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Garbage Guardian: Revolutionizing waste management through Internet of Things and a mobile application

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Abstract

As city populations grow rapidly, municipal solid waste has increased significantly. Current waste management techniques face many challenges, including inefficient waste collection, overflowing bins, increased transportation and maintenance costs, and environmental pollution. Conventional waste management models mostly rely on manual checks, and collection follows a fixed schedule; both lead to resource waste and delayed collection. This study proposes Garbage Guardian, an Internet of Things (IoT)-based waste management model with a mobile application that supports real-time waste level monitoring, automated waste segregation, and efficient waste collection. The system uses ultrasonic and infrared sensors connected to the NodeMCU to monitor bin waste levels and wirelessly transmit sensor data to the cloud server. The proposed framework provides real-time notifications, cloud-based monitoring, waste-collection support, and a mobile application interface for citizens, waste collectors, and local government. The system's effectiveness was tested by measuring waste level detection, notification delay, waste segregation, and IoT-enabled communication performance. The experimental results show that waste level detection in the smart waste bin ranges from 95% to 99%, and notification delay ranges from 0.8 s to 1.0 s. Furthermore, the proposed system offers waste segregation efficiency ranging between 94% and 97%. The results demonstrate the proposed framework's ability to provide reliable real-time waste monitoring, timely notifications, and effective waste segregation for smart waste management, indicating that it can support efficient, safe, and sustainable waste management. The framework also supports the development of smart and sustainable cities by improving waste-collection efficiency, reducing negative environmental impacts, and promoting the use of smart technologies in waste collection.

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1. Introduction

Rising urbanization, industrialization, and consumer habits have led to a drastic rise in municipal solid waste; thus, effective waste management has become a major challenge for contemporary cities. This is mainly because municipal solid waste management

significantly affects the environment, public health, and overall urban sustainability. Most current solid waste collection systems operate on fixed schedules and rely on manual supervision. As a result, waste collection is often delayed, and garbage collection vehicles consume large amounts of fuel (Anitha & Parthiban, 2025). The system also fails to optimize the work and manpower needed for the collection operation. Therefore, it is crucial to design and build automated waste management systems for cities.

In recent years, advances in the Internet of Things (IoT) and wireless technologies have contributed significantly to smart city applications. Smart cities are designed to incorporate many sensing elements, IoT communication, and cloud computing. IoT-based smart waste management systems use these technologies to monitor solid waste, making waste management more effective and eco-friendly. Smart waste bins can sense their waste capacity, and this data can be continuously reported to a system via IoT communication; in turn, it can generate alerts for waste collectors as bin capacity increases. A mobile application can notify and facilitate communication between garbage collectors, citizens, and municipal authorities.

Several IoT-based smart waste management systems have been proposed. However, many of them lack proper sensing and real-time monitoring. Most frameworks also lack intelligent notifications and waste classification. Moreover, waste collection vehicles often do not follow optimal routes, wasting fuel and money. Therefore, there is a strong need for smart waste management systems that incorporate waste monitoring, automatic waste classification, optimal path selection for waste collection, and IoT communication among waste collectors, municipal authorities, and citizens.

To address these challenges, this study presents an IoT-based smart waste management system integrated with a mobile application. In this proposed system, IoT detects and monitors garbage levels in real time. The system has sensors, such as ultrasonic and infrared (IR) sensors, and is coupled with NodeMCU. NodeMCU is an IoT controller that interfaces with sensors and transmits data wirelessly to the cloud. The framework can generate real-time alerts to notify the waste collection agency when garbage levels rise in a smart bin. It also includes an intelligent route planner that can determine the optimal waste-collection path, reducing time and costs. Waste collectors and garbage monitoring agencies can also use the mobile application to communicate and receive real-time notifications.

The system was evaluated for waste level detection, notification response, IoT communication, and waste segregation. Results indicate that the proposed system can support real-time waste monitoring, demonstrating the

potential of IoT in smart waste management. The following are the contributions of the work presented in this study:

- (i) An IoT-based smart waste management system, Garbage Guardian, which integrates smart waste bins, sensing modules, NodeMCU processing, cloud connectivity, and a mobile application interface for real-time waste monitoring.
- (ii) To overcome the limitations of conventional systems, which are limited to monitoring waste in general, the proposed system was designed to provide a complete smart waste management system that incorporates waste level monitoring, notification generation, waste segregation, and cloud-based information sharing.
- (iii) The system uses a cloud-based system that enables real-time waste information transmission and accessibility to the users through a mobile application.
- (iv) The proposed smart waste management framework was implemented and tested experimentally to evaluate the functionality in terms of waste level detection, notification response, IoT communication, and waste segregation capability.

2. Literature review

Rapid urbanization, industrialization, and high population density have increased municipal solid waste production, creating severe environmental, economic, and public health problems worldwide. Because existing solid waste management infrastructure relies on fixed collection schedules, manual visual inspection, and ineffective segregation systems, they often result in overflowing bins, reduced recycling efficiency, increased fossil fuel consumption, greater environmental pollution, and heightened risks of disease transmission. To address these challenges, IoT, artificial intelligence (AI), cloud computing, wireless sensor networks, and mobile technology were incorporated to build intelligent systems for sustainable waste management, improving waste management efficiency and contributing to smart city development.

The initial study on smart waste management systems focused on applying sensor-based monitoring and wireless communication systems to support waste collection operations. Longhi *et al.* (2012) introduced the first smart waste management system, which used a wireless sensor network to monitor garbage levels and improve vehicle routing for waste collection. Similarly, a smart bin developed by Folianto *et al.* (2015) could monitor waste levels and automatically send information to the management team about waste status. This reduced unnecessary collection trips and the operational cost of waste collection. In Islam *et al.* (2012), ultrasonic sensors

and a Global System for Mobile Communications module were used together to monitor and warn about bin fullness in real time, helping prevent garbage overflow. Researchers showed that IoT-based smart technologies can improve the operational cost-effectiveness and efficiency of solid waste management by reducing the need for human labor.

Over time, research shifted to automated waste segregation to improve recycling efficiency and sustainable waste management. Doriya *et al.* (2020) proposed an automated waste segregator that separates waste into biodegradable and non-biodegradable categories using moisture and metal sensors, with a microcontroller controlling the system. Malleswari *et al.* (2020) proposed a smart waste segregator capable of automatically segregating wet, dry, and metallic waste using sensor technology. Perangin Angin *et al.* (2018) proposed a smart segregation system that combined IoT-based monitoring with sensor-based classification to enhance the recycling process. These studies emphasize the importance of automated waste segregation in reducing manual handling and improving overall recycling efficiency.

Beyond segregation, other researchers focused on improving vehicle routes to waste collection locations and developing waste-collection methods that could reduce fossil fuel consumption and other operational inefficiencies. Anagnostopoulos *et al.* (2017) proposed a smart city solution for waste management that integrated IoT sensors into a dynamic route optimization algorithm during waste collection. Similarly, Sharma and Vrat (2018) proposed a smart waste collection solution using the global positioning system and wireless communication to optimize vehicle routes and waste collection schedules. These studies showed that route optimization reduces mileage, lowers fuel use, shortens collection time, and increases productivity (Kim *et al.*, 2025).

More recently, the proliferation of IoT and cloud computing has enabled more connected, data-driven waste systems. Anand *et al.* (2023) proposed a cloud-integrated IoT waste management system that uses ultrasonic, IR, weight, and camera sensors for real-time waste monitoring and content identification, enabling remote monitoring and recycling planning through cloud processing. Oyerinde *et al.* (2025) created an IoT-based waste management system that monitors garbage in real time and sends notifications to users through ultrasonic sensors and a NodeMCU device, combined with an Android application. This improved collection efficiency and sanitation in urban settings, but AI-driven analytics and intelligent waste segregation were not applied to this system.

The adoption of AI and machine learning tools has further advanced intelligent waste management systems

through predictive analytics, automated decision-making, and intelligent waste classification. Wang *et al.* (2021) proposed a deep learning-enabled waste classification system connected to cloud computing, using convolutional neural networks to identify garbage types. Huynh *et al.* (2020) used deep learning systems such as EfficientNet and ResNet for automated waste sorting with high classification accuracy, while Arunkumar *et al.* (2022) employed hybrid machine learning systems combining decision tree and extreme learning machine for predictive analysis in smart cities. These studies found that AI-driven systems improve classification accuracy, predictive analysis, and decision-making in waste management operations (Alourani *et al.*, 2025; Ghosh & Goswami, 2025; Ishaque & Florence, 2025; Utku, 2026).

Researchers have investigated combining IoT, route optimization, and edge AI for intelligent waste management. Nikam (2025) proposed an IoT-based smart waste management system with route optimization to reduce fuel cost, operational cost, and distance traveled during waste collection. Tadavi *et al.* (2025) proposed the integration of IoT-based smart waste bins with route optimization and highlighted that future studies can include machine learning for predictive waste analytics. Kapadia and Mehta (2024), and Punia (2025) integrated an IoT-enabled waste management system with edge AI for real-time monitoring, route optimization of vehicles, and intelligent recycling decision-making. These approaches improved operational efficiency and reduced greenhouse gas emissions, but scalability and real-world implementation challenges remain.

Nikhilendra *et al.* (2025) created a smart waste monitoring system that could notify authorities in real time once a particular waste limit in bins was reached through IoT-based sensor technology. Similarly, Tee *et al.* (2025) proposed a smart waste monitoring system that used ultrasonic and load cells as waste level and bin-weight sensors. In addition, Wafi and Chairulfata (2026) introduced the BINSAl monitoring system, which incorporates enhanced sensor calibration, improved global positioning system stability, and a modular system design to improve monitoring accuracy and notification effectiveness. IoT-enabled smart bins thus demonstrate a means to improve efficiency in waste collection and urban sanitation.

The importance of IoT-enabled waste monitoring systems as a tool to enhance sustainability and efficiency in urban waste collection management was also supported by the most recent research conducted by Shrivastava *et al.* (2025) and Kumar *et al.* (2025), in which they highlighted the role of the use of intelligent sensing and real-time

monitoring technologies.

Another area of research explored in the literature is smart segregation and sustainable recycling. For example, Kishore *et al.* (2024) designed an IoT-based smart wet and dry waste management system using sensor technology, data networks, and data analytics for smart waste segregation and effective monitoring. Similarly, Ramesh *et al.* (2022) created an IoT system that segregates wet waste from dry waste and further sorts dry waste into separate categories of plastic, paper, metal, and glass using Arduino sensors. These smart waste management systems would greatly improve recycling efficiency and the sustainable processing of waste through automated segregation.

Gowda *et al.* (2022) introduced an advanced smart waste segregation and management system using Arduino technology to enhance automated waste segregation and efficiency. Gangwani *et al.* (2019) reviewed waste segregation techniques and described the importance of smart segregation systems for managing waste effectively. Ahash *et al.* (2018) built an automatic waste segregator using Arduino, and it segregated and recycled waste efficiently. Shyamala *et al.* (2016) also constructed a smart waste management and monitoring system to segregate smart city waste.

Pandey *et al.* (2021) designed an IoT-based smart garbage segregator to automate waste segregation and monitoring. Jasmine *et al.* (2020) developed an automatic waste segregator controlled by an Arduino controller, which segregates waste and recycling.

Another area addressed in recent studies is citizen engagement through mobile applications in IoT waste management systems. Sneha *et al.* (2023) reviewed several IoT waste management systems that incorporate a mobile app, solar panels, and ultrasonic sensors to monitor waste sustainably. Additionally, Jaison *et al.* (2024) designed a smart waste management system with an automatic lid and real-time ultrasonic sensor monitoring to improve the system's hygiene and efficiency. Such studies contribute to developing public engagement and mobile use to improve public awareness and involvement in waste management practices.

Sosunova and Porras (2022) conducted a systematic literature review of IoT-based smart waste management systems and smart cities, emphasizing the need for intelligent monitoring infrastructure. Pardini *et al.* (2020) developed a smart waste management framework based on citizen engagement and IoT to improve waste management. Furthermore, Pardini *et al.* (2019) conducted a review of solid waste management solutions

based on IoT and the benefits to smart cities. Harith *et al.* (2020) presented a prototype for an IoT-based smart waste management system for smart cities, whereas Raghavendra and Srinivasulu (2022) presented a mobile application model for smart solid waste management collection and monitoring.

In the system proposed by Wang *et al.* (2021), waste classification was performed using images, and waste-type classification was analyzed to improve waste separation efficiency. Their study highlights that the proposed system enhances automated waste segregation and recycling efficiency. This demonstrates a potential IoT and AI-based approach for waste segregation that can improve the efficiency of municipal solid waste management.

Sosunova and Porras (2022) provided a detailed survey of IoT-enabled smart waste management systems, covering recent advances in IoT-based sensing technologies, communication protocols, cloud computing, route optimization, and smart waste collection systems. This survey discusses the challenges of IoT-enabled smart waste management. The survey presents the pros and cons of current smart waste management systems and outlines research directions and challenges, such as scalability, interoperability, data security, and the implementation of IoT-based smart waste management. In addition, the study highlights the importance of an IoT-based integrated smart waste management system that can deliver different smart services through a common platform.

Although the literature has made significant progress in designing IoT-based waste management systems, it has not addressed some research gaps. However, few studies have integrated smart monitoring, automated segregation, waste classification, route optimization, and citizen-facing services within a single unified platform. No studies address a state-of-the-art mobile application, citizen engagement, AI predictive systems, system maintenance, scalability and cybersecurity, and edge AI challenges in design, cost, maintenance, and interoperability across various urban environments. Therefore, improving smart waste management efficiency and smart city waste management requires research on a smart system that incorporates IoT waste monitoring, AI waste analytics, automated waste segregation, route optimization, and cloud- and mobile application-based waste management.

While significant research has been conducted in smart waste management, improvements are still needed in scalability, prediction, monitoring integration, and citizens' awareness and decision-making intelligence. A review of related work is shown in Table 1.

Table 1. Critical analysis of existing Internet of Things- and artificial intelligence-based smart waste management systems

Author & year	Methodology/ technology	Key findings	Limitations	Research gap
Longhi <i>et al.</i> (2012)	Wireless sensor networks, smart bins	Enabled real-time monitoring of waste bins and optimized collection routes	Limited scalability and no AI integration	Need for intelligent analytics and scalable IoT framework
Folianto <i>et al.</i> (2015)	Sensor-based smart bin system	Reduced unnecessary waste collection trips through fill-level monitoring	No segregation or route optimization	Integration of smart segregation and optimized routing required
Islam <i>et al.</i> (2012)	Ultrasonic sensors, GSM communication	Improved overflow prevention and real-time monitoring	Limited cloud analytics support	Need for cloud-integrated smart waste systems
Anagnostopoulos <i>et al.</i> (2017)	IoT sensors, dynamic route optimization	Optimized waste collection routes and reduced fuel consumption	Did not focus on waste segregation	Need for integrated monitoring and segregation system
Malleswari <i>et al.</i> (2020)	Sensor-based waste segregation	Automated separation of wet, dry, and metallic waste	Limited monitoring and scalability	Need for scalable smart segregation framework
Doriya <i>et al.</i> (2020)	Moisture sensors, metal sensors, microcontroller	Automated biodegradable and non-biodegradable waste segregation	Lack of cloud connectivity and AI analytics	Need for IoT-enabled intelligent segregation systems
Perangin Angin <i>et al.</i> (2018)	IoT-enabled smart segregation	Improved recycling efficiency using IoT monitoring	Limited mobile application integration	Need for citizen-centric waste management systems
Huynh <i>et al.</i> (2020)	Deep learning (EfficientNet, ResNet)	Achieved high-accuracy automated waste classification	High computational complexity	Need for lightweight AI models for IoT devices
Wang <i>et al.</i> (2021)	IoT, deep learning, image-based waste classification	Improved waste classification accuracy using deep learning and IoT integration	Focused mainly on waste classification without integrated waste monitoring and notification services	Need for a unified framework integrating monitoring, segregation, and user communication.
Sosunova and Porras (2022)	Systematic review of IoT-based smart waste management systems	Reviewed recent developments in sensing technologies, communication protocols, cloud computing, and intelligent waste management	Identified challenges related to scalability, interoperability, security, and practical deployment	Need for integrated prototype implementations and real-world validation of IoT-enabled waste management systems
Arunkumar <i>et al.</i> (2022)	DT-ELM machine learning model	Enhanced predictive waste analysis in smart cities	Limited real-time deployment	Need for integrated real-time AI-IoT framework
Ramesh <i>et al.</i> (2022)	Arduino, multiple sensors, IoT segregation	Automated segregation of wet, dry, plastic, paper, and metal waste	No predictive analytics integration	Need for AI-driven waste analysis and optimization
Anand <i>et al.</i> (2023)	Ultrasonic, infrared, weight sensors, cloud platform	Real-time waste monitoring and waste composition analysis	Limited mobile application support	Need for citizen interaction and mobile integration
Sneha <i>et al.</i> (2023)	Ultrasonic sensors, smart bin, mobile app	Improved real-time monitoring and user interaction	Lack of AI-based analytics	Need for intelligent decision-making mechanisms
Kishore <i>et al.</i> (2024)	IoT sensors, data analytics	Enhanced automated wet and dry waste segregation	Limited scalability analysis	Need for scalable smart waste infrastructure
Jaison <i>et al.</i> (2024)	Ultrasonic sensors, automated lid system	Improved hygiene and smart waste collection efficiency	No predictive analytics or routing optimization	Need for AI-integrated waste collection framework
Oyerinde <i>et al.</i> (2025)	NodeMCU, ultrasonic sensors, Android app	Real-time monitoring with mobile application integration	No intelligent waste segregation	Need for integrated AI-based segregation system
Nikhilendra <i>et al.</i> (2025)	IoT smart bin monitoring	Prevented overflow through real-time notifications	Lack of predictive analytics	Need for machine learning-based prediction models

(cont'd...)

Table 1. (Continued)

Author & year	Methodology/ technology	Key findings	Limitations	Research gap
Nikam (2025)	IoT sensors, route optimization	Reduced operational cost and fuel consumption	Limited citizen engagement	Need for mobile-based public interaction features
Tadavi <i>et al.</i> (2025)	Smart bins, route optimization algorithms	Improved collection efficiency and reduced pollution	No AI-based predictive analysis	Need for predictive waste forecasting systems
Tee <i>et al.</i> (2025)	Ultrasonic sensors, load cells, IoT	Improved waste level and weight monitoring	Limited sustainability analysis	Need for energy-efficient smart waste systems
Punia (2025)	IoT, edge AI, smart routing	Enhanced operational efficiency and reduced emissions	Complexity and scalability challenges	Need for lightweight scalable edge AI systems
Wafi & Chairulfata (2026)	IoT monitoring, GPS, smart sensors	Achieved high monitoring accuracy and notification reliability	No predictive AI integration	Need for predictive AI-enabled waste monitoring

Abbreviations: AI: Artificial intelligence; CNN: Convolutional neural network; DT-ELM: Decision tree–extreme learning machine; GSM: Global System for Mobile Communications; GPS: Global Positioning System; IoT: Internet of Things.

Based on the literature review, most developed waste management systems support specific features, including monitoring, waste sorting, and route optimization for transportation and collection. Few have explored integrating IoT, AI, cloud technology, and mobile applications into a single system.

Thus, this study aims to develop an intelligent, versatile smart waste management system that can enhance efficiency, improve ecological preservation, and more actively involve citizens.

3. Methodology

This section discusses the methodology used to develop and implement the Garbage Guardian smart waste management system. IoT technology, smart sensors, cloud computing, analytics, and a mobile application were integrated into the proposed model to enhance waste monitoring, segregation, collection, and citizen engagement in urban settings.

The key elements of this methodology are real-time monitoring of waste content, notification sending, intelligent waste segregation, optimized waste collection, and centralized data management. This section covers the overall system design and details the hardware and software tools used, the cloud integration architecture, the experimental setup, and the performance evaluation parameters.

3.1. System-wide architecture

The “Garbage Guardian” is an integrated smart waste

management system for urban areas, based on IoT and a mobile application for waste monitoring, segregation, and collection. It comprises smart bins, sensor networks, cloud infrastructure, mobile applications, and route optimization to enable real-time monitoring of waste content and intelligent waste-collection control. The system architecture comprises four distinct layers: the sensing layer, communication layer, cloud processing layer, and application layer. Figure 1 illustrates the overall architecture of the proposed Garbage Guardian smart waste management system, showing the interaction among the smart waste bins, waste segregation unit, NodeMCU controller, cloud platform, and mobile application.

The sensors used to measure the fill level, ultrasonic sensors and IR sensors, were included in the smart bins, which formed the sensing layer. A wireless connection via NodeMCU served as the communication layer for transmitting sensor data to the cloud. The cloud processing layer handled data storage, analysis, notifications, and route optimization. The application layer included the mobile app, which provides an interface for waste collection monitoring and tracking, as well as for citizens and municipal authorities to report waste issues. The smart waste system enables real-time monitoring and automated notifications for optimal waste collection scheduling and public participation, ultimately increasing operational efficiency and environmental performance.

3.2. Design and development of smart waste bins

Internet of Things-enabled smart waste bins measure

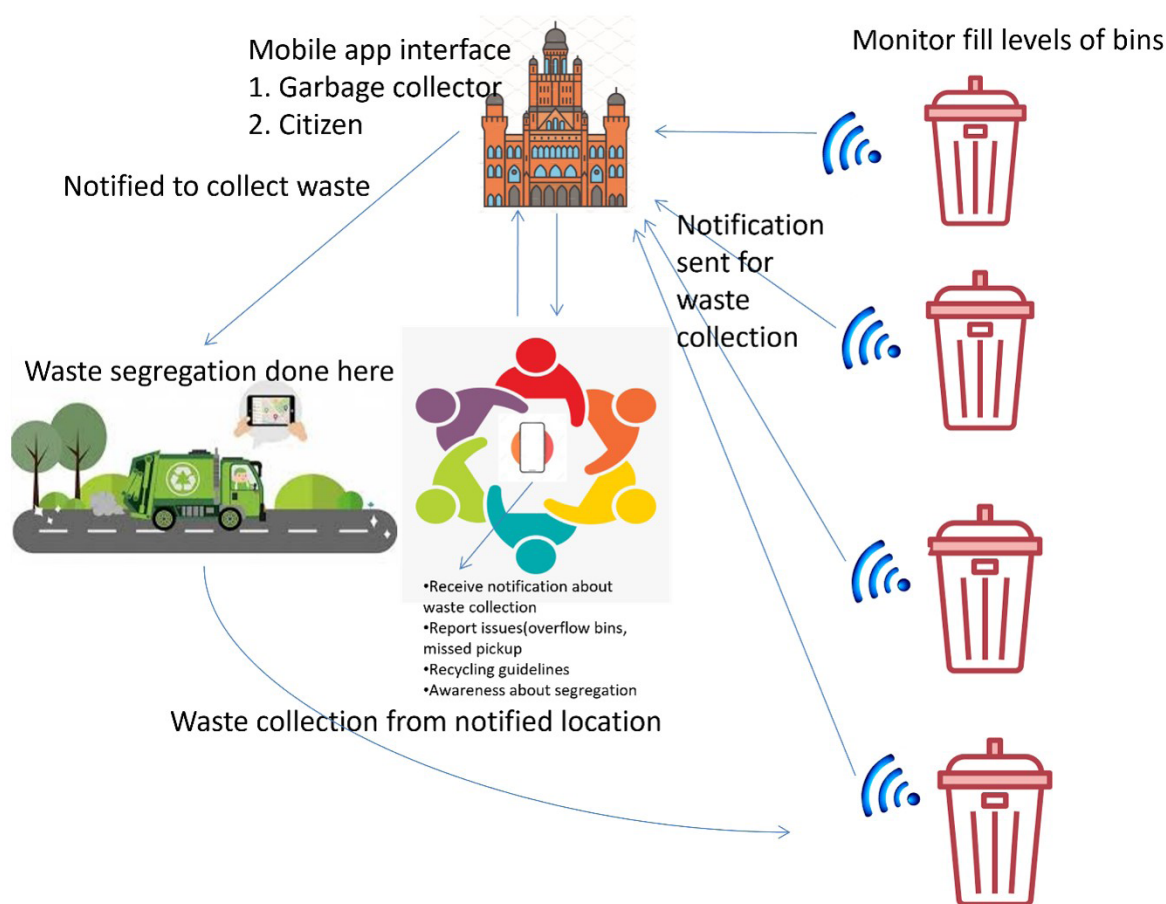


Figure 1. Overall architecture of the proposed Garbage Guardian smart waste management system

waste content and report overflows at any time. Ultrasonic sensors were used to calculate the fill level of the bins. This was conducted by measuring the distance between the sensor and the waste material placed inside. IR sensors were used to sense objects and measure the waste placed inside. The sensor data was processed using the NodeMCU and transmitted to the cloud via a wireless connection. The smart bin reports data in real time.

If the fill level exceeds a threshold, both the cloud server and mobile application send notifications to municipal authorities. Smart waste bins can save time spent checking, improve city cleanliness, and minimize operational delays. The hardware configuration of the smart waste bin integrates sensing, processing, and communication hardware for real-time waste monitoring. The hardware implementation of the proposed Garbage Guardian smart waste bin is based on the circuit configuration shown in Figure 2.

The ultrasonic and IR sensors are connected to the NodeMCU controller for continuous detection of waste

levels and object presence within the bin. The system processes the collected sensor data locally and transmits it to the cloud platform through wireless communication protocols. The detailed electrical connections and interfacing of the sensors with the NodeMCU controller are illustrated in the circuit diagram (Figure 2). The waste monitoring smart system ensures effective waste management in sustainable and smart urban development.

3.3. Smart waste segregation mechanism

The new system was designed to separate waste automatically to improve recycling rates and reduce manual sorting. The waste segregation system is attached to the waste lorry and consists of compartments for separating plastic, metal, paper, wet waste, and dry waste. The system sorts waste during collection using a sensor-based identification system. The segregation process improves recycling quality and reduces mixing of recyclable waste. It also helps reduce manual waste management processes. The waste segregation data can further be used to analyze future planning and management and optimize resources.

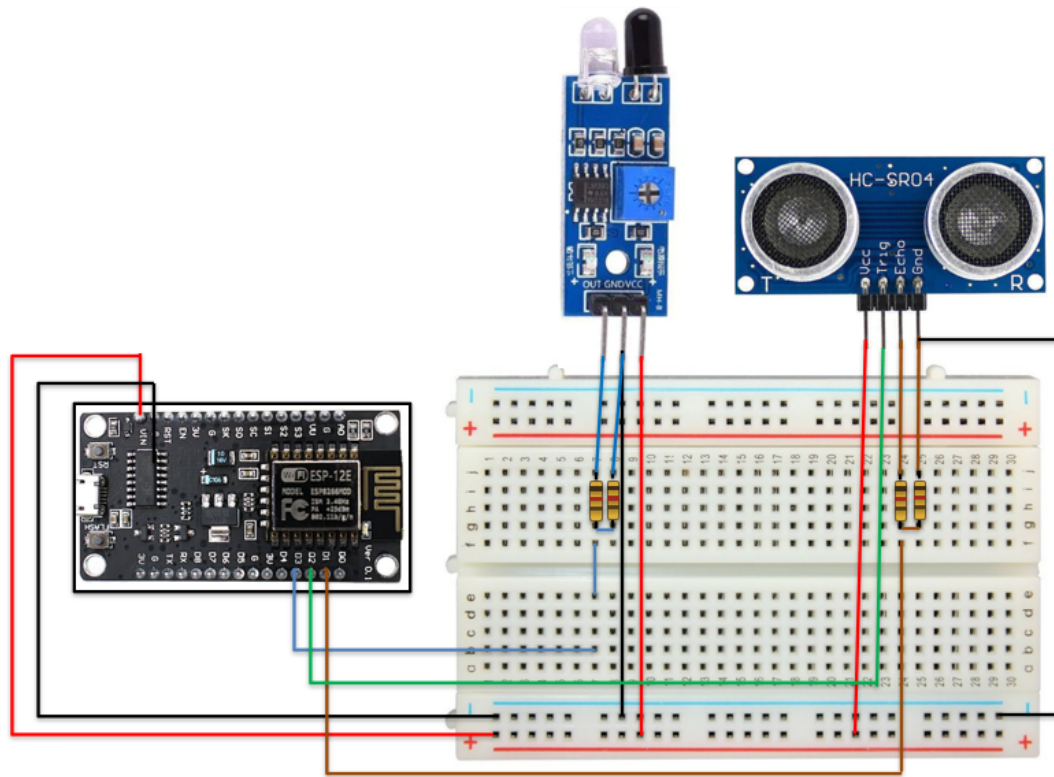


Figure 2. Circuit diagram of the Internet of Things-based smart waste bin. Created using Microsoft PowerPoint.

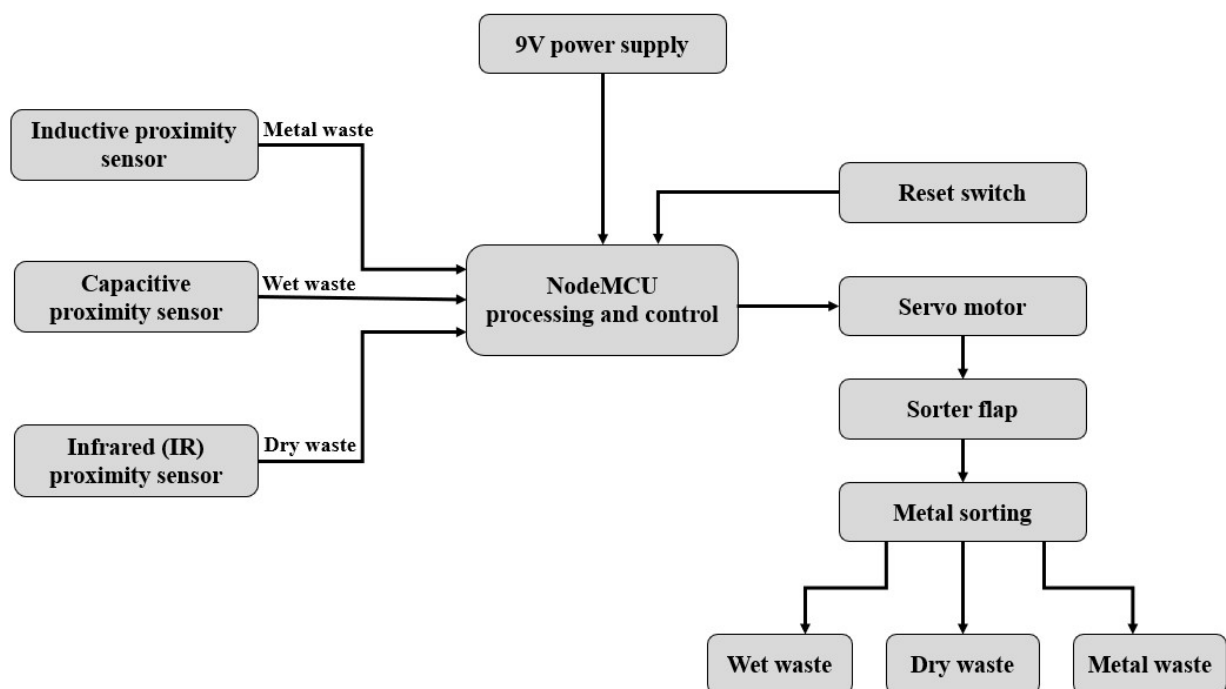


Figure 3. Block diagram of the smart waste segregation unit. Created using Microsoft PowerPoint.

Figure 3 shows the connections between the ultrasonic sensors, NodeMCU controller, power supply, and communication modules, enabling the system to monitor waste in real time and connect to the cloud. The waste segregation mechanism is an integrated, modern system for waste processing and implementing a circular economy.

3.4. Mobile application development

To enable real-time communication and interaction between city officials, garbage collectors, and the general public, we propose a mobile application for Garbage Guardian. This app will serve as a tool for the city to monitor garbage collection activities, provide citizens with updates on collection schedules and registration, facilitate reporting of collection-related complaints, and encourage greater public participation in maintaining a clean and sustainable urban environment.

The mobile app has two main parts: one for citizens and another for garbage collectors. The citizen-facing application will allow citizens to register complaints when they notice overflowing waste bins, track garbage collection activities, receive notifications about collection activities, and receive general waste-awareness alerts and updates on garbage collection activities. The mobile application is designed to enhance citizen participation.

The garbage collector module allows the city and garbage collectors to monitor waste collection activities through their mobile devices and track the current status of every waste collection bin. Waste bin data will also update the mobile app, which will notify the city and garbage collectors whenever any bin exceeds its waste threshold. In addition, garbage collectors will have access to the mobile app dashboard, which will show which bins to empty next and in what order.

The mobile app is also connected to our platform, allowing sensor data from the smart waste bins to update the platform constantly and sync to the mobile app. This enables real-time data, making it easy for city officials and garbage collectors to make appropriate, intelligent decisions about where and when to collect waste. The mobile application interface developed for the proposed Garbage Guardian system is shown in Figure 4.

The mobile app interface includes user registration, real-time bin monitoring and alerts, complaint reporting, and a waste management dashboard. The mobile application interface enables easy, efficient communication between the city and the general public and makes the city's garbage management process more efficient.

Figure 5 shows the garbage collector dashboard, which serves as the control point for real-time oversight

of smart waste collection. The dashboard reports critical system details such as total bins installed, bins flagged for immediate collection, ongoing waste collection, and bin collection history. It includes live bin monitoring on map visualizations, helping local authorities identify high-priority collection areas.

The dashboard also supports optimized route planning, waste collection tracking, and alert notifications to improve collection efficiency and reduce overflowing waste. Real-time monitoring and data visualization improve decision-making, communication, and resource utilization in the Garbage Guardian smart waste management system.

In summary, the proposed system integrates a mobile application to enhance communication, increase citizen engagement in managing the city's waste, monitor and alert the city's waste collection activities on their mobile devices, monitor bin status, and enable more efficient garbage management to reduce and eliminate instances of overflowing waste bins.

3.5. Cloud integration and Internet of Things communication

The system uses cloud computing for data storage, management, and reporting. The sensor data is sent to the cloud platform in real time using the NodeMCU and wireless communication. The cloud server stores all data, including waste level data, collection information, notifications, segregation data, and user information.

The proposed Garbage Guardian system leverages cloud computing and IoT communication for centralized monitoring, data transmission, and intelligent waste management operations. Smart waste bins continuously collect waste level data from ultrasonic and IR sensors, and the NodeMCU controller processes it. The sensors forward the data to the cloud platform via Wi-Fi and MQTT/HTTP.

The cloud platform serves as the system's central data hub. It stores all essential details such as waste levels, bin locations, collection times, notifications, and waste types. By enabling cloud integration, this framework empowers the municipal department to access real-time waste collection data through both the mobile application and the monitoring panel. Furthermore, real-time data synchronization directly from the sensors enhances the overall accuracy and transparency of the system.

The proposed IoT communication framework sends automatic notifications to relevant personnel via the mobile app as soon as waste levels reach the predefined collection limit, helping avert overflow by enabling immediate response. Additionally, the cloud integration framework supports data analysis and route optimization by examining

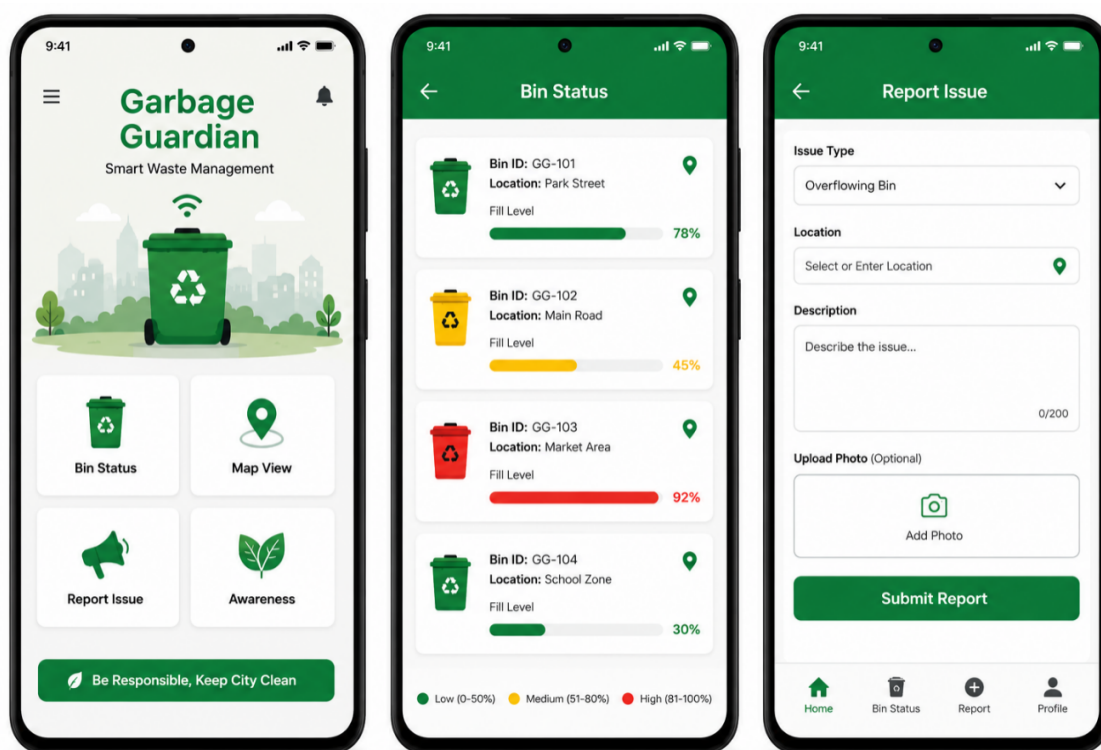


Figure 4. Mobile application interface of the proposed Garbage Guardian system

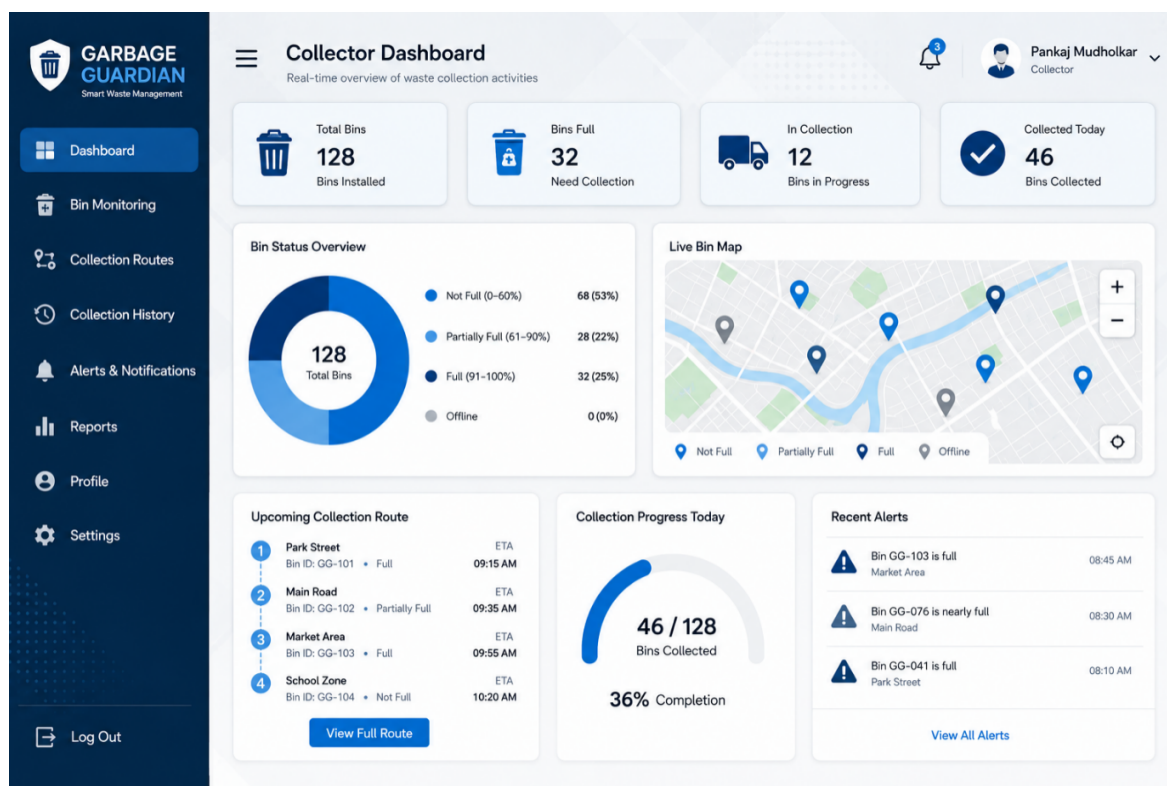


Figure 5. Garbage collector monitoring dashboard

historical and current waste-generation data. This ensures that collection scheduling and resource allocation can be better planned and improved for operational efficiency.

As shown in Figure 6, the proposed IoT communication framework connects smart bins, cloud servers, mobile apps, and the local government via IoT communication protocols. The suggested system enables real-time, secure data communication among components for centralized monitoring, real-time alerts, and efficient waste management. The use of IoT and cloud framework improves the scalability, accessibility, and sustainability of the proposed Garbage Guardian system.

The proposed approach was implemented by developing the Garbage Guardian framework, comprising the smart waste bin unit, waste segregation unit, mobile application, and a cloud-based, IoT-enabled communication system.

The developed framework was then tested through experimental evaluations to ensure functionalities such as waste monitoring, data transmission, notification generation, and waste segregation support.

4. Experimental study and performance evaluation

An experimental study was conducted to verify the

effectiveness and practicality of the proposed Garbage Guardian smart waste management framework. The proposed smart waste management solution consists of smart waste segregation, IoT-based smart bins, a mobile application, and cloud computing.

The developed system comprises ultrasonic and IR sensors, a NodeMCU-based embedded processor, Wi-Fi, cloud services, and a mobile application.

The smart bins were used to identify waste levels in smart waste collection, and the waste level sensing data was transmitted to the cloud platform through wireless communication. The IoT system collected data from the waste level sensor, processed it, and generated notifications when the waste level exceeded a predetermined set point. A mobile application was designed to support smart waste management and enable authorities and collection workers to monitor smart waste and waste overflow notifications.

4.1. Experimental setup and evaluation procedure

The primary purpose of building the Garbage Guardian prototype was to recreate a smart garbage bin environment and examine the interplay among the sensor, processing, communication, and mobile application layers of the proposed system. The sensor readings were collected from

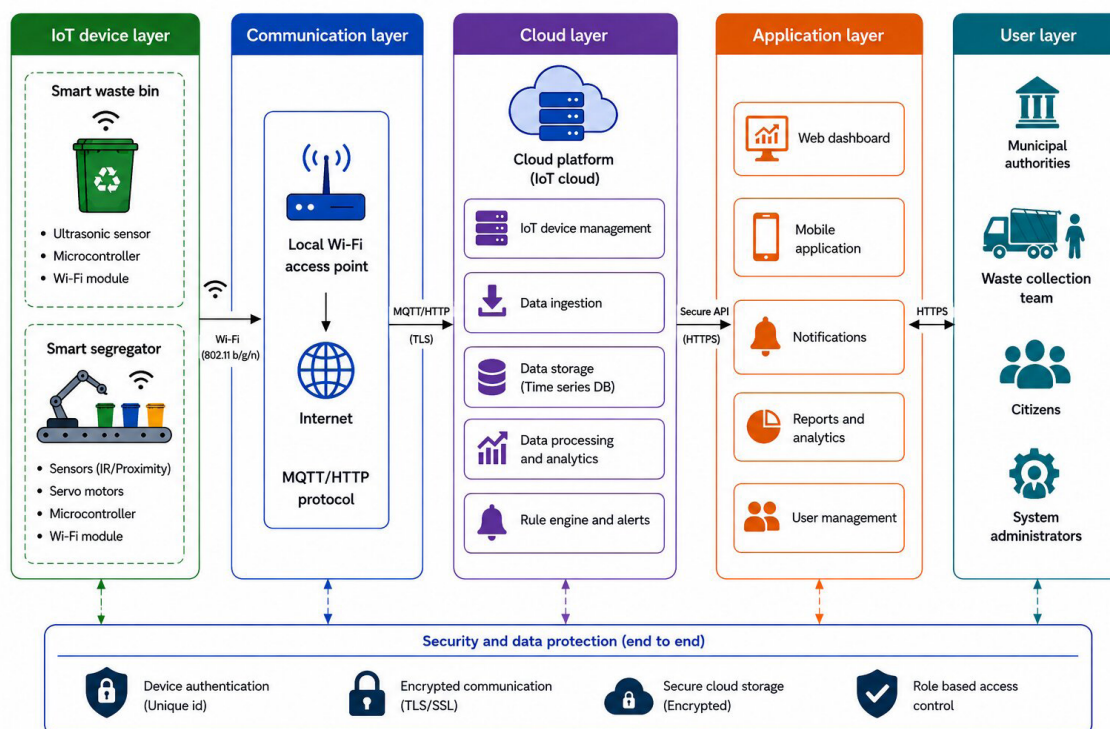


Figure 6. Internet of Things communication and cloud integration. Created using Microsoft PowerPoint.

the smart waste bin. The collected data was processed by the NodeMCU board and transmitted over a Wi-Fi communication channel to the cloud. The retrieved information was stored in the database, which can be accessed and viewed through the Garbage Guardian mobile application. The application also generated alerts when the garbage bin approached its maximum filling capacity. The results were recorded to analyze the system's performance against its functionalities.

To assess the developed system, several tests were carried out in two phases. At first, each module was verified, and then the complete system was evaluated to assess the functional requirements. The performance analysis was based on several parameters: waste level detection, notification latency, IoT communication connectivity, cloud connectivity, and waste segregation. The sensor module was tested by detecting waste levels at different garbage fill percentages in the waste bin. The communication module was tested for cloud connectivity by transmitting sensor readings. The mobile application was evaluated for data availability and alert generation, while the cloud database was verified for storing data and generating notifications and alerts to the users through

the application. Waste segregation was also evaluated for different waste categories, and the corresponding results were recorded.

The developed Garbage Guardian system and its experimental setup are shown in Figure 7. The system consists of a smart waste bin integrated with sensor modules, a processing unit, and a cloud interface for remote communication and monitoring.

The experimental analysis was implemented to evaluate the proposed system in a controlled environment using smart bins. Sensor readings were obtained and verified to confirm the accuracy of waste level detection and connectivity between the hardware and software platforms. To verify the proposed smart system, waste level detection, response time for notifications, segregation effectiveness, and route optimization were evaluated using the variables shown in Table 2.

To validate waste level detection accuracy, we compared the measured waste level with the waste level sensed by the sensors under different operating conditions. Table 3 shows the detection performance, where the ultrasonic sensor demonstrated accurate waste level identification in

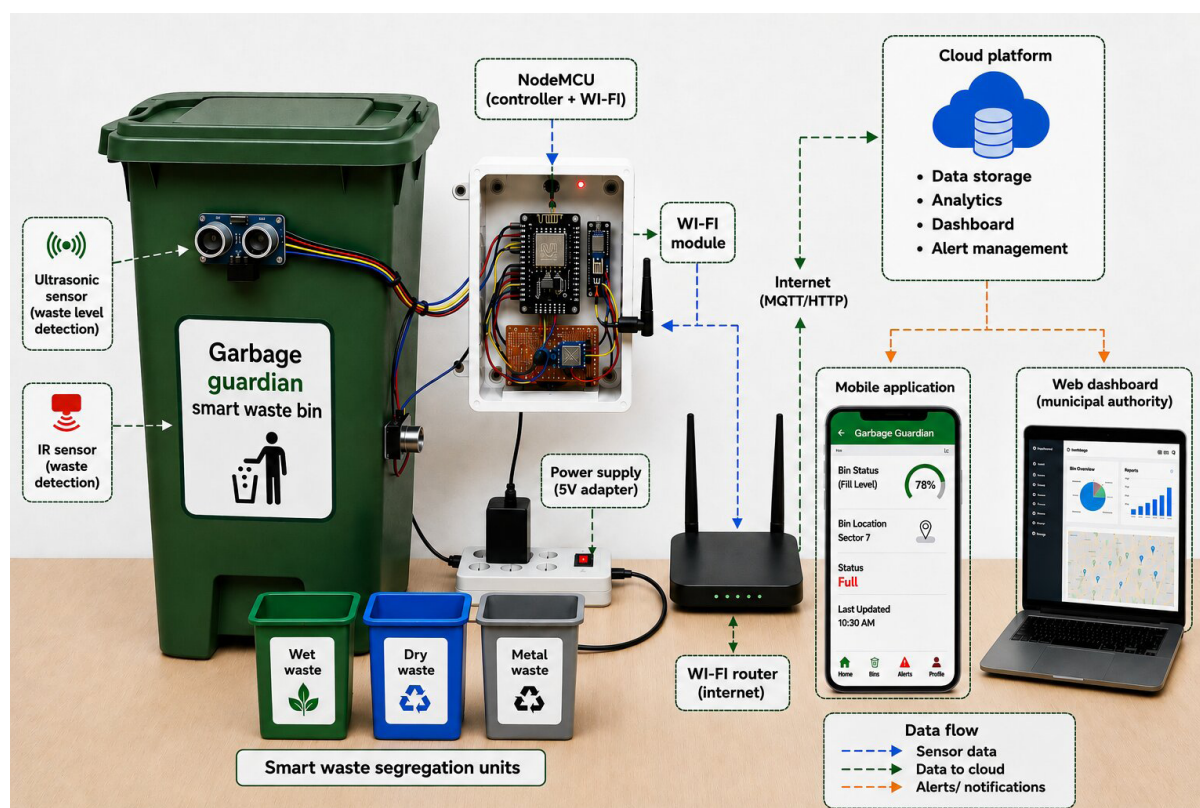


Figure 7. Experimental setup of the proposed Garbage Guardian system. Created using Microsoft PowerPoint.

smart waste collection bins.

Table 2. Experimental parameters used for performance evaluation

Parameter	Description
Waste level detection accuracy	Accuracy of sensor-based waste level monitoring
Notification response time	Time required for alert generation
Waste segregation accuracy	Accuracy of waste classification process
Cloud communication efficiency	Reliability of Internet of Things data transmission

The experimental setup was used to evaluate the developed system's performance under laboratory conditions. The values presented in the subsequent tables and graphs were obtained from the functional evaluation of the developed system. These values indicate the performance of the implemented Garbage Guardian framework and are intended to demonstrate its functional feasibility rather than provide a statistically robust analysis.

Table 3 shows the results of the experimental evaluation of the proposed IoT-based smart waste monitoring system for different waste levels in the bin. The proposed system detected the waste level with 95% to 99% accuracy across different levels. The comparison between the actual and detected waste levels across different conditions indicates that the proposed system measures waste levels with very little deviation from the actual value. The difference between the actual and detected waste levels depends on the waste arrangement in the container, surface irregularities, and the position where the waste is placed inside the bin.

Table 3. Waste level detection analysis

Actual waste level (%)	Detected waste level (%)	Detection accuracy (%)
20	19	95
40	39	97
60	59	98
80	79	98
100	99	99

The experimental results show that the sensing mechanism reliably monitors waste levels, providing

real-time waste status and indicating the feasibility of the proposed system for smart waste monitoring applications.

Figure 8 shows the actual and detected waste levels under different experimental conditions. It shows that the detected waste level is very close to the actual waste level, indicating the accuracy of the ultrasonic sensor-based system in monitoring waste levels under different experimental conditions. The experimental evaluation shows that the proposed waste level measurement mechanism is accurate enough for real-time waste level monitoring.

Figure 9 shows the waste level detection accuracy of the proposed smart waste monitoring system at different waste levels. The results show that the waste level detection accuracy of the proposed IoT-based smart waste monitoring system varied from 95% to 99%, indicating stable and accurate system performance. The detection accuracy results show that the proposed system performed better as waste levels increased. This demonstrates that the proposed IoT-enabled waste monitoring system effectively detects waste levels in real time and supports smart waste management applications.

The results confirm that the developed system accurately monitors waste levels and generates timely notifications before overflow. The developed sensor-based monitoring system supports waste collection by improving collection performance and reducing unnecessary checks. To assess notification performance, we analyzed the proposed system's response time to evaluate cloud connectivity and mobile application integration. The system's response time was measured as the time elapsed from when the threshold level is reached to when the notification is delivered to the collector. The results are listed in Table 4.

Table 4. Notification response time analysis

Trial	Threshold detection time (s)	Notification received time (s)	Response time (s)
1	2.1	3.0	0.9
2	2.3	3.2	0.9
3	2.0	2.8	0.8
4	2.4	3.4	1.0
5	2.2	3.1	0.9

Table 4 shows the outcome of the experiment conducted to assess the notification efficiency of the proposed mechanism, i.e., how long it takes the system to notify the user when it detects waste levels beyond threshold limits.

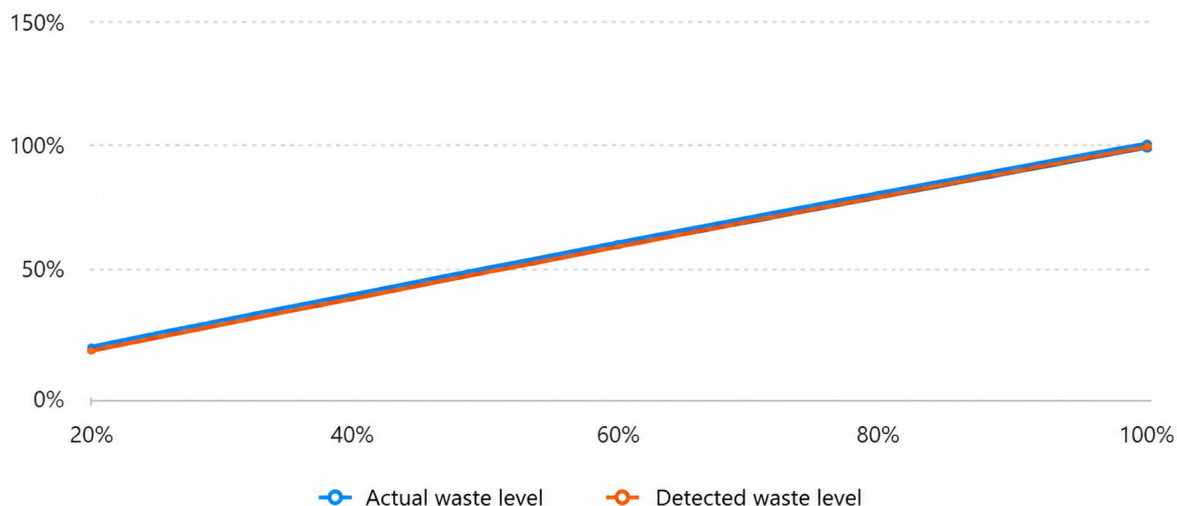


Figure 8. Comparative analysis of actual and detected waste levels

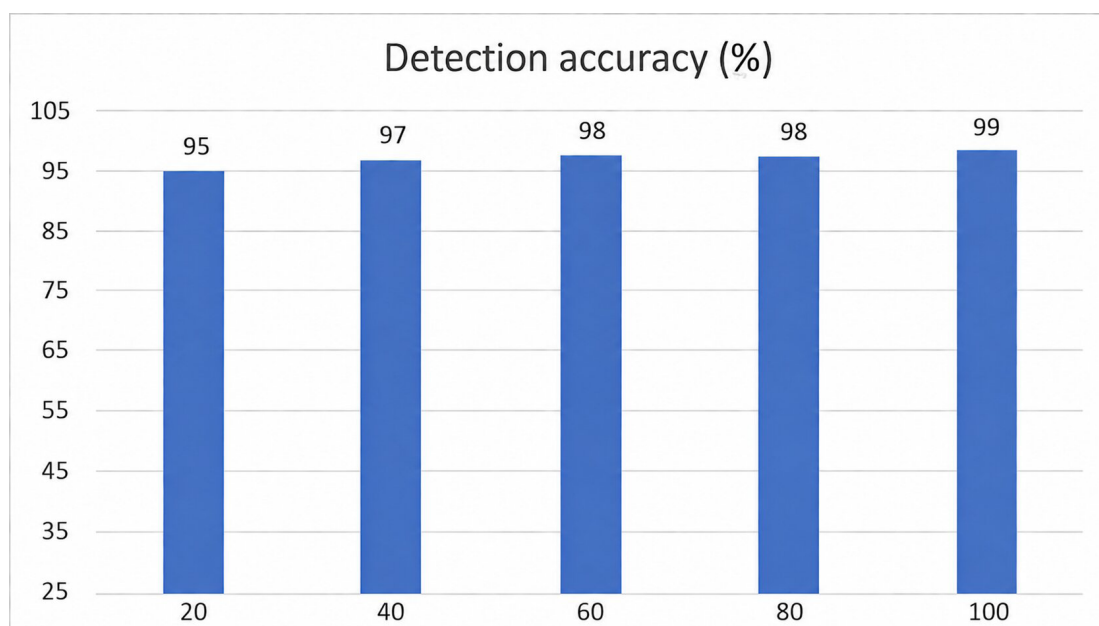


Figure 9. Waste level detection accuracy

This shows that the system takes between 0.8 s and 1 s to send notifications, indicating that the system is working properly. The notification response time results presented in Table 4 are graphically represented in Figure 10.

The graph also shows that the system takes the same time (0.8–1 s) to send notifications even with multiple notifications, demonstrating the suitability of the proposed IoT notification system for real-time waste monitoring in the smart city.

The performance analysis confirms that the IoT-enabled

smart cloud system generates real-time notifications with minimal delay. Developing a mobile application is an effective tool for monitoring and improving response time. A waste segregation performance study was conducted to confirm waste segregation accuracy and the separation of plastic, metal, paper, wet, and dry waste from mixed trash. Waste separation efficiency was evaluated as the ratio of separated materials to the total number of materials in the waste mixture. The following formula (Equation 1) was used to measure waste separation efficiency:

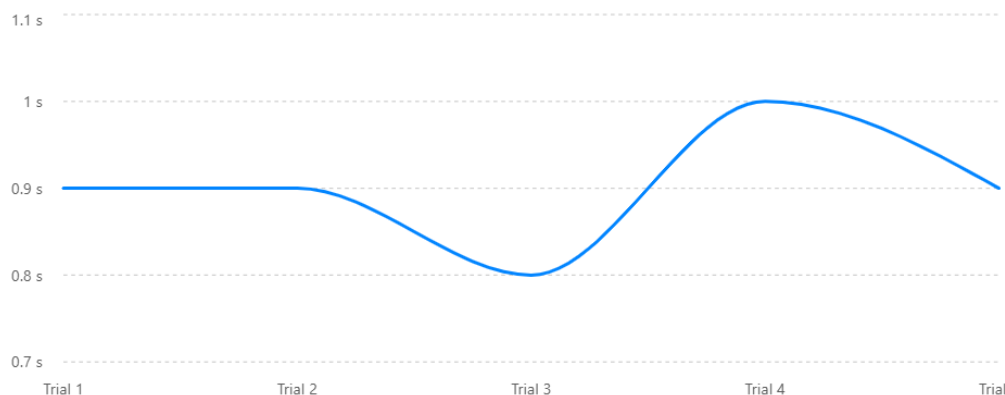


Figure 10. Notification response time graph

$$\text{Segregation accuracy (\%)} = \left(\frac{\text{Correctly segregated waste items}}{\text{Total waste items processed}} \right) \times 100 \quad (1)$$

Table 5 shows the results of experiments testing the accuracy of the proposed mechanism in segregating waste into different categories, such as plastic waste, metal, paper, wet waste, and dry waste. The results show 94% to 97% segregation accuracy across the categories.

Table 5. Waste segregation accuracy analysis

Waste category	Segregation accuracy (%)
Plastic	96
Metal	95
Paper	94
Wet waste	97
Dry waste	96

For plastic waste, the highest segregation accuracy was obtained because the plastic material has a unique sensing capability. However, segregation accuracy for wet waste was slightly lower because the waste's wetness varied.

Figure 11 shows the segregation accuracy for different waste categories. The results indicate very high segregation accuracy for each waste category; therefore, the smart waste segregation mechanism proposed in the paper is effective and useful.

The operational performance of the proposed waste segregation mechanism was evaluated under controlled laboratory conditions. The assessment was carried out to verify the ability of the proposed mechanism to identify representative waste types and perform the segregation process accordingly. Furthermore, the evaluation validates the operational behavior of the developed system and its suitability for integration with the IoT-based smart waste management framework. Table 6 presents the results of the experimental evaluation of the waste segregation mechanism.

Table 6. Functional validation of the proposed waste segregation mechanism

Waste category	Detection by sensor	Segregation status	Functional validation
Wet waste	Successful	Successful	Validated
Dry waste	Successful	Successful	Validated
Metallic waste	Successful	Successful	Validated

Based on the results, the representative wastes were detected, and the segregation mechanism worked as intended. The sensing and controlling mechanism could support the segregation purpose of the proposed mechanism and the IoT-based smart waste management.

The present study evaluated the proposed waste segregation mechanism only at the prototype level. However, the obtained results demonstrate its capability to support waste segregation in IoT-based smart waste

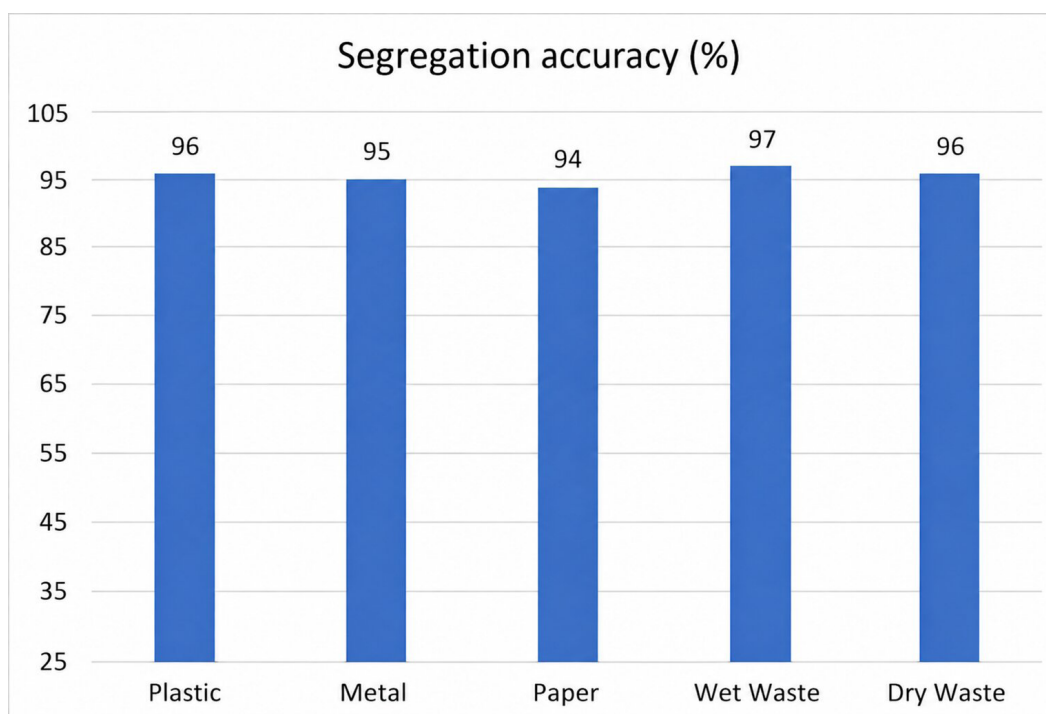


Figure 11. Waste segregation accuracy analysis for different waste categories

management systems. Future work should evaluate the mechanism under large-scale deployment and realistic operational conditions to further validate its effectiveness and scalability.

5. Conclusion

This study developed Garbage Guardian, a smart waste management solution that uses IoT technology to combine smart waste bins, real-time sensor monitoring, NodeMCU-powered control, and cloud integration with a mobile app. The system enables automated collection of waste level data, real-time notifications, live cloud data sharing, and support for waste segregation at the source.

In this study, Garbage Guardian was evaluated using experimental results, and the functionality and efficiency of the developed system and proposed framework were discussed. The experimental results for waste level monitoring show that ultrasonic sensor-based monitoring is accurate, and the detected values were close to the actual values with only a small difference. The notification mechanism results indicate that the framework can send notifications based on the information provided, and with the integration of IoT and cloud services, it can enable real-time monitoring through the mobile application. The experimental waste segregation evaluation demonstrated the applicability and potential of implementing the

proposed framework for supporting waste segregation in IoT-based waste management. The results indicate that the developed Garbage Guardian IoT-based smart waste management framework can provide an effective solution for real-time waste level monitoring and waste management activities.

However, the present study has several limitations. The developed framework was evaluated under controlled conditions, and further validation is required for large-scale deployment in real municipal waste collection environments. Real-world scenarios should also examine variations in waste composition, environmental conditions, network connectivity, and long-term reliability.

Future work should focus on large-scale implementation of the framework in real environments, integrating a global positioning system-based waste collection vehicle tracking system, implementing advanced data analytics to predict waste generation, improving the waste segregation system, and investigating the scalability of the proposed solution for a large-scale smart city.

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Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

All data analyzed have been presented in the paper.

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