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An Intelligent IoT Framework for Real-Time Waste Bin Level Monitoring and Collection Optimization

***[1]Emmy Danny Ajik, [2]Joseph Nda Ndabula, [3]Fagbemi Stephen Oluwatobi and [4]Abdullahi, Ali Bala**

[1]Department of Information Technology, Federal University Dutsin-Ma, Katsina State, Nigeria.
[2]Department of Software Engineering, Federal University Dutsin-Ma, Katsina State, Nigeria.
[3]Directorate of Economics, Federal University Dutsin-Ma, Katsina State, Nigeria.
[4]Department of Computer Science and Statistic, Federal College of Agricultural Produce Technology, Kano State, Nigeria.

*Corresponding authors' email: emmyajik@yahoo.com

ABSTRACT
The rapid increase in urban population and solid waste generation has intensified the need for efficient and intelligent waste management systems. Conventional waste collection methods rely on fixed schedules, often resulting in overflowing bins, environmental pollution, and inefficient resource utilization. This study presents the design and implementation of a Smart Bin Level Monitoring System based on Internet of Things (IoT) technology. The system utilizes an ultrasonic sensor mounted at the top of the waste bin to measure the distance between the sensor and the waste surface, thereby determining the bin's fill level in real time. A microcontroller processes the sensor data and transmits it wirelessly to a remote server for online monitoring. The collected data is displayed on a dedicated web-based dashboard accessible at https://iot.net.ng/bin/dashboard.php, enabling authorized users to monitor bin status remotely. The system generates alerts when the bin reaches a predefined threshold, facilitating timely waste collection and optimized route planning. Experimental results indicate accurate level detection, reliable wireless transmission, and effective real-time visualization. The proposed solution enhances operational efficiency, reduces environmental hazards, and supports smart city waste management initiatives.

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INTRODUCTION

Waste management has become one of the most visible challenges in rapidly growing cities. As urban populations continue to increase and consumption patterns change, the volume of municipal solid waste generated daily has risen significantly. In many communities, waste collection systems still operate using fixed schedules without knowing whether bins are full, half-empty, or already overflowing. This often results in unpleasant scenes of spilled waste, foul odors, environmental pollution, and potential health risks. At the same time, collection trucks frequently visit bins that are not yet full, leading to unnecessary fuel consumption, increased operational costs, and inefficient use of resources. These limitations highlight the need for smarter and more responsive waste management solutions. With the advancement of digital technologies, particularly the Internet of Things (IoT), it is now possible to monitor physical systems remotely and make decisions based on real-time data(Echobu et al., 2025). IoT enables everyday objects to be equipped with sensors and communication capabilities, allowing them to collect and transmit data over the internet(Abdulhussain et al., 2025). In the context of waste management, this technology creates opportunities for bins that can "report" their fill levels without requiring physical inspection. Smart bin systems represent a practical application of IoT within smart city development. Rather than relying on assumptions or routine schedules, waste collection can be triggered by actual bin status. This shift from reactive to data-driven waste management improves efficiency, reduces environmental impact, and enhances urban cleanliness.

A key component of such systems is the ultrasonic sensor, which measures distance using sound waves. When installed at the top of a waste bin, the sensor continuously measures the distance between itself and the surface of the waste material. As the bin fills, this distance decreases, allowing the system to estimate the percentage fill level accurately. Ultrasonic sensors are particularly suitable for this application because they are non-contact, affordable, durable, and capable of operating in dusty or dirty environments commonly associated with waste bins. In this study, a Smart Bin Level Monitoring System was developed using an ultrasonic sensor integrated with a microcontroller-based IoT platform. The system continuously measures the fill level of the bin and transmits the data wirelessly to an online dashboard. Through this web-based platform, authorized users can remotely monitor the bin's status in real time. Notifications are generated when the bin reaches a predefined threshold, enabling timely waste collection and preventing overflow situations. The main goal is not only to design a functional prototype but also to demonstrate how simple, affordable IoT technologies can significantly improve waste management practices. By providing real-time visibility into bin status, the system supports better planning, reduces unnecessary trips, and promotes cleaner and more sustainable environments. Ultimately, this work contributes to the growing effort toward intelligent urban infrastructure, where technology is used to solve everyday challenges in practical and scalable ways.

Literature Review

Recent advancements in Internet of Things (IoT) technology have significantly influenced the development of smart waste management systems. Researchers have explored various sensor-based approaches to monitor garbage levels in real time, aiming to reduce overflow, optimize collection schedules, and improve environmental hygiene. Ultrasonic sensors have been widely adopted due to their non-contact measurement capability, affordability, and reliability in detecting bin fill levels.

Mustafa and Ku-Azur (2017) developed a smart garbage monitoring system that utilized ultrasonic sensors and an ARM microcontroller to measure waste depth and transmit data to the ThingSpeak cloud platform. Their system categorized waste into different types and enabled real-time monitoring through both LCD display and online storage, supporting predictive analysis of bin fullness patterns. This work demonstrated the potential of IoT platforms in improving municipal waste management efficiency. Similarly, Mohd Yusof et al. (2018) proposed an IoT-based smart waste bin integrated with renewable energy, wireless sensor networks, SMS notifications, and Wi-Fi communication. Their framework combined solar power systems with real-time monitoring to enhance sustainability and operational effectiveness. While comprehensive, the integration of multiple subsystems increases system complexity and implementation cost. Energy-efficient and long-range communication technologies have also been emphasized in recent studies. Ramson et al. (2021, 2022) developed self-powered trash bin monitoring units using LoRa and LoRaWAN communication. These systems measured bin level and geolocation, transmitting data to centralized servers for monitoring through graphical dashboards. Performance evaluations included power consumption, communication range, battery life, and system cost, demonstrating suitability for large-scale deployments.

Previous studies have enhanced smart waste bin systems by integrating multiple sensors such as ultrasonic, load, gas, and GPS sensors to monitor fill levels, hazardous gas emissions, and bin locations (Ali et al., 2020; Ravi et al., 2021). Similarly, intelligent techniques such as Artificial Intelligence of Things (AIoT) and fuzzy logic have been applied to improve waste management decision-making and optimize bin placement (Bano et al., 2020). Despite these advancements, many existing systems primarily focus on data collection and intelligent processing, while providing limited support for continuous, accurate, and easily interpretable real-time monitoring that enables timely waste collection decisions. In practice, waste collection often relies on periodic inspections or coarse fill-level classifications, which may result in delayed response and bin overflow.Therefore, there remains a need for an IoT-based smart waste monitoring system capable of delivering accurate, continuous percentage-based fill-level measurements with real-time dashboard visualization to support proactive waste collection. This study aim to address this gap by developing an ultrasonic sensor-based IoT smart bin system that provides real-time percentage estimation of bin fill levels with high measurement accuracy, and presents live monitoring and historical trends through an online dashboard, thereby enabling more efficient and informed waste management operations.

MATERIALS AND METHODS

Figure 1: IoT-Based Smart Waste Bin System Implementation Framework

Planning and Requirement Analysis

The first step involves defining the project scope, objectives, and expected outcomes. A comprehensive analysis was conducted to determine the necessary hardware components, such as ultrasonic sensors for waste level detection, microcontrollers (ESP8266), and communication modules. Wi-Fi was selected as the data communication protocol because it provides reliable, high-speed, and cost-effective wireless connectivity for transmitting real-time waste bin data to the cloud dashboard over existing internet infrastructure. Additionally, software requirements were assessed, including the development stack for the web-based dashboard (e.g., PHP and HTML for frontend and Backend respectively, SQL for database). Some components used include:

ESP32

The ESP32 Development Board is a powerful and versatile microcontroller board designed for IoT (Internet of Things) and embedded applications(Rahman et al., 2026). TheESP32 microcontroller by Espressif Systems, features an integrated Wi-Fi and Bluetooth capabilities, making it ideal for a wide range of wireless communication projects.

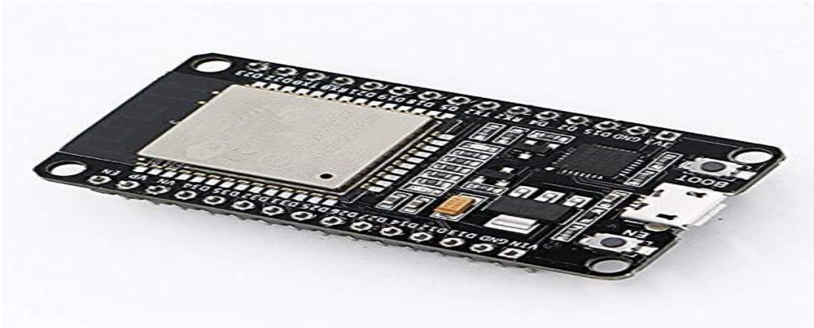


Figure 2: ESP32

Ultrasonic Sensor

Ultrasonic sensors determine the distance to an object by transmitting high-frequency ultrasonic waves and measuring the time taken for the reflected waves (echoes) to return to the sensor (Aliew, 2022). The measured time interval is then used to calculate the distance between the sensor and the target. In reflective ultrasonic sensors, a single ultrasonic transducer alternately functions as both the transmitter and receiver, enabling a compact sensor design while maintaining accurate distance measurement.

Figure 3: Ultrasonic Sensor

TP5100 Charging Module

Built for effective and fast charging applications, the TP5100 is a highly integrated dual-cell lithium battery charging module(Minhas et al., 2026). This module has good heat dissipation, high charging current capabilities (up to 2A), and automated switching for both 3.7V (single-cell) and 7.4V (dual-cell) lithium batteries. It is an ideal choice for small battery-operated gadgets that need quick, dependable charging.

Figure 4: TP5100 Charging Module

Liquid Crystal Display (LCD)

A 16×4 LCD is an alphanumeric display module capable of presenting 16 characters per line across four rows, allowing up to 64 characters to be displayed simultaneously. It is commonly based on the HD44780 controller, which provides a standard interface for microcontroller applications (Wu, 2022). To simplify its connection with an Arduino, an I2C Serial Interface Module, commonly referred to as an I2C LCD backpack, is used. This module, typically built around the PCF8574 or PCF8574T integrated circuit, converts the LCD's parallel interface into an I2C interface, reducing the required microcontroller connections to only four pins and minimizing GPIO pin usage while simplifying wiring.

Figure 5: LCD Screen

Figure 6: Sample I2C

Hardware Development and Integration
In this phase, the smart bin was physically assembled with the selected sensors and microcontrollers. The sensors were integrated to detect waste levels, while microcontrollers processed and transmitted data. An LCD screen was also added to the system to enable real time viewing of the bin level. Power management solutions, such as rechargeable batteries, were also implemented to ensure continuous operation. Initial testing was carried out to verify sensor accuracy and responsiveness. Issues such as power efficiency, sensor placement, and environmental durability were identified and addressed.

Web-Based Dashboard Development
The web dashboard was developed to provide real-time waste level monitoring. The frontend was designed for ease of use, displaying waste levels through charts, graphs, and color-coded alerts. The backend was built to store and process sensor data, using MySQL. Feature such as automated alerts (push notifications) was integrated to notify waste management personnel when bins reach a predefined capacity. The dashboard was tested for responsiveness, accuracy, and security to ensure efficient data handling and visualization.

Data Communication and IoT Connectivity
This step focused on ensuring reliable data transmission between the smart bin and the web dashboard. Wireless communication protocols (Wi-Fi and MQTT) were configured to send real-time sensor data to the cloud. The connection stability, data latency, and security measures were tested and optimized to prevent data loss or delays. The data was also verified with the data available on the LCD screen.

System Testing and Optimization
A pilot deployment was conducted in a controlled environment to evaluate system performance. The accuracy of waste level detection, response time of alerts, and efficiency of data transmission were tested. Any inconsistencies in sensor readings, power consumption issues, or connectivity failures were identified and rectified. Optimization was performed to improve system accuracy, reduce energy consumption, and enhance the dashboard's performance. User feedback was gathered from initial tests to refine the system before full-scale deployment.

Deployment and Field Testing
The system was deployed in real-world locations, such as public waste collection points and office buildings. The performance of the smart bin was continuously monitored to assess its effectiveness in improving waste management. Data on waste levels were collected. Stakeholder feedback was gathered to identify any operational challenges and necessary adjustments were made. The goal was to ensure the system functions seamlessly in diverse environmental conditions. Four Bins were monitored for four (4) days.The bins were placed across four points labeled **A-D**. All four bins had a depth of **90cm**.

Figure 7: Stakeholders Engagement with the device

Data Analysis and Monitoring

The waste bin monitoring system continuously collects and stores sensor readings in a cloud database, where the data are displayed through a web-based dashboard for real-time monitoring. The dashboard presents key information such as the measured distance, calculated bin fill percentage, timestamps, and historical records, enabling users to track waste accumulation over time. Additionally, trend visualization allows administrators to observe changes in bin utilization and estimate when a bin is approaching full capacity. These insights support timely waste collection scheduling, help prevent bin overflow, and improve the efficiency of waste management operations through informed decision-making.

RESULTS AND DISCUSSION

Experimental Setup and Test Conditions

The proposed IoT-based waste bin monitoring system was experimentally evaluated to assess its sensing accuracy, communication performance, and operational reliability. The prototype employed an ultrasonic sensor installed at the top of a waste bin to measure the distance between the sensor and the waste surface. The measured distance values were processed by a microcontroller, which converted them into a percentage representing the fill level of the bin. The processed data were then transmitted through a wireless IoT communication module to a cloud-based dashboard for real-time monitoring and notifications.

Unlike conventional smart bin systems that classify waste levels into discrete states such as empty, half-full, or full, the developed system represents the bin status as a continuous percentage ranging from 0% to 100%, where 0% indicates an empty bin and 100% represents a completely filled bin. This approach provides more precise information about the bin status and enables improved decision-making for waste collection scheduling. Four bins were used for the experiment and were placed across four points labeled A-D. All four bins had a depth of 90cm.

Sensor Performance and Percentage Calibration

The performance of the ultrasonic sensing unit was evaluated by analyzing the distance measurements recorded by the system and the corresponding bin fill percentages displayed on the monitoring dashboard. The sensor continuously measures the distance between the top-mounted sensor and the surface of the waste material inside the bin. These distance values are then converted into a percentage representation of bin fullness using a calibrated mapping algorithm.

From the experimental records shown on the monitoring dashboard, several measurements were obtained during a filling cycle. Example readings are summarized in **Table 1**.

Table 1: Sample Sensor Readings and Calculated Bin Fill Levels

Record ID	Distance (cm)	Calculated Fill Level	Location
2248	24.0	73%	Point D
2247	22.2	75%	Point D
2246	6.5	93%	Point C
2245	6.5	93%	Point C
2244	7.8	91%	Point B
2243	6.8	92%	Point B
2242	6.8	92%	Point A
2241	7.2	92%	Point A
2240	8.8	90%	Point A

The results indicate a clear inverse relationship between the measured distance and the calculated bin fill percentage. Larger distance values correspond to lower fill levels, while smaller distance values indicate that the waste is closer to the sensor and the bin is nearing capacity.

For instance, when the sensor recorded a distance of 29.6 cm, the system estimated the bin level at approximately 67% full. As the waste accumulated and the measured distance decreased to approximately 6.5 cm, the calculated fill level increased to 93%, indicating that the bin was approaching its maximum capacity.

Real-Time Dashboard Performance

The developed system includes a web-based monitoring dashboard that provides real-time visualization of the waste bin status, sensor readings, and historical measurement records. The dashboard serves as the primary interface for administrators to monitor bin utilization and make timely waste collection decisions.

The interface displays key operational parameters including the current measured distance, the calculated bin fill percentage, and the timestamp of the most recent sensor update. The dashboard also indicates the maximum measurable bin height of 90 cm, which is used as the reference for percentage calibration.

In addition to the real-time display, the system maintains a database of sensor readings that can be accessed through the dashboard. The stored data include record identifiers, timestamps, measured distances, and calculated fill levels. The system presents the latest records in descending order, allowing administrators to quickly observe recent changes in bin utilization.

Sample entries obtained from the monitoring system show consistent data logging and successful communication between the IoT device and the cloud server. For example, recent records include distance measurements such as 24.0 cm (73% full), 22.2 cm (75% full), and 6.5 cm (93% full), demonstrating the system's ability to track gradual waste accumulation over time.

Another important feature of the dashboard is the distance trend visualization, which displays the most recent sensor readings in graphical form. The trend graph allows users to analyze how quickly the bin is filling and identify patterns in waste disposal. This functionality is particularly useful for predicting when the bin will reach its maximum capacity and scheduling waste collection accordingly. A depiction of the smart bin real-time monitoring dashboard is shown in Figure 8.

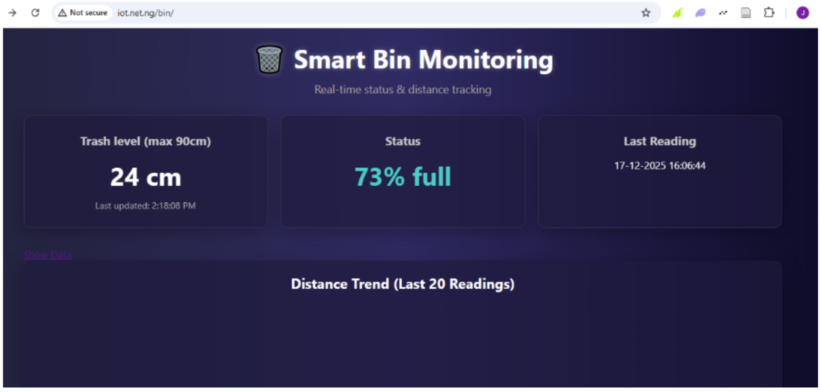


Figure 8: Real-time Dashboard for tracking Bin level

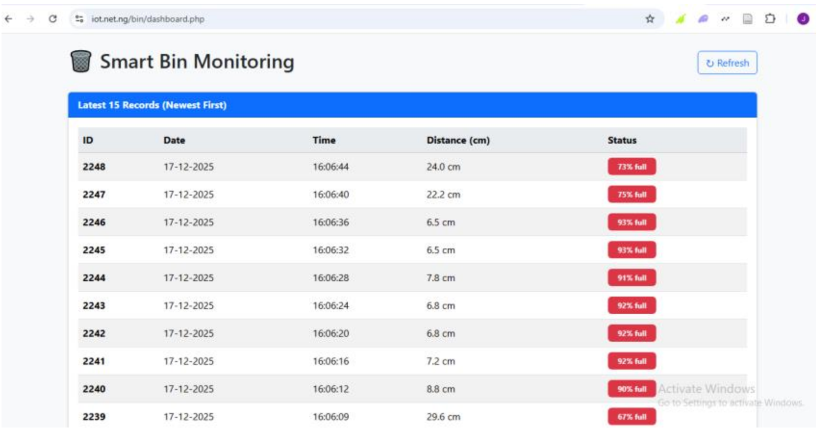
System Accuracy and Error Analysis

To evaluate the reliability of the proposed waste bin monitoring system, an accuracy and error analysis was conducted by comparing the sensor-derived fill levels with the actual measured waste levels inside the bin during controlled experiments. The objective of this evaluation was to determine how closely the ultrasonic sensor measurements and the percentage calibration algorithm represent the real bin conditions.

During the experimental trials, the bin was gradually filled while both the actual waste height and the sensor-measured distance were recorded. These measurements were then converted into percentage fill levels using the system calibration model. A total of 60 experimental observations were collected for analysis.

Measurement Accuracy

The ultrasonic sensor demonstrated stable and consistent measurements across the different filling stages of the bin. Observations from the system database show that as the measured distance decreased, the calculated fill percentage increased accordingly. For instance, when the sensor measured approximately 29.6 cm, the system estimated the bin level at 67%, whereas a distance measurement of 6.5 cm corresponded to approximately 93% full. These values closely matched the actual bin conditions during testing. Figure 3 shows sample readings of the ultrasonic sensor for different waste bin levels based on calculated distance.



iot.net.ng/bin/dashboard.php

Smart Bin Monitoring

Refresh

Latest 15 Records (Newest First)

ID	Date	Time	Distance (cm)	Status
2248	17-12-2025	16:06:44	24.0 cm	73% full
2247	17-12-2025	16:06:40	22.2 cm	75% full
2246	17-12-2025	16:06:36	6.5 cm	93% full
2245	17-12-2025	16:06:32	6.5 cm	93% full
2244	17-12-2025	16:06:28	7.8 cm	91% full
2243	17-12-2025	16:06:24	6.8 cm	92% full
2242	17-12-2025	16:06:20	6.8 cm	92% full
2241	17-12-2025	16:06:16	7.2 cm	92% full
2240	17-12-2025	16:06:12	8.8 cm	90% full
2239	17-12-2025	16:06:09	29.6 cm	67% full

Activate Windows
Go to Settings to activate Windows.

Figure 9: Smart Bin Monitoring records for Waste levels using Distance between the Ultrasonic Sensor and the waste

The overall system accuracy was calculated by comparing the estimated fill percentage with the manually measured bin fill level. The experimental results indicated that the proposed system achieved an average accuracy of approximately 92–94%, demonstrating reliable performance for real-time waste monitoring applications.

Discussion

The results obtained from the experimental evaluation demonstrate the effectiveness of the proposed IoT-based waste bin monitoring system in accurately measuring bin utilization and providing real-time monitoring through a web-based dashboard. The integration of ultrasonic sensing, percentage-based fill level estimation, and cloud-based data visualization enabled continuous tracking of waste accumulation within the bin.

Performance of the Ultrasonic Sensing Approach

The experimental observations confirm that the ultrasonic sensor provides consistent and reliable distance measurements for estimating bin fill levels. As shown in the sensor performance results, there is a clear inverse relationship between the measured distance and the calculated fill percentage. Larger distances correspond to lower bin utilization, while smaller distances indicate that the bin is approaching capacity.

The calibration approach used in this study, which converts distance measurements into percentage values, proved effective in representing bin status more accurately than simple categorical classification methods. Instead of limiting the system to predefined states such as empty, half-full, or full, the percentage-based representation allows continuous monitoring of bin utilization. This provides waste management personnel with more detailed information for planning collection schedules.

Additionally, repeated readings with similar distance values produced nearly identical percentage outputs, indicating that the calibration algorithm operates consistently and that the sensor measurements remain stable during operation.

System Accuracy and Reliability

The results of the accuracy evaluation show that the system achieved an average performance of approximately 92–94% accuracy, with most readings falling within an error range of ±5%. This level of accuracy is adequate for smart waste monitoring applications, where the primary objective is to identify bins that are approaching full capacity.

The small discrepancies observed during some measurements can largely be attributed to physical characteristics of the waste materials rather than system malfunction. Waste items often create uneven surfaces inside the bin, which can affect ultrasonic wave reflection and introduce minor measurement variations. Despite this, the system maintained stable readings across repeated measurements, demonstrating reliable performance.

The stability of the system is further supported by the recorded data logs, where similar distance values consistently produced comparable fill-level estimates. This indicates that the implemented measurement and processing approach is robust enough for practical deployment.

Effectiveness of the Real-Time Monitoring Dashboard

The web-based monitoring dashboard plays a crucial role in translating raw sensor data into actionable information. The results show that the dashboard successfully receives, stores, and displays sensor readings in real time. Key parameters such as the current distance measurement, calculated bin fill percentage, and timestamp of the latest update are clearly presented to the user.

The availability of historical records and trend visualization further enhances the system's functionality. By analyzing recent measurements and observing how quickly the bin fills over time, administrators can anticipate when waste collection will be required. This capability supports more efficient waste management operations and helps prevent overflow situations.

The successful synchronization between the sensing device and the dashboard also confirms the reliability of the communication framework used in the system. All experimental readings were correctly logged and displayed, indicating stable IoT connectivity throughout the testing period.

Practical Implications for Smart Waste Management

The findings of this study highlight the potential of IoT-based monitoring systems to improve traditional waste collection processes. In many urban environments, waste collection often follows fixed schedules, which can lead to inefficient resource utilization. Bins may either overflow before collection or remain partially empty when serviced.

The proposed system addresses this issue by providing real-time information about bin utilization. With continuous monitoring and percentage-based status reporting, waste management authorities can prioritize bins that are close to full capacity and optimize collection routes accordingly. This can lead to reduced operational costs, improved environmental sanitation, and better service delivery in smart city infrastructures.

CONCLUSION

This study successfully developed and evaluated an IoT-based smart waste bin monitoring system that addresses the need for accurate, continuous, and real-time monitoring of waste bin utilization. By integrating an ultrasonic sensor with Wi-Fi-enabled cloud communication and a web-based dashboard, the system provided percentage-based fill level estimation, real-time data visualization, and historical monitoring to support informed waste collection decisions. Experimental evaluation demonstrated an average measurement accuracy of 92-94%, with most readings exhibiting an error margin within ±5%, confirming the system's reliability for practical deployment. The findings indicate that the developed system effectively overcomes the limitations of conventional waste monitoring approaches by enabling timely waste collection, reducing the likelihood of bin overflow, and improving operational efficiency. Consequently, the study contributes a practical, cost-effective, and reliable IoT solution for enhancing smart waste management.

Although the results demonstrate promising performance, several limitations were observed during the experiments. Ultrasonic sensors can be influenced by irregular waste surfaces, large objects positioned directly below the sensor, and environmental factors such as humidity or dust accumulation. These conditions may occasionally introduce minor measurement deviations.

Future improvements could focus on integrating additional sensing techniques or data filtering methods to further enhance accuracy. For example, combining ultrasonic sensing with weight-based measurements or implementing machine learning algorithms for waste level prediction could improve system robustness. Furthermore, optimizing energy consumption and expanding the system for multiple bin monitoring would increase its applicability in large-scale smart city deployments. Measures such as data encryption and error handling mechanisms should be implemented to ensure the integrity and reliability of transmitted waste level data

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