosa Journal of Multidisciplinary Research (FJMR)
Vol. 4, No. 10, 2025: 5255-5264

Design and Build Internet of Things (IoT)-Based Smart Waste Bin for Waste Management

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A R T I C L E I N F O
Keywords: Smart Waste Bin, Barcode Sensor, ESP32, Waste Management

Received : 16, September
Revised : 30, September
Accepted: 28, October

A B S T R A C T
The waste problem in Indonesia is still a big challenge due to the inefficient conventional management system. This research aims to design and build Smart Waste Bin based on the Internet of Things (IoT) as a solution for monitoring and automated waste management. The system uses barcode sensors to detect waste types, ESP32 microcontrollers as the main controller, and an IoT cloud platform to display data in real-time through a web dashboard. The research uses engineering methods with a waterfall model, including needs analysis, design, implementation, and testing. The results showed that the system was able to detect waste with 95% accuracy and send data to the cloud with an average delay of less than three seconds. The implementation of the Smart Waste Bin has been proven to increase the efficiency and responsiveness of waste management, as well as support the concept of smart waste management that is environmentally friendly and sustainable.

DOI: https://doi.org/10.55927/fjmr.v4i10.597
ISSN-E: 2829-8896
https://npaformosapublisher.org/index.php/fjmr

INTRODUCTION

The waste problem is an environmental issue that is still a big challenge in Indonesia. Based on data from the Ministry of Environment and Forestry (MoEF), national waste production reaches more than 200,000 tons per day, and only about 60% is handled through the official collection and transportation system (Kurniawan, 2023). The rest is still thrown out in the open or burned on the spot, which causes air, water, and soil pollution. Population growth, increasing plastic consumption, and rapid urbanization are exacerbating this situation, especially in urban areas with high levels of density. This condition shows that conventional waste management systems are no longer efficient and require a more intelligent, adaptive, and sustainable technology-based approach (Wulandari et al., 2022).

One of the technologies that has great potential to answer this problem is the Internet of Things (IoT). IoT allows physical devices, such as sensors and microcontrollers, to communicate with each other over an internet network, so they can collect, transmit, and analyze data in real-time. In the context of waste management, IoT can be used to create a Smart Waste Bin system that is capable of automatically monitoring waste capacity, providing alerts when bins are full, and sending information to the control center for scheduled transportation. The application of this concept has been widely researched in various countries, for example by Vishnu et al. (2021) and Okubanjo et al. (2024), which proves that IoT-based systems can improve waste transport efficiency by up to 30–40% compared to manual methods.

In Indonesia itself, the implementation of the Smart Waste Bin system is still relatively limited and is generally only carried out on a campus research scale or industrial environment. Most communities and local governments still rely on the traditional way of monitoring and transporting waste, which is to wait until the garbage cans are visually full or based on a fixed schedule, without considering the actual conditions on the ground. As a result, there are often delays in transportation that cause the accumulation of waste at Temporary Disposal Sites (TDS) and in public areas. This condition shows the need for innovative solutions that are able to automatically monitor the condition of the garbage cans and provide the latest information online.

This research is here to answer this need through the design of an Internet of Things (IoT)-based Smart Waste Bin that is able to detect waste through scanning results. The developed system integrates a barcode sensor with a microcontroller. With this system, the status of the waste can be monitored via LCD with a successful indicator automatically.

The main goal of this research is to design and build a prototype of an IoT-based Smart Waste Bin that can help the waste management process become more efficient and responsive to environmental conditions. This system is expected to minimize transportation delays, reduce the risk of waste buildup, and support smarter and more sustainable environmental management. In addition, this research also aims to create a simple, economical, and applicable waste management technology model at various scales of society, such as housing, schools, campuses, and other public areas.

Overall, the results of this research are expected to make a real contribution to the development of IoT-based solutions in the environmental sector, especially in realizing the concept of integrated and efficiency-oriented smart waste management. With this Smart Waste Bin, the waste management system not only becomes more modern and responsive, but also in line with the principles of sustainable development goals (SDGs), especially in goal 11, namely "Realizing inclusive, safe, resilient, and sustainable cities and settlements."

LITERATURE REVIEW

Smart Waste Management

The concept of Smart Waste Management is a waste management system that utilizes digital technology to improve the efficiency of the waste collection, monitoring, and transportation process (Fatimah et al., 2020). This system utilizes sensors to detect waste and display information related to waste on the LCD. Thus, transportation can be scheduled based on actual needs, rather than just a fixed schedule. Several studies have proven that the implementation of IoT-based smart systems can increase operational efficiency by up to 30–40%, save time, and reduce transportation operational costs (Okubanjo et al., 2024; Patel & Jain, 2021).

In addition to the efficiency aspect, the implementation of Smart Waste Management also contributes to the Sustainable Development Goals. This is because the system is able to reduce the accumulation of waste, reduce carbon emissions from excessively operating transport vehicles, and encourage community participation in maintaining the cleanliness of the environment (Yu et al., 2021).

Smart Waste Bin and Sensor Technology

The concept of Smart Waste Management is an integral part of the development of Smart City which emphasizes efficiency, sustainability, and resource optimization through the use of digital technology. In this context, waste management systems no longer only focus on collection and disposal, but also include monitoring, analysis, and data-driven decision-making. According to Fatimah et al., (2020), Intelligent waste management systems enable integration between sensor technology, wireless communication networks, and cloud computing to create an adaptive and efficient management ecosystem.

Smart Waste Bin is a concrete implementation of the Smart Waste Management concept. These devices are designed to automatically detect waste using various types of sensors, such as ultrasonic sensors, infrared sensors, and load cells. Among these types of sensors, the HC-SR04 ultrasonic sensor is the most widely used because it has a high accuracy rate, a detection range of up to 400 cm, and low power consumption (Chi et al., 2021; Saputri et al., 2023). These sensors work by emitting ultrasonic waves onto the waste surface and calculating the bounce time to determine the distance between the sensor and the surface.

In the traditional system, waste collection is carried out on a fixed schedule without considering the actual condition of the garbage bin in the field. This often leads to two main problems: (1) transportation delays in locations that are already full, causing buildup, and (2) transportation is carried out in an unfilled tank, thus wasting time, energy, and fuel (Vishnu et al., 2021). To overcome this, the concept of Smart Waste Management comes with the principle of automatic monitoring and centralized control, where each bin unit can monitor its own capacity and send information to the management center in real-time.

These systems generally integrate volume sensors, weight sensors, or gas sensors with Internet of Things (IoT)-based communication modules. The resulting data is sent over a wireless connection (Wi-Fi, GSM, or LoRa) to a cloud server, then visualized in the form of a dashboard or digital map. This allows the operator or janitor to identify locations that require immediate action. Several studies attest to the effectiveness of this approach: Okubanjo et al., (2024) reported a 38% increase in waste collection efficiency through IoT-based smart bin systems in Nigeria, while Patel & Jain (Patel & Jain, 2021) found a reduction in operational costs of up to 25% in India with the implementation of a similar system.

Furthermore, the Smart Waste Management system not only has an impact on technical efficiency, but also contributes to the achievement of the Sustainable Development Goals (SDGs), especially the 11th goal of "Inclusive, Safe, Resilient, and Sustainable Cities and Settlements." With digitally connected systems, carbon emissions from transport vehicles can be reduced as transport routes become more planned and fuel-efficient. In addition, IoT-based management also assists local governments in building a reporting and traceability system for waste management activities, thereby increasing transparency and public accountability.

According to Jadhav et al. (2022), Smart Waste Management is the first step towards implementing a Circular Economy in the hygiene sector. The data obtained from IoT sensors can be used to analyze waste consumption and production patterns, thereby encouraging waste minimization policies. In addition, this technology allows integration with machine learning systems to predict waste production trends based on time, location, and type of waste.

Thus, the concept of Smart Waste Management is not only limited to the application of sensors and connectivity, but also a holistic approach that integrates technology, social behavior, and public policy. In the Indonesian context, the implementation of this system still has great opportunities to be developed, especially with the support of digital infrastructure and increasing awareness of sustainable environmental management. This research is part of an effort to realize a modern waste management system that is effective, efficient, and environmentally friendly through the application of the IoT-based Smart Waste Management concept.

Research by Kashyap & Kalyan (2023) Showing that the use of ultrasonic sensors in the Smart Bin system is able to detect waste capacity with an error of less than 5%. Meanwhile, Vishnu et al. (2021) developed an IoT-based monitoring system with a GSM connection that can provide automatic alerts to janitors when the bins are full. From these studies, it can be concluded that the use of ultrasonic sensors combined with IoT provides an effective solution for real-time monitoring of waste volumes.

Microcontrollers and IoT Platforms

In IoT systems, the main controller device acts as a processing and communication center between sensors and the cloud platform. One of the most widely used devices is the ESP32, as it has built-in Wi-Fi and Bluetooth modules, low power, and fast data processing capabilities (Ansari et al., 2023; Harianto et al., 2024). With these microcontrollers, data from sensors can be sent to platforms such as Blynk, Thingspeak, or Firebase IoT to be displayed in the form of graphs, tables, and visual indicators on a web dashboard.

Umsura et al., (2024) In his research, it was stated that IoT cloud-based systems facilitate decision-making through historical and predictive data analysis. This allows the management to plan the optimal waste transportation route based on the capacity and location of the bin, thereby reducing fuel consumption and operational time.

IoT Integration and Waste Management Efficiency

The integration of IoT in waste management not only improves technical efficiency, but also supports environmental sustainability and the circular economy. Fatimah et al. (2020) emphasized that this system can support data collection for policy-based waste management and community education. By utilizing real-time data from the smart bin system, decision-makers can evaluate people's consumption patterns and determine waste reduction strategies at the source.

From various previous studies, it can be identified that most of the focus is still limited to the technical aspects of capacity monitoring without considering the integration of online dashboards that can be accessed directly by cleaners in the field. Therefore, this research presents novelty by integrating an ultrasonic sensor system, ESP32 microcontroller, and web-based cloud dashboard for real-time monitoring of the condition of the garbage can. This approach is expected to improve operational efficiency, accelerate decision-making, and encourage the creation of a smart and sustainable waste management system.

METHODOLOGY

This research uses an engineering design research approach with a waterfall development model. This model was chosen because it provides a systematic and structured work stage starting from needs analysis to evaluation of results. This approach also makes it easier for researchers to test and improve the system gradually. Figure 1 shows the waterfall model cycle.

Figure 1. Waterfall Model

The initial stage was carried out through an analysis of field conditions and waste management systems in the community. Based on the results of observations, it was found that the waste disposal process is still difficult to do independently, this is influenced by several factors, including lack of awareness of environmental cleanliness and the lack of availability of garbage shelters around.

The main components of the hardware include:

1. Barcode sensors are used to identify garbage.
2. Microcontrollers are used as the main control units that process data from sensors and transmit measurement results to IoT platforms.
3. 5V Power Supply is used as the energy source of the system.
4. LCD is used to display the status of the trash can.

The data sent by the sensors is processed by ESP32 and forwarded to a cloud-based IoT server to be displayed through a web dashboard. The system is designed using the Arduino IDE programming language. The barcode sensor is mounted on the front facing forward. The ESP32 sensor unit is housed in a waterproof container inside the tub, to protect against moisture. Once the hardware is functioning properly, the system is calibrated to ensure the sensor readings match the scanned debris.

The program was developed using an Arduino IDE with a distance measurement algorithm, conversion of a number of economic values based on the volume identified via a barcode, and the delivery of data to the IoT platform every 5 seconds. The Smart Waste Bin prototype was tested to measure connection stability, sensor accuracy, and notification timeliness.

System Flowchart

Figure 2 shows a process flow diagram on a trash can.

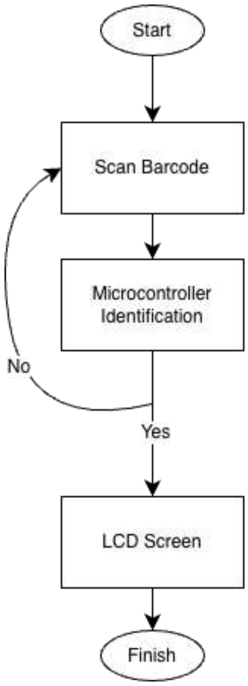

Figure 2. Flowchart System Process

Conceptually, the workflow of the system can be described as follows:

1. The barcode sensor detects scanned junk.
2. The microcontroller detects the scanned waste, reading the volume capacity of the waste.
3. Data is sent to an IoT cloud server using a Wi-Fi connection.
4. The LCD displays the waste data according to the scanned results.

This flow describes the data cycle from detection to notification in an IoT-based Smart Waste Bin monitoring system.

RESEARCH RESULT

The system test is carried out with three main scenarios:

Barcode Sensor Accuracy Test

The test was carried out by scanning the waste gradually into the tank until it was full, then comparing the sensor reading results with manual measurements. The results showed an average accuracy rate of 95%.

IoT Connection and Data Transmission Test

The system is tested in a household Wi-Fi network to verify the stability of the connection and the time of data transmission to the cloud platform. The test results showed that the data was displayed on the LCD pad with an average delay of less than 3 seconds.

Based on the test results, the system functions well and meets the specified functional needs. Sensor accuracy, data transmission stability, and notification speed demonstrate satisfactory performance for small-scale smart waste management applications.

DISCUSSION

The results of this study demonstrate that the IoT-based Smart Waste Bin system operates effectively in detecting, identifying, and transmitting waste data in real time. The use of a barcode sensor provides a high level of accuracy, reaching 95%, which reflects the system's ability to recognize and categorize waste materials precisely. This accuracy is in line with findings from previous studies, such as Kashyap and Kalyan (2023), who reported a similar performance level in IoT-enabled waste identification systems. The integration of the barcode sensor ensures that waste input is properly logged and verified before data is sent to the cloud, allowing the system to maintain consistent and reliable monitoring results.

Connectivity performance using the ESP32 microcontroller and the cloud server was also found to be stable, with an average data transmission delay of less than 3 seconds. This indicates that the communication link between the hardware and the IoT platform is efficient and capable of supporting real-time monitoring operations. The low latency is essential for systems requiring continuous updates, especially in large-scale applications such as smart cities or campus waste management networks. The use of Wi-Fi communication in this study provides a balance between accessibility and reliability; however, it may limit the operational range compared to long-range communication technologies such as GSM or LoRa.

The success of this implementation demonstrates that even with low-cost components, IoT-based systems can achieve satisfactory performance for small- to medium-scale waste monitoring. Furthermore, the cloud-based data visualization through a web dashboard provides a user-friendly interface that enables operators or municipal staff to track waste bin status easily. The ability to display real-time conditions supports faster decision-making, such as adjusting collection schedules and identifying locations requiring immediate attention. These advantages align with the principles of Smart Waste Management, where efficiency, automation, and sustainability are prioritized through digital integration.

Nevertheless, several limitations were identified during the study. The system was tested primarily on specific types of waste and within a limited network coverage area. In real-world implementation, environmental conditions such as temperature, humidity, and lighting can affect sensor performance and data transmission reliability. Future improvements should focus on enhancing connectivity through hybrid communication methods—combining Wi-Fi and cellular networks—to ensure broader scalability. Additionally, incorporating machine learning algorithms could enable automatic waste classification based on image recognition or pattern analysis, extending the system's functionality beyond barcode identification.

Overall, the IoT-based Smart Waste Bin system shows strong potential to support the implementation of Smart Waste Management initiatives in public spaces such as schools, offices, and residential areas. By enabling data-driven decision-making and optimizing waste collection schedules, this system contributes not only to operational efficiency but also to environmental sustainability and urban cleanliness. In the long term, integrating this technology with municipal management platforms could help establish a fully connected smart city waste ecosystem that aligns with global sustainability goals.

CONCLUSIONS AND RECOMMENDATIONS

1. The IoT-based Smart Waste Bin system is successfully designed and implemented well to detect and manage waste.
2. The barcode sensor has high accuracy (95%) and stable data connectivity via ESP32 with a send time of less than 3 seconds.
3. This system has the potential to support the wider implementation of smart waste management and is recommended for further development.

ADVANCED RESEARCH

For further research, an IoT-based Smart Waste Bin system can be developed by applying machine learning for automatic classification of various types of waste, integrating LoRa or GSM connectivity for long-distance communication, and using renewable energy to be more sustainable. The development of a data-based analytics dashboard is also suggested to support the system towards the concept of a smart environment that is integrated with smart city management.

ACKNOWLEDGMENT

The researcher expressed his gratitude to the Accounting Information Systems Study Program and the Department of Accounting, Politeknik Negeri Banjarmasin, which have provided support in the implementation of this research. Thanks are also expressed to the IoT research team and colleagues who have assisted in the process of designing, implementing, and testing the system. Moral and technical support from all parties involved played a major role in the success of this research.

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