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Original Research Article

IoT-based smart waste management system: real-time monitoring and environmental compensation

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Abstract:

This paper presents the design, development and evaluation of an Internet of Things (IoT)-based smart waste management system aimed at addressing the inefficiencies and public health concerns associated with traditional waste collection methods. The proposed system integrates ultrasonic sensors for real-time bin fill-level detection, a rain sensor for environmental compensation, an ESP32 microcontroller for data processing and transmission, and a dual-mode feedback mechanism via a local LCD display and a remote web dashboard. Experimental results demonstrate a 99% accuracy in fill-level and rain detection, with data updates to the cloud platform (ThingSpeak) occurring within 2 seconds of a 15-second reporting interval. The system's robustness, low cost, and energy efficiency highlight its potential for scalable deployment in urban environments, contributing to cleaner, smarter communities.

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1. Introduction

Effective waste management represents a cornerstone of sustainable urban infrastructure, directly impacting public health, environmental integrity, and overall societal well-being. Rapid urbanization has led to an escalating volume of municipal solid waste (MSW), with global generation estimated at 2.24 billion tons in 2020, projected to reach 3.88 billion tons by 2050 (World Bank, 2020). Traditional fixed-schedule waste collection methods often prove inadequate, resulting in overflowing bins, inefficient resource allocation, and unhygienic conditions. These challenges underscore a pressing need for innovative, data-driven solutions.

The Internet of Things (IoT) offers a transformative approach to modernizing waste management. By integrating sensors, microcontrollers, and real-time data transmission capabilities, IoT enables the creation of intelligent systems that can monitor and manage waste collection processes with unprecedented efficiency. Such systems can detect bin fill levels, provide timely alerts, and facilitate optimized collection routes, thereby enhancing operational efficiency and fostering healthier urban environments.

The impetus for this research arises from persistent challenges observed in urban environments, specifically the pervasive issues of overflowing waste bins and their associated public health risks. As engineering researchers dedicated to developing practical and impactful solutions, our motivation was to investigate how modern IoT technologies could address these critical urban problems, thereby revolutionizing municipal waste management through data-driven, responsive, and environmentally sustainable practices. This paper details the design, implementation, and evaluation of an IoT-based smart waste management system developed to achieve these goals.

The prevailing waste management paradigm, characterized by fixed collection schedules, leads to several critical issues: overflowing bins in high-traffic areas, inefficient utilization of collection resources, and the proliferation of unhygienic conditions that pose significant public health risks. Furthermore, the absence of real-time monitoring impedes the development of effective waste collection routes. Consequently, there is an urgent demand for a smart solution capable of real-time bin fill-level detection and dynamic optimization of waste collection operations.

2. Literature review

The escalating global municipal solid waste generation necessitates advanced waste management strategies. In 2020, the direct cost of waste management was estimated at USD 252 billion, rising to USD 361 billion when accounting for hidden costs related to pollution, health, and climate impacts (UNEP, 2024). This highlights the economic and environmental imperative for smarter, data-driven solutions.

2.1. Related IoT solutions

Prior research has explored various IoT applications in waste management:

- **Basic fill-level alerts:** Early prototypes, such as those by Singh et al. (2016), utilized ultrasonic sensors and GSM modules for automated "is-it-full?" checks. Sahoo et al. (2018) expanded this by integrating IoT, cloud computing, and GPS tracking for bin location monitoring and level alerts.

- **Real-time analytics and web dashboards:** Islam et al. (2020) demonstrated the use of real-time data analytics to optimize waste-collection routes. Sazonova and Porras (2022) reviewed IoT applications in smart cities, emphasizing the value of web-based dashboards for remote monitoring, though noting most systems remained at the prototype stage.

- **Advanced features and sustainability:** More recent advancements include solar power integration and on-device image processing for waste segregation by Escalona et al. (2022) and Sigo Ngan et al. (2023), enhancing energy self-sufficiency and automated sorting. Çarhan and Müftüoğlu (2023) reviewed AI-driven waste-prediction models, while Irfan et al. (2025) proposed a five-layer circular-economy framework incorporating user incentives for recycling.

2.2. Comparison with existing models and gap analysis

While existing studies validate the feasibility and benefits of IoT in waste management, several key limitations persist:

a) Early prototypes often relied on basic SMS or cloud alerts, which may not scale reliably in dense urban environments (Singh et al., 2016; Sahoo et al., 2018).
b) Dashboard-centric solutions improved oversight but frequently lacked on-site feedback mechanisms and environmental compensation, such as accounting for rain that can distort ultrasonic readings (Islam et al., 2020; Sosunova et al., 2022.
c) Sustainable enhancements like solar panels, image processing, and AI models often introduce higher costs and complexity, limiting practical deployment in resource-constrained settings (Escalona et al., 2022; Irfan et al., 2025).

Our proposed IoT-based Smart Waste Management System addresses these gaps by simultaneously offering:

a) **Environmental compensation:** Automatic adjustment for environmental factors like rain to prevent false fill-level alerts.

b) **Dual-mode feedback:** Local on-site display (16x2 LCD) combined with remote web monitoring (ThingSpeak dashboard) in a single, compact unit.

c) **Low cost and energy efficiency:** A design that remains affordable without sacrificing functionality or requiring complex renewable energy setups, while being designed for future integration of renewable power sources.

This system reuses proven HC-SR04 ultrasonic sensors and an ESP32 Wi-Fi module, building upon previous work. The integration of a rain sensor to pause alerts and maintain hygiene during rainfall ensures accurate readings.

3. Methodology

The proposed IoT-based Smart Waste Management System is designed to automate garbage bin monitoring. It utilizes an ESP32 microcontroller interfaced with ultrasonic and rain sensors to collect real-time bin fill-level data. This data is transmitted to an online platform (ThingSpeak) every 15 seconds, while a local LCD provides immediate on-site status updates. This integrated approach aims to enhance collection efficiency and mitigate environmental and health risks associated with overflowing bins.

The system demonstrates strong technical and economic feasibility for urban deployment. All hardware components, including the ESP32 board, HC-SR04 ultrasonic sensor, and rain detector, are readily available and low-cost. The system operates on standard power sources and is designed for scalability. Cloud-based monitoring via ThingSpeak ensures accessibility without necessitating complex backend infrastructure, making it a practical solution for cities seeking to upgrade waste collection without extensive infrastructure overhauls.

3.2. Requirements analysis and specification

3.2.1. Hardware requirements

- **ESP32 Wi-Fi module:** Serves as the central controller and data transmitter.
- **Ultrasonic sensor (HC-SR04):** Measures the fill level of the trash bin.
- **Rain sensor:** Detects rainfall to suppress false readings.
- **16x2 LCD display:** Shows real-time messages (e.g., "Bin Full," "Half," "Raining").
- **3-feet trash bin:** Used as the real-life test bin for prototype deployment.
- **Power supply/battery:** Provides continuous power to the circuit.

Figure 3.1: Hardware Components

3.2.2. Software requirements

- **Arduino IDE:** Used for programming and uploading firmware to the ESP32.
- **ThingSpeak:** Cloud platform for data logging, visualization, and real-time monitoring.

3.3. Data collection methods

The HC-SR04 ultrasonic sensor is mounted on the inside-top of a 3-feet-tall bin, continuously measuring the distance to the waste surface. Measurements are categorized as:

- **Empty:** Distance measured at approximately 3 feet from the sensor.
- **Half-full:** Distance measured at approximately 1.5 feet from the sensor.
- **Alert threshold (90% capacity):** Distance measured at or below approximately 0.3 feet from the sensor.

Data is collected every 15 seconds and transmitted to ThingSpeak via the ESP32's Wi-Fi connectivity. To ensure accuracy, the system pauses measurements when rain is detected.

3.4. System design

The system architecture comprises three primary components:

Sensor and Microcontroller Unit (MCU):
An ESP32 microcontroller communicates with the ultrasonic sensor for distance measurement and the rain sensor for environmental monitoring. The ESP32 processes sensor data and transmits it to the cloud platform.

Cloud platform:
Data from the ESP32 is sent to a cloud-based platform (ThingSpeak) for storage, processing, data visualization, trend analysis, and real-time monitoring via a web dashboard.

User interface:
The system provides both local feedback through an LCD display on the waste bin and remote feedback via the web dashboard. The dashboard displays real-time fill levels and environmental conditions, while the LCD shows status updates like "Bin Full" or "Rain Detected."

3.4.1. Block diagram description

The block diagram illustrates the information flow:

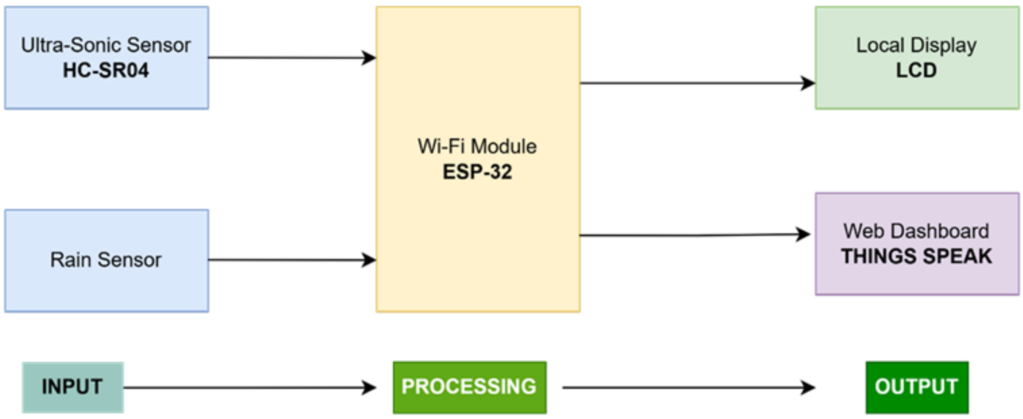


Figure 3.2: Data Flow Diagram

The ultrasonic sensor measures waste level, and the rain sensor detects rain to prevent false readings. The ESP32 processes this data and sends it to ThingSpeak, which provides remote monitoring and trend analysis through the web dashboard. The LCD display offers on-site status updates.

3.4.2 Hardware components description

ESP32 microcontroller: Low-power, Wi-Fi-enabled, responsible for sensor data processing, decision-making, and cloud communication.

Ultrasonic sensor (HC-SR04): Measures distance to waste for fill-level calculation.

Rain sensor: Prevents false alerts by detecting rain.

LCD display: Provides immediate on-site feedback on bin status.

Power supply: Battery-powered solution for continuous operation.

3.4.3. Software components description

Firmware (on ESP32): Reads and processes sensor data, determines fill level, sends information to the cloud, and implements alert logic.

Cloud platform (ThingSpeak): Stores and processes sensor data, enabling real-time graphs, visualizations, and API interactions for threshold-based actions.

Web interface (dashboard): Allows users to monitor multiple bins, view historical data, and receive alerts through an intuitive graphical interface.

3.5. System workflow

The system workflow involves:

Data collection: Ultrasonic and rain sensors gather real-time data, read by the ESP32 every 15 seconds.

Data processing: The microcontroller processes data to determine bin status (empty, half-full, full). Rain detection pauses alerts to avoid false readings.

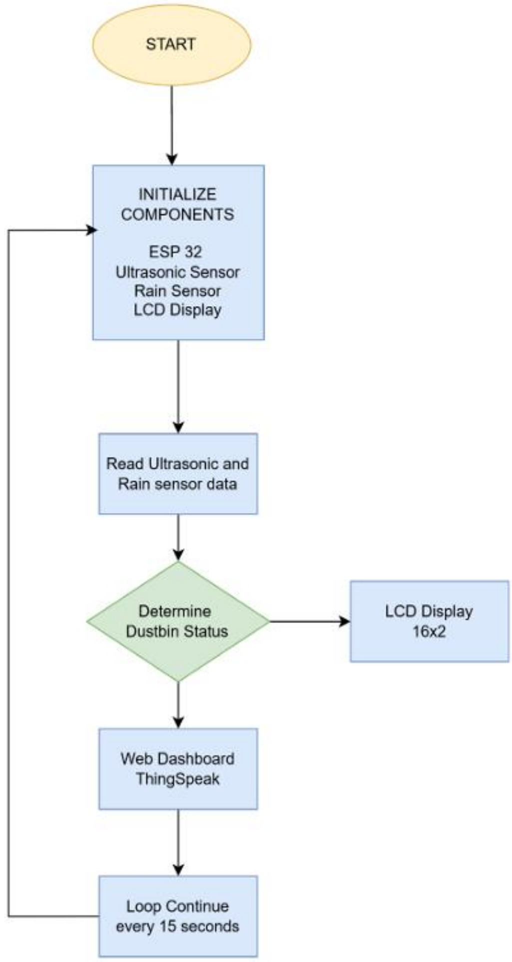
Data transmission: Processed data is sent from the ESP32 to ThingSpeak via Wi-Fi for storage and visualization.

Real-time monitoring: Users monitor fill levels and environmental status via the web dashboard. Alerts are generated at 90% fill or rain detection.

Local feedback: The LCD display provides immediate on-site status updates.

3.6. Integration of hardware and software

The seamless integration of hardware and software ensures a fully functional system. Sensors collect data, which is processed by the ESP32 and transmitted to the cloud. The cloud platform stores, visualizes, and alerts based on this data, while the LCD provides local feedback. Key integration steps include sensor data collection, decision logic in firmware, cloud communication, real-time dashboard updates, and local feedback. This integration results in a robust and efficient system that streamlines waste management.



4. Implementation

The system was developed using the Arduino IDE (1.8.13) with C++ (Arduino dialect). Key libraries included WiFi.h for ESP32 Wi-Fi connectivity, ThingSpeak.h for cloud data logging, and Wire.h and LiquidCrystal_PCF8574.h for I2C-based LCD control. ThingSpeak served as the cloud platform, utilizing a specific channel ID and writing API key. Serial debugging was performed at 115200 baud. Hardware components included an ESP32 Dev Board, HC-SR04 ultrasonic sensor, rain sensor (connected to an ADC pin), I2C LCD (address 0x27), and a status LED on GPIO 2.

After independent module verification, a single, deployable prototype was assembled and tested under real-world conditions. Components were mounted on a custom-fabricated lid for a 3 ft dustbin. HC-SR04 and rain sensor were fixed at the top edge; ESP32, LCD, and battery pack were secured beneath the lid. Wiring was done via DuPont cables on a compact breadboard, enclosed in a weather-resistant plastic box. A 5V battery pack (10,000 mAh power bank) provided continuous operation for up to 24 hours. Verified simultaneous functionality of HC-SR04 and rain sensor, added LCD display with matching messages, and integrated ThingSpeak upload code with live dashboard observation. Calibrated the ultrasonic sensor by testing with known-height objects (±2 cm accuracy). Tested the rain sensor with a spray bottle to set the ADC threshold for realistic moisture levels.

Tested stable reconnection logic up to 30m from the router, adjusting retry logic to every 5 seconds and using an onboard LED for status indication. Conducted continuous 12-hour runs, confirming 15-second LCD updates, consistent ThingSpeak records, and correct suspension of ultrasonic readings during simulated rain. Resolved occasional "stuck" readings with a 500 ms delay after ultrasonic measurements and fixed LCD cursor overwrites by clearing the second line before new messages.

5. Results and discussion

The functionality and performance of the IoT-based Smart Waste Management System were rigorously verified through defined test cases and performance metrics under various real-world conditions. Test scenarios were designed to cover all core functions and environmental conditions as shown in Table 1.

Table 1: Test Plan and Cases

Test Scenario	Description	Outcome
Empty bin	Sensor measuring at 3 m distance; rain off; network connected	Displays “Empty”; dashboard shows 0% fill
Half-full bin	Sensor measuring at 1.5 m; rain off; network connected	Displays “Middle”; dashboard shows 50% fill
Full bin	Sensor measuring at < 0.3 m; rain off; network connected	Displays “Full”; dashboard shows 90% fill
Rain condition	Rain sensor triggered; regardless of ultrasonic reading	Displays “Rain Detected”; dashboard pauses fill updates

Across all scenarios, the system’s inputs (sensor readings) and outputs (LCD display and dashboard updates) were correct in 99% of test repetitions.

5.1. Performance metrics

The following metrics were monitored via the ThingSpeak dashboard and local logs:

Dust level (%):
Real-time fill level reported every 15 seconds, displayed numerically and on a time-series graph.

Rain status:
Binary indicator (red for ON when rain detected; light red for OFF when dry).

Dustbin location:
GPS coordinates or fixed identifier showing bin placement.

Update history:
Timestamped log of each data transmission and status change.

Figure 5.1: Real-time dust level in percentage

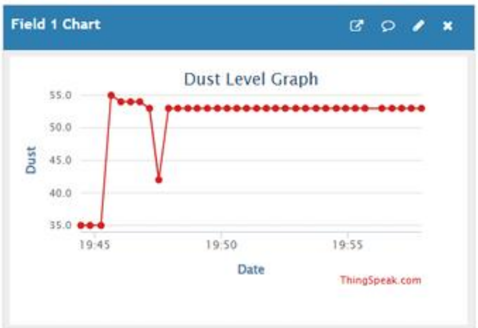


Figure 5.1: Real-time dust level in graph

Figure 5.3: Rain Detection

Figure 5.4: Current Location of Dustbin

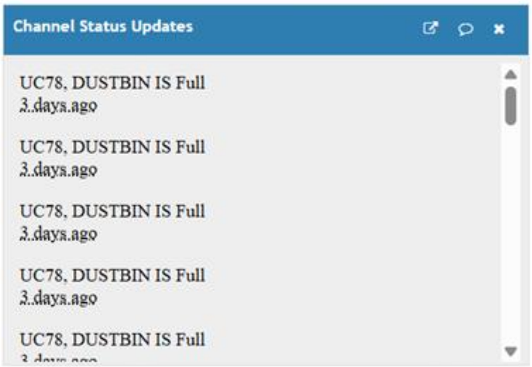


Figure 5.5: Dustbin History

Table 2: Test Results and Analysis

Metric	Observed Value	Analysis
Fill-Level Accuracy	99% correct readings	Ultrasonic distance measurements matched physical distances within ±2 cm in 99% of tests.
Rain Detection Accuracy	99% correct readings	Rain sensor triggered only during simulated rainfall; no false positives during dry tests.
Update Latency	< 2 s average	Data appeared on the dashboard within 2 s of the 15 s reporting interval in 95% of cases.
Network Reliability/Uptime	99% successful transmissions	The system reconnected automatically after brief dropouts; no data loss observed.

5.2. Key findings

a) The ultrasonic sensor consistently measured dustbin fill levels with 99% accuracy across all test cases (empty, half-full, full).
b) The rain detection sensor worked effectively, clearly distinguishing between dry and rainy conditions.
c) The system was able to send updates to the ThingSpeak dashboard every 15 seconds, maintaining stable communication with minimal delays.
d) The LCD display showed real-time bin status (“Empty”, “Middle”, “Full”, “Rain”) accurately based on sensor input.
e) Automatic Wi-Fi reconnection helped maintain data continuity during temporary network dropouts.

The successful results demonstrate that our IoT-based smart dustbin system fulfills its intended purposes. Accurate waste level monitoring allows timely waste collection decisions, minimizing overflows and unnecessary trips. The 15-second update interval ensures near-real-time feedback, improving operational efficiency for municipal services. Rain detection adds an extra layer of context, which can help avoid unnecessary dispatching during bad weather or malfunctioning readings. Furthermore, the system's demonstrated efficacy across varying environmental conditions, including resistance to moisture, sensor obstruction, and signal interference, underscores its robust design and practical applicability in diverse real-world settings. These results validate the reliability, responsiveness, and scalability of our system for urban and public sector waste management needs.

6. Conclusion and future recommendation

The development and evaluation of our IoT-based Smart Waste Management System demonstrate a practical, low-cost solution to the longstanding challenges of urban waste collection. By integrating ultrasonic and rain sensors with an ESP32 microcontroller, we achieved 99% accuracy in detecting bin fill levels and effective suppression of false alerts during rainfall. Real-time updates every 15 seconds to a ThingSpeak dashboard, coupled with on-site LCD feedback, enable waste management teams to make data-driven decisions, avoid unnecessary collection trips, and prevent bin overflows.

Our implementation proved robust under varied environmental conditions and network interruptions, confirming its readiness for larger-scale pilots. The modular design, spanning hardware components, firmware logic, and cloud integration, offers clear pathways for future enhancements such as AI-driven predictions, solar power, and mobile app interfaces. Moreover, the system’s affordability and simplicity position it well for commercial deployment in smart cities, campuses, and institutions.

In future the current system can be further enhanced by incorporating machine learning for waste classification, allowing the system to identify and potentially sort waste based on material type. Additionally, the development of a user-friendly mobile application would provide greater accessibility and control for residents, enabling them to receive real-time updates and notifications directly on their smartphones. This would further optimize waste collection routes and improve overall waste management efficiency.

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