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Real-time smart waste monitoring using IoT technologies

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Abstract. In many developing regions, traditional waste management methods face persistent challenges, such as fixed collection schedules, overflowing bins, environmental pollution, and high operational costs. To address these issues, this study presents a smart waste management system (SWMS) that uses Internet of Things (IoT) technologies for real-time monitoring and data-driven decision support. The system integrates an ESP32 microcontroller, an ultrasonic sensor, a global system for mobile communications (GSM) module, and a custom Android application. Three prototype bins were evaluated through 150 sensing trials. The sensing subsystem achieved an overall mean absolute error (MAE) of 1.35 percentage points and a root mean square error (RMSE) of 2.12 percentage points. One GSM data-transmission attempt accompanied each sensing trial, giving 150 transmission attempts, while 31 measured observations met or exceeded the 80% alert threshold and initiated short message service (SMS) alerts. Location-level GSM measurements produced observed AT+CSQ signal-quality values of 8.70, 14.00, and 18.92 for the indoor laboratory, corridor/entrance, and semi-outdoor locations, corresponding to approximate received signal strength indicator (RSSI) values of -95.6, -85.0, and -75.2 dBm, respectively. The mean application response time was 1.43 ± 0.31 s. Because packet-level acknowledgement outcomes and independent SMS delivery receipts were not retained, no retrospective transmission success or SMS delivery percentages are claimed. The results support the practical use of the prototype for waste-bin monitoring and threshold-based alerting under the tested conditions, particularly in settings where continuous Wi-Fi connectivity may not be available.

Keywords: Internet of Things (IoT), smart waste management, embedded systems, mobile app, real-time data monitoring, GSM-based communication, ultrasonic sensor, ESP32 microcontroller

1. Introduction

Growing urbanisation, rising populations, and expanding industrial activities have made solid waste management an increasingly urgent global concern [1]. Currently, the world generates an estimated 2.01 billion metric tonnes of waste each year, and this figure is expected to increase significantly by 2050 [17]. In many regions, inadequate waste management practices, including open dumping, poorly maintained landfills, and irregular collection schedules, continue to pose serious risks to both the environment and public health. These practices contribute to air and water pollution, greenhouse gas emissions, and the spread of diseases. They also increase the likelihood of urban flooding by blocking drainage systems [16]. Traditional waste management systems often depend heavily on manual supervision and fixed collection schedules. Such approaches frequently lead to missed pickups, overflowing bins, and inefficient use of both labour and fuel [12]. These operational challenges highlight the limitations of conventional methods and underscore the need for modern waste management solutions that enable real-time monitoring and data-driven decision-making [4].

Smart waste management systems that combine automation with Internet of Things (IoT) technologies have emerged as a practical alternative to traditional waste-handling methods. By using sensor-equipped bins, waste levels can be monitored continuously, making it easier for collection authorities to plan routes and schedules more efficiently [3, 9]. Beyond this, recent research shows that the field is increasingly influenced by artificial intelligence (AI), connected sensing, and digi-

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tal monitoring systems that enable more responsive and data-driven waste services [14]. Earlier prototype-based studies also demonstrated that IoT-enabled waste monitoring can be implemented successfully in real operating environments [11]. More recent work on embedded monitoring platforms has further shown that compact controllers such as the ESP32 are well suited for practical smart-system applications [6].

Recent studies also indicate that smart waste monitoring has progressed far beyond basic bin-level sensing. Systematic and bibliometric reviews have documented the rapid expansion of this research area while pointing to ongoing challenges, including poor interoperability, limited deployment readiness, a lack of standardisation, and difficulty moving from prototype systems to routine waste-management practice [2, 5, 20]. On the implementation side, several IoT-based solutions now combine sensing with cloud services, geolocation, low-power wide-area network (LPWAN) communication, and multi-platform monitoring frameworks to improve system visibility and support better collection planning [8]. Other studies have explored real-time garbage-level monitoring using alternative sensing methods, including time-of-flight technology, together with IoT-driven data pipelines for urban waste oversight [15].

At the same time, recent contributions have expanded the scope of smart waste management to include route optimisation, machine-learning-assisted decision-making, proactive servicing, and automated waste classification. For instance, review-based evidence suggests that IoT-supported route optimisation can significantly improve collection efficiency and reduce travel distance [13]. Related applied studies have introduced machine-learning-guided models for smart-city waste monitoring and optimisation [10], intelligent campus-scale waste-monitoring systems [19], and proactive IoT and machine-learning frameworks designed to predict service needs before bins overflow [18]. In addition, the broader literature has increasingly incorporated AI-driven waste classification into larger automation strategies aimed at improving urban sustainability [7].

Even though these studies demonstrate the value and increasing maturity of IoT-based waste management, many recent solutions rely on extensive cloud integration, route-optimisation frameworks, AI-based classification tools, or other relatively complex infrastructure layers [2, 7, 8, 10, 13, 18, 19]. Such architectures may introduce additional implementation and maintenance demands, particularly where connectivity and technical support are constrained. There is therefore value in examining simpler smart waste-monitoring configurations for settings with weak or intermittent Wi-Fi, while limiting claims about cost, energy use, scalability, and service efficiency to quantities that have been directly evaluated.

Against this background, the present study focuses on developing a practical smart waste management system for environments with limited digital infrastructure. The system integrates an ESP32 microcontroller, an ultrasonic sensor for measuring fill level, a global system for mobile communications (GSM) module for wireless communication, and a mobile application for real-time monitoring and alert notification. The contribution of the study lies not in proposing a fundamentally new sensing principle or algorithmic framework, but in demonstrating how established IoT components can be integrated into a deployment-oriented system for real-time waste supervision under the tested conditions. Accordingly, the paper provides a detailed description of the system hardware architecture, circuit configuration, mobile application design, and performance evaluation.

2. Materials and methods

2.1. System overview

The proposed smart waste management system was designed to support more responsive waste collection and enable real-time monitoring of waste accumulation. The system's Internet of Things framework integrates sensing, data processing, wireless communication, and user interaction through a mobile application. Waste-level information is gathered from smart bins, processed locally by an embedded controller, and transmitted wirelessly to a remote platform for access by authorised users. The primary objectives are to provide timely bin-status information, support threshold-based

collection prioritisation, and reduce the risk of unnoticed bin overflow.

2.2. Hardware components

The system's hardware architecture consists of an embedded microcontroller, sensing components, a communication module, and a power supply. The ESP32 microcontroller serves as the central control unit due to its compatibility with Internet of Things applications, integrated processing capabilities, and support for embedded communication interfaces. To determine the fill level of the waste bin, an ultrasonic sensor measures the distance between the sensor and the waste surface. This non-contact approach was selected because it is straightforward to integrate with the prototype and well suited to solid-waste-level monitoring.

2.3. System architecture and data flow

The overall system is structured into three interconnected layers, namely the sensing layer, the processing and communication layer, and the application layer. Within the sensing layer, an ultrasonic sensor periodically measures the distance to the waste surface. These measurements are received by the ESP32 microcontroller, where they are processed and converted into corresponding waste fill-level percentages.

The processing and communication layer handles the transfer of processed fill-level data from the ESP32 to the GSM module via the serial communication interface. The GSM module then uses the cellular network to relay the data to the remote server/platform. The mobile application obtains the current bin status from that remote platform. When the predefined fill threshold is reached, the GSM module also sends a short message service (SMS) alert to the assigned operator over the cellular network.

This communication path is infrastructure-mediated rather than a direct wireless link between the bin and the mobile device. Consequently, the approximately 50–120 m separation between campus test sites represents only the physical spacing of the evaluation locations and must not be interpreted as GSM communication range. Cellular coverage and radio conditions can affect registration time, data-transfer delay, and message delivery. The three sites also differed in surrounding structures (indoor laboratory, corridor entrance, and semi-outdoor walkway), but the influence of physical obstruction was not isolated as a separate controlled factor. GSM signal quality was characterised using the modem's AT+CSQ command, which returns a cellular signal quality (CSQ) index. The observed CSQ values were 8.70, 14.00, and 18.92 at the indoor laboratory, corridor/entrance, and semi-outdoor locations, respectively. For the reported CSQ range, approximate received signal strength indicator (RSSI) values were obtained using $\text{RSSI (dBm)} = 2\,\text{CSQ} - 113$, giving -95.6, -85.0, and -75.2 dBm, respectively. Per-attempt signal values, packet-level acknowledgement outcomes, and a dedicated retransmission/fault-handling evaluation were not retained.

At the application layer, a mobile application retrieves the transmitted data from the server and presents users with the waste bin's current status. This allows waste management personnel to make prompt and informed collection decisions. Figure 1 illustrates the overall architecture of the proposed smart waste management system and highlights the interaction between the sensing unit, embedded controller, communication module, and mobile application.

2.4. Circuit design and working principle

The circuit design integrates the ESP32 microcontroller with the ultrasonic sensor, GSM module, and power supply into a unified system. The ultrasonic sensor is connected to the microcontroller through dedicated trigger and echo pins, allowing precise timing measurements. By calculating the time interval between the emission of the ultrasonic pulse and the reception of the reflected signal, the system determines the distance to the waste surface.

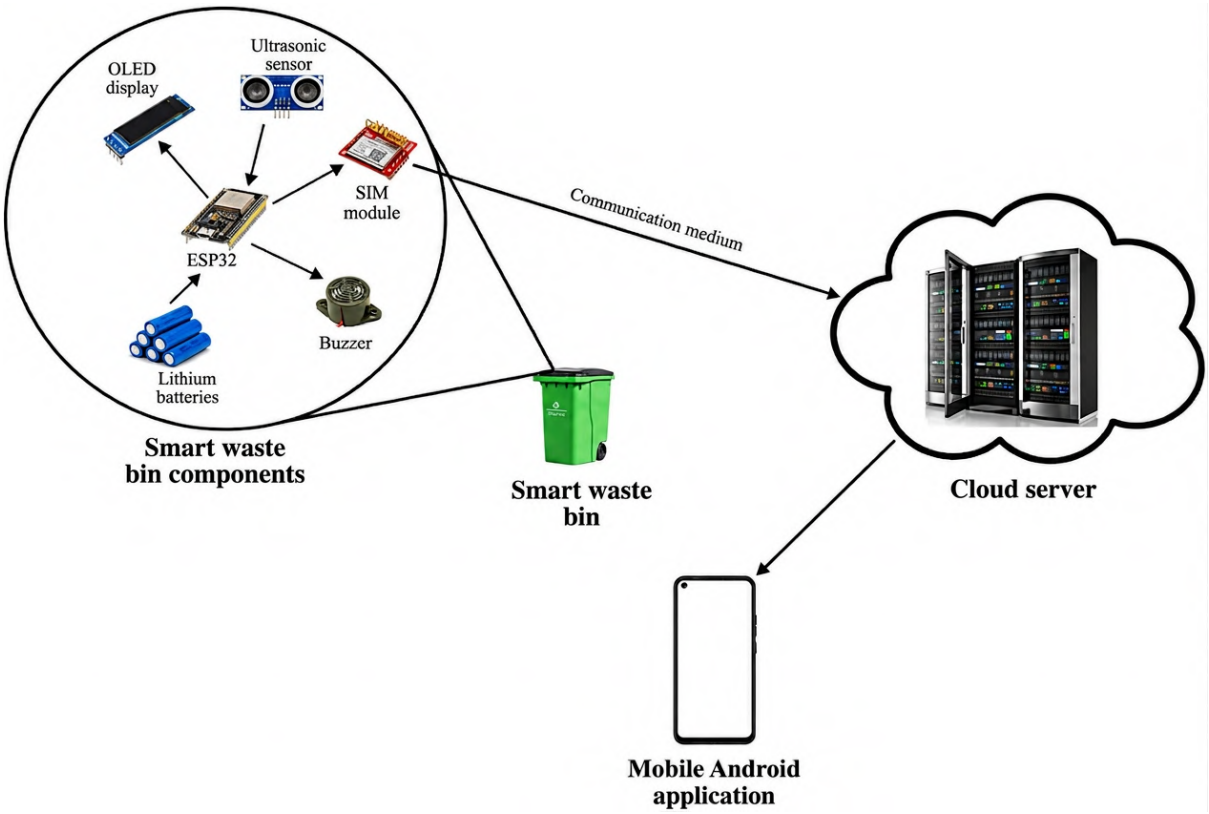


Figure 1: System architecture of the smart waste management system.

Figure 2 presents the complete circuit configuration and illustrates how the ultrasonic sensor and GSM module interface with the ESP32 microcontroller. Communication between the microcontroller and the GSM module is achieved through serial interfaces that use standard AT command sets. Once the waste level data has been processed, the microcontroller transmits the information via the GSM module. If the measured waste level exceeds the predefined threshold values, the system automatically sends notification messages to the appropriate waste management authorities.

2.5. Software and mobile application development

The system software consists of the embedded firmware running on the ESP32 microcontroller and a mobile application developed for user interaction. The embedded firmware handles sensor data acquisition, computes waste fill levels, evaluates threshold conditions, and manages communication.

The mobile application provides real-time visualisation of the waste bin status, allowing users to monitor fill levels and receive alert notifications. Figure 3 presents the main user interface of the mobile application for real-time waste bin monitoring. The application is designed to be intuitive and easy to operate, enabling waste management personnel to use it effectively without requiring extensive technical knowledge.

2.6. Hardware prototype and physical implementation

A physical prototype of the smart waste management system was developed to validate the proposed design. Initially, the hardware components were assembled to reflect a real-world implementation of the system, as illustrated in figure 4. These components were subsequently integrated into a standard waste bin to form a fully functional smart bin. The ultrasonic sensor was mounted on the inner top section of the bin lid, allowing it to accurately measure the waste level regardless of how the waste was arranged inside the bin.

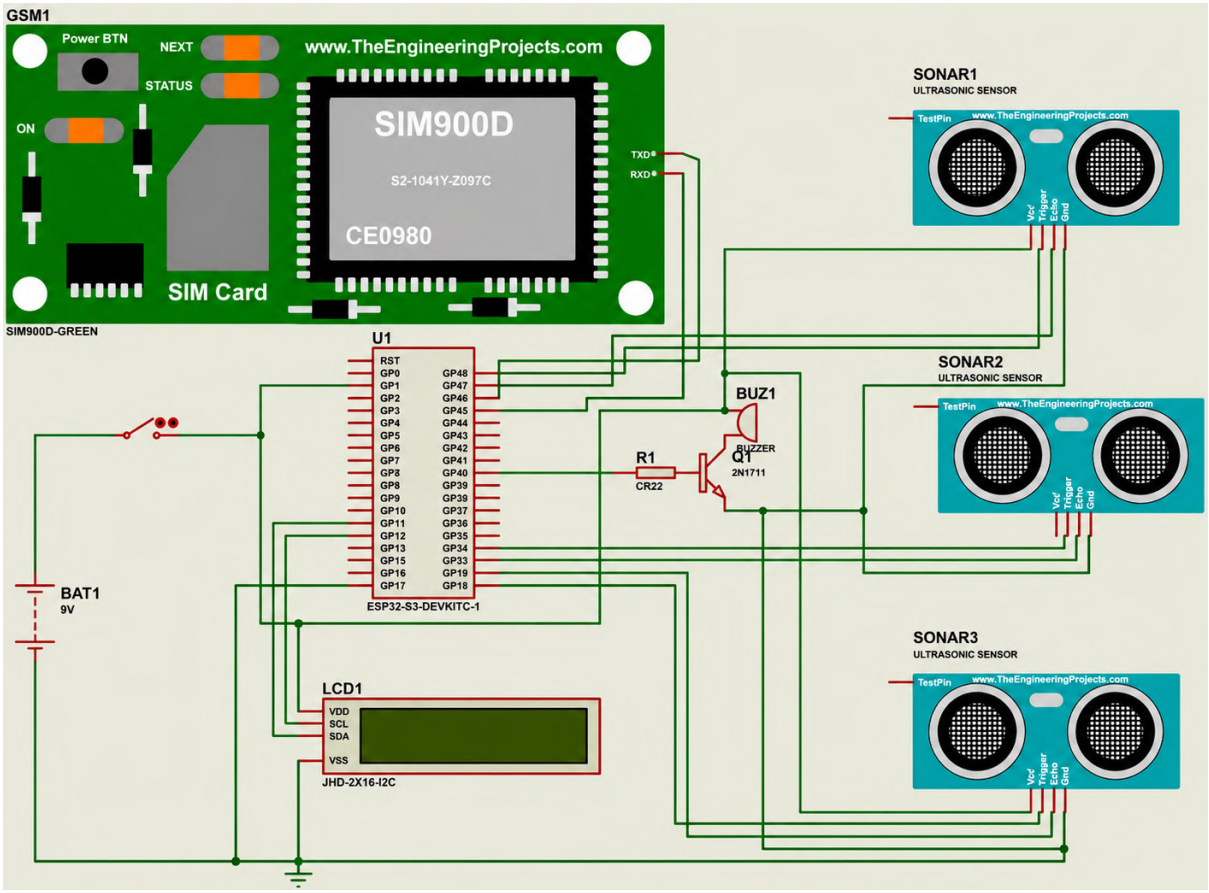


Figure 2: Circuit schematic diagram.

The ESP32 microcontroller and GSM communication module were housed in a protective enclosure attached to the exterior of the waste bin. This enclosure shielded the components from exposure to water, dust, and potential mechanical damage. Power sources and signal wiring were carefully arranged to ensure stable and reliable system operation. Prior to deployment, all system components were thoroughly integrated and tested to confirm correct functionality. The completed smart waste bin prototype, shown in figure 5, confirms that the selected components could be integrated into a functioning smart-bin system under the tested conditions.

3. Results

3.1. Experimental setup and system testing

The developed smart waste management system was evaluated through a series of functional and performance tests carried out under controlled conditions designed to reflect practical operating conditions as closely as possible. To ensure transparency and ease of reproducibility, the experimental conditions, test settings, and evaluation criteria were clearly defined before testing began. The main features of the experimental setup and the evaluation protocol are summarised in table 1.

Three identical smart-bin prototypes were used throughout the study. Each bin had a height of 48 cm and a top opening measuring 34 cm × 28 cm. In the empty condition, the effective sensing depth from the face of the ultrasonic sensor to the bottom of the bin was 42 cm. In all three units, the sensor was mounted centrally beneath the lid at approximately 2.5 cm below the lid surface. To ensure consistency across the evaluation, the same ESP32 microcontroller, GSM module, and power configuration were used in each prototype.

The system was assessed using four principal performance indicators: fill-level detection accuracy,

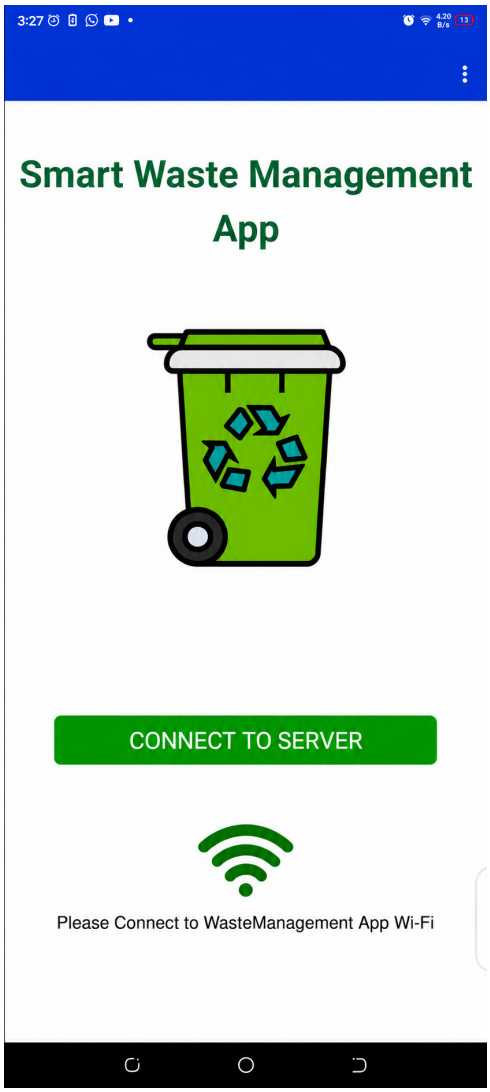


Figure 3: Main mobile application interface.

observed GSM communication behaviour, mobile application response time, and SMS alert operation. For the sensing evaluation, each prototype was tested at five reference fill states corresponding to 0%, 25%, 50%, 75%, and 100% of the usable sensing span. Ten readings were recorded at each reference state for each of the three prototypes, giving 150 measured sensing observations in total. For statistical processing, the recorded distance values were converted to normalised fill percentage relative to the calibrated empty-to-full sensing span. Small endpoint excursions caused by measurement noise were bounded to the physically meaningful 0–100% fill interval before error statistics were calculated. At each reference level ($n = 30$), the mean, standard deviation (SD), and two-sided 95% confidence interval (CI) based on the Student's t distribution were computed. Overall mean absolute error (MAE) and root mean square error (RMSE) were calculated over all 150 trials.

Because waste rarely settles in a perfectly uniform manner during normal use, the three prototype units were assigned different waste-surface conditions to examine measurement behaviour under increasingly irregular reflecting surfaces. Prototype 1 was evaluated on a flat, compact surface made from stacked paper and carton sheets. Prototype 2 used irregular mixed dry waste, including crumpled paper, nylon, plastic containers, and food packs. Prototype 3 used soft irregular waste composed of fabric pieces and compressible packaging materials. Each assigned surface condition therefore contributed 50 readings (five fill states × ten repeated readings). Since surface category and prototype identity were not independently randomised, the between-condition comparison is

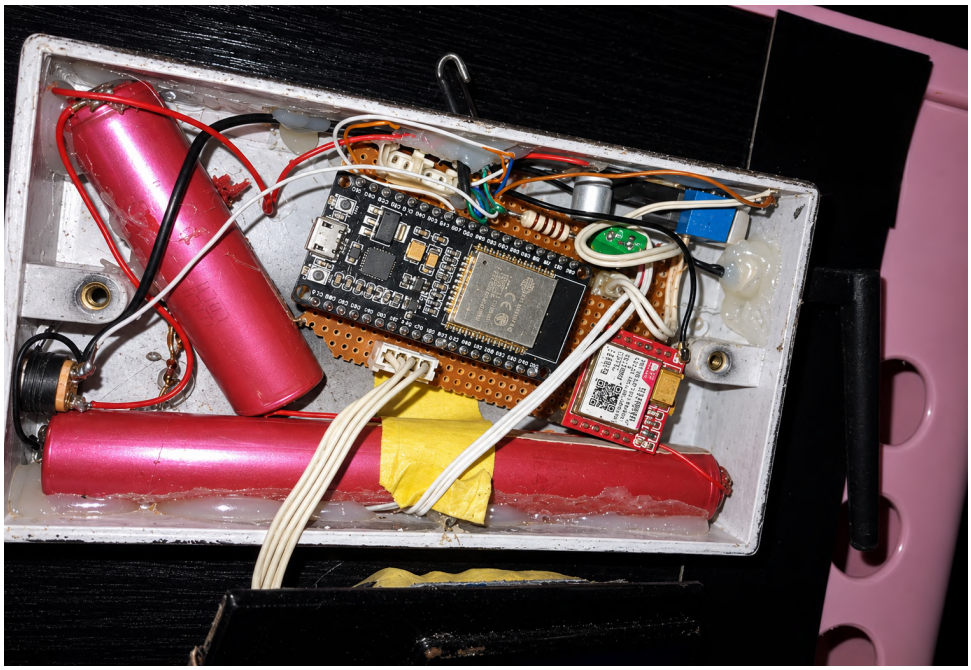


Figure 4: Practical implementation of the smart waste bin system.



Figure 5: Smart waste bin prototype.

interpreted descriptively rather than as an isolated causal estimate of surface type.

The system's alert threshold was set to 80% bin capacity. Each of the 150 sensing measurements was followed by one GSM data transmission attempt to the remote monitoring platform, resulting in 150 transmission attempts within the test sequence. Whenever the processed fill level reached or exceeded 80%, the firmware initiated an SMS alert to the assigned operator. Thirty-one of the 150 measured observations met this threshold, resulting in 31 SMS alert attempts: 10 from prototype

Table 1
Experimental setup and evaluation protocol.

Parameter	Description
Number of prototype bins tested	3
Bin height	48 cm
Bin top opening	34 cm × 28 cm
Effective sensing depth	42 cm
Sensor location	Centre of underside of lid
Sensor mounting offset	2.5 cm below lid surface
Fill levels tested	0%, 25%, 50%, 75%, and 100%
Repeated readings per fill level	10
Total sensing trials	150
Alert threshold	80% fullness
Reliability test duration	14 days
Waste-surface assignment	Prototype 1: flat compact; prototype 2: irregular mixed dry waste; prototype 3: soft irregular waste
Test locations	Indoor laboratory; corridor entrance; semi-outdoor walkway
Physical separation between test locations	Approximately 50–120 m (site spacing only; not GSM communication range)
Performance indicators	Fill-level accuracy, application response time, observed communication continuity, and SMS alert operation
Communication logging	150 GSM transmission attempts; 31 threshold-triggered SMS alert attempts; location-level observed AT+CSQ retained; packet-level acknowledgement and independent SMS delivery receipts not retained
Electrical readings per operating condition	10
Nominal battery capacity used for runtime projection	2000 mAh
Duty-cycle assumption for runtime projection	95% idle, 3% ultrasonic sensing, 2% GSM transmission

1, 10 from prototype 2, and 11 from prototype 3. The additional trigger in prototype 3 resulted from a single nominal 75% test observation in which the measured fill level slightly exceeded the programmed 80% threshold. To expose the prototypes to conditions closer to everyday deployment, the bins were tested at three campus locations: an indoor laboratory, a building entrance corridor, and a semi-outdoor walkway. The sites were approximately 50–120 m apart; this value describes only the spacing between test locations and not the communication range of the GSM link. Communication behaviour was observed over 14 days. Location-level AT+CSQ measurements gave observed CSQ values of 8.70, 14.00, and 18.92 for the indoor laboratory, corridor/entrance, and semi-outdoor locations, respectively, corresponding to approximate RSSI values of -95.6, -85.0, and -75.2 dBm. Packet-level acknowledgement outcomes and independent SMS delivery receipts were not retained, so numerical delivery-success rates were not reconstructed retrospectively.

Electrical characterisation was also performed using ten repeated measurements for each operating condition: supply voltage, idle current, ultrasonic-sensing current, average current during GSM transmission, and peak GSM current. Reported electrical values are therefore expressed as mean ± standard deviation. Battery endurance was not measured by a full discharge test. Instead, a projected runtime was calculated for a nominal 2000 mAh battery, assuming a stated duty cycle of 95% idle, 3% ultrasonic sensing, and 2% GSM transmission. This runtime is an analytical projection and does not include conversion losses, battery derating, network-dependent changes in GSM activity, or battery ageing. The test results showed that the ultrasonic sensing unit tracked the manually verified fill levels with good accuracy. The detailed sensing results are presented in table 2.

Across the 150 sensing observations, the overall trial-wise MAE was 1.35 percentage points, and the RMSE was 2.12 percentage points. The overall mean bias was 0.10 percentage points (95% CI:

Table 2
Fill-level sensing performance across the 150 measured trials.

Reference fill level (%)	Mean measured fill ± SD (%)	95% CI of mean fill (%)
0	0.58 ± 1.07	0.18–0.98
25	25.13 ± 2.65	24.14–26.13
50	50.03 ± 2.82	48.98–51.09
75	75.37 ± 2.28	74.52–76.22
100	99.40 ± 1.01	99.02–99.77
Overall trial-wise MAE	1.35 percentage points	
Overall RMSE	2.12 percentage points	
Overall mean bias	0.10 percentage points	
95% CI of overall mean bias	−0.24 to 0.44 percentage points	

Table 3
Descriptive sensing performance by assigned waste-surface condition.

Assigned waste-surface condition	*n*	Mean bias (95% CI), pp	SD (variance), pp	MAE / RMSE, pp
Flat compact waste (prototype 1)	50	0.26 (0.03 to 0.49)	0.81 (0.65)	0.58 / 0.84
Irregular mixed dry waste (prototype 2)	50	0.01 (−0.49 to 0.51)	1.75 (3.06)	1.17 / 1.73
Soft irregular waste (prototype 3)	50	0.04 (−0.86 to 0.94)	3.16 (9.97)	2.29 / 3.13

-0.24 to 0.44), with an error variance of 4.51 (percentage points)^2, and the mean measured fill values remained close to their corresponding reference states. To further examine measurement behaviour under different waste arrangements, a descriptive breakdown by assigned waste-surface condition is presented in table 3.

The surface-condition summary shows a progressive increase in dispersion as the reflecting surface became more irregular. Because each surface category was associated with a single prototype, these differences are reported as descriptive, condition-specific results rather than as evidence of an independent surface-type effect. The communication, alert, and electrical performance results obtained during the system evaluation, including the projected battery runtime under the stated duty-cycle assumption, are summarised in table 4.

During the 14-day evaluation, remote updates were observed on the monitoring platform following each of the 150 sensing trials, and every observation that reached the 80% threshold initiated an SMS alert. Cellular reception was strongest at the semi-outdoor site and weakest in the indoor laboratory. Because packet-level acknowledgement outcomes and independent SMS delivery receipts were not retained, successful-transmission and SMS-delivery percentages are not reconstructed retrospectively.

The electrical measurements show that GSM transmission draws a substantially higher mean current than idle or sensing operation. Under the stated 95%/3%/2% duty-cycle assumption, the weighted current was 39.14 mA, corresponding to a projected runtime of approximately 51.1 h (2.1 days) for a nominal 2000 mAh battery. This value is a projection rather than a measured full-discharge endurance result.

Beyond basic fill-level detection, the system also demonstrated the ability to present operational information through its dashboard interface. As illustrated in figure 6, the interface provides an example dashboard view that includes summary indicators such as monitored bins, full bins, completed collections, missed pickups, and active trucks, along with bin-specific information, including serial number, fill level, location, and service status. These displayed values, summarised in table 5, show how the proposed system can support operational awareness and decision-making.

The dashboard and alert interfaces that support these operational functions are shown in figures 6

Table 4
Communication, alert, and electrical performance of the proposed system.

Performance metric	Result
Mean application response time (mean ± SD)	1.43 ± 0.31 s
Response-time range	1.02–2.08 s
GSM data-transfer observation	150 GSM transmission attempts were initiated, one after each sensing trial; remote updates were observed during monitored sessions
SMS alert observation	31 threshold-triggered SMS alert attempts were initiated at measured fill levels ≥80%
Reliability assessment period	14 days
GSM transmission attempts	150 total attempts; packet-level success/failure acknowledgement counts were not retained
Numerical GSM success rate	Not reconstructed because packet-level acknowledgement outcomes were not retained
GSM signal strength by location	Indoor lab: CSQ 8.70 (∼ −95.6 dBm); corridor/entrance: CSQ 14.00 (∼ −85.0 dBm); semi-outdoor: CSQ 18.92 (∼ −75.2 dBm)
Retransmission / fault-handling performance	Not quantitatively evaluated in the reported protocol
Supply voltage ($n = 10$)	3.78 ± 0.04 V
Idle current ($n = 10$)	31.44 ± 1.47 mA
Ultrasonic-sensing current ($n = 10$)	67.96 ± 4.64 mA
GSM average transmission current ($n = 10$)	361.73 ± 23.93 mA
GSM peak current ($n = 10$)	1772.08 ± 145.88 mA
Projected weighted operating current	39.14 mA (95% idle / 3% sensing / 2% GSM)
Projected runtime with nominal 2000 mAh battery	51.1 h (approximately 2.1 days; analytical projection)
SMS alert attempts / confirmed deliveries	31 alert attempts; independent handset-delivery receipts were not retained, so a delivery-success percentage is not reported

Table 5
Example dashboard indicators displayed by the system interface.

Indicator	Example displayed value	Operational relevance
Total monitored bins	24	Shows the monitoring scope of the interface
Full bins	9	Indicates bins requiring immediate attention
Collected today	15	Reflects completed collection activity
Missed pickups	4	Highlights unattended bins and service gaps
Active trucks	5	Supports resource allocation and collection planning

and 7, respectively.

Taken together, these findings indicate that the proposed system provided accurate fill-level monitoring, timely application updates, observed threshold-alert operation, and a dashboard-based operational view under the tested conditions.

3.2. Reliability assessment

Reliability testing was carried out over 14 days using the three prototype bins through repeated sensing, data transmission, and notification cycles. The aim was to determine whether the integrated system could sustain stable short-term operation under the defined test conditions.

Occasional delays were observed under the weaker indoor reception condition. Because packet-level acknowledgement and independent SMS-receipt outcomes were not retained, the communication observations are not interpreted as proof of a specific transmission or delivery success percentage.

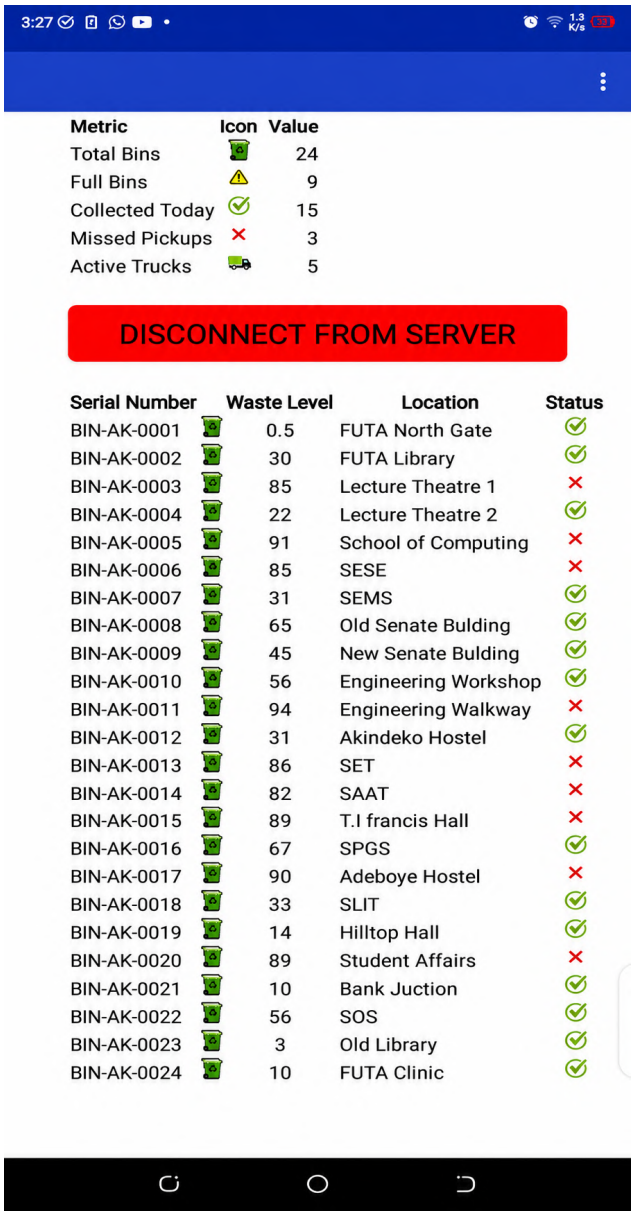


Figure 6: Mobile dashboard for bin status and system summary.



Figure 7: SMS alert issued when waste level exceeded the threshold.

Overall, the 14-day evaluation indicates short-term operational stability of the integrated prototype under the indoor and semi-outdoor conditions tested. Performance under prolonged deployment, severe interference, weak or intermittent cellular coverage, and geographically distributed operation remains to be established.

3.3. Performance overview

Beyond sensing and communication performance, the prototype demonstrated practical value through its dashboard-oriented mobile interface: rather than limiting the user's view to the fill state of a single bin, the application presents service-related indicators such as bin status, completed collections, missed pickups, and active service resources, converting sensor outputs into information that supports prioritisation and routine waste-collection planning.

The sensing, communication, and electrical results in tables 2–4 therefore demonstrate prototype functionality under the defined test conditions. Claims concerning comparative cost advantage, long-term battery endurance, scalability, improvements in collection efficiency, and large-scale deployment

still require broader field validation.

4. Discussion

4.1. Comparative analysis

The proposed smart waste management system was evaluated against representative solutions reported in the literature to clarify its contribution. As summarised in table 6, earlier studies [3, 9, 11] have demonstrated the value of IoT-based waste monitoring in different application settings, and the present work places greater emphasis on implementation simplicity and GSM-based connectivity for environments where continuous Wi-Fi cannot be assumed. Because the selected literature does not report component cost, power consumption, communication latency, scalability, or maintenance requirements under a common experimental protocol, table 6 is presented as a qualitative functional comparison, and no quantitative advantages in cost, energy, latency, or scalability are claimed for the proposed prototype.

Table 6
Qualitative functional comparison of the proposed system with related smart waste-monitoring studies.

Study	System emphasis	Communication/ deployment orientation	Relative strength	Relative limitation
Ishaq et al. [9]	IoT smart waste-bin monitoring for biomedical waste	Application-specific monitoring	Strong domain-specific use case	More specialised than the present general solid-waste system
Alnanih, Elrefaei and Al-Ahwal [3]	IoT-driven smart waste management with software engineering integration	Broader architecture focus	Strong integration perspective	Different architecture and evaluation emphasis; direct cost, power, and latency comparison is not established here
Kadus, Nirmal and Kulkarni [11]	IoT-based smart waste management	Real-time smart-bin concept	Established proof of IoT feasibility	Direct quantitative cost, power, latency, and maintenance comparison is not established here
Proposed study	ESP32- and GSM-based real-time monitoring	GSM-based monitoring for limited Wi-Fi settings	Integrated sensing, remote display, and SMS alerts	No retained packet-level success/failure acknowledgement log, full-discharge battery endurance test, quantitative cross-study cost comparison, or large-scale field deployment

More recent work has expanded smart waste management beyond simple fill-level detection to cloud-based platforms, route optimisation, machine-learning-supported decision-making, proactive collection strategies, and AI-driven waste classification [2, 5, 7, 8, 10, 13, 15, 18–20], architectures that may involve additional infrastructure, integration, and technical support requirements depending on the implemented architecture and deployment environment. In contrast, the present prototype focuses on a defined set of core functions comprising real-time waste-level monitoring, GSM-based data transmission, dashboard-based status display, and threshold-triggered alert generation.

The value of the proposed system, therefore, lies in its practical integration of sensing, cellular communication, remote status display, and threshold-based alerting, rather than in a fundamentally new algorithmic or sensing contribution. The three-prototype evaluation provides evidence of short-term functionality under the defined test conditions. However, a formal comparative cost study,

maintenance analysis, battery-endurance assessment, and large-scale field deployment were beyond the scope of the present work.

4.2. System limitations

Although the system demonstrated effective performance under the defined test conditions, several limitations remain. First, the present study evaluated three prototype bins under controlled and semi-controlled conditions rather than through a large-scale field deployment. As a result, the findings primarily confirm prototype functionality and short-term operational stability. However, they do not yet demonstrate system performance across broader geographic areas or under prolonged real-world use.

Second, the statistical analysis was conducted using all 150 trial-level sensing observations to characterise measurement performance across the reference fill levels and assigned waste-surface conditions. Table 2 reports the mean, standard deviation, and 95% confidence interval for each reference fill level. In contrast, table 3 presents condition-specific bias, standard deviation, variance, mean absolute error, and root mean square error. A limitation of this analysis is that each waste-surface category was associated with a single prototype unit, and, therefore, surface condition and prototype identity were not independently randomised. Consequently, the observed differences among the waste-surface conditions should be interpreted descriptively and should not be regarded as evidence of an independent causal effect of surface type.

Third, the study did not include a formal comparative cost analysis against other smart waste-monitoring systems or conventional waste-collection practices. Although the prototype was implemented using commonly available embedded components, their use alone does not establish a comparative cost advantage. A comprehensive economic evaluation would require consideration of component acquisition costs, installation expenses, maintenance requirements, network charges, replacement cycles, and potential operational savings before conclusions regarding cost-effectiveness could be established.

Fourth, the study did not quantify the effects of the proposed system on collection efficiency, route distance, fuel consumption, labour requirements, or service costs relative to conventional waste-management practices. Although the dashboard and alert functions demonstrate the system's monitoring and decision-support capabilities, improvements in operational efficiency cannot be established from the present prototype evaluation alone. Such effects would require field-based assessment involving waste-collection personnel and appropriate baseline or comparative operating conditions.

Fifth, direct electrical measurements were obtained for the principal operating states of the prototype (table 4), confirming the substantially greater instantaneous current demand associated with GSM transmission compared with that during idle and sensing operations. Battery endurance, however, was not determined through a full-discharge experiment. The estimated runtime of approximately 51.1 h (2.1 days) for a nominal 2000 mAh battery is therefore an analytical projection based on the stated duty-cycle assumption. The estimate does not account for conversion losses, battery-capacity derating, variations in network-dependent GSM activity, or battery ageing, and should consequently not be interpreted as experimentally verified battery endurance.

Sixth, the communication evaluation documented 150 GSM transmission attempts, 31 threshold-triggered SMS alert attempts, and location-specific GSM signal-quality measurements (table 4). However, packet-level acknowledgement outcomes, independent handset delivery receipts for individual SMS events, per-attempt CSQ measurements, and quantitative records of retransmission or fault-handling behaviour were not retained. Consequently, the communication results are limited to recorded attempt counts and measured signal conditions, and no retrospective packet-transmission or SMS-delivery success rates are claimed. In addition, the approximately 50–120 m distance reported in the experimental setup represents only the physical separation among the campus test locations. It should not be interpreted as the GSM link's communication range.

Finally, the current design does not incorporate predictive analytics, artificial intelligence for

waste classification, or additional sensing capabilities, such as monitoring weight, gas, humidity, or temperature. These features were not part of the present implementation, but they represent meaningful directions for future system enhancement.

5. Conclusion

This study presented the development and evaluation of a smart waste management system that integrates an ESP32 microcontroller, an ultrasonic sensor, GSM-based communication, and a mobile application for real-time waste-level monitoring and alert notification. Across 150 measured sensing trials, the prototype achieved an overall MAE of 1.35 percentage points and an RMSE of 2.12 percentage points. At the same time, the condition-specific analysis showed greater variability in softer, more irregular waste surfaces. The system also produced timely remote updates and threshold alerts during the monitored tests.

The significance of the study lies primarily in its practical and deployment-oriented contribution. Rather than introducing a fundamentally new sensing method or edge-computing algorithm, the work demonstrates how established IoT components can be combined into a functional monitoring and alerting system for environments where continuous Wi-Fi connectivity may be unavailable. No quantitative advantage in component cost, power consumption, battery life, maintenance burden, scalability, or collection efficiency is claimed from the present prototype evaluation.

At the same time, the present evaluation remains limited in scope: GSM transmission drew a substantially higher mean current (peaking at 1.77 ± 0.15 A) than idle or sensing operation, the projected runtime of approximately 51.1 h for a nominal 2000 mAh battery was not verified by a full-discharge endurance test, and packet-level acknowledgements and independent SMS delivery receipts were not retained. Future work should therefore include automated per-attempt logging of acknowledgement status, SMS delivery confirmation, CSQ/RSSI, retransmission behaviour, and failure cause, together with long-duration battery testing, randomised surface-condition testing across prototype units, comparative cost and maintenance analysis, and large-scale field deployment with waste-collection personnel.

Author contributions

Conceptualization, Olayiwola C. Adesoba; methodology, Olayiwola C. Adesoba and Samuel O. Falade; software, Samuel O. Falade; writing – original draft, Olayiwola C. Adesoba; writing – review and editing, Olayiwola C. Adesoba and Samuel O. Falade. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data generated and analysed during this study are available from the corresponding author upon reasonable request.

Conflicts of interest

The authors declare no conflict of interest.

Declaration on Generative AI

Generative AI tools were employed in the preparation of this manuscript. The authors reviewed and edited all AI-assisted content and take full responsibility for the content of the publication.

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