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Real-Time Waste Monitoring System Based On IOT Sensors

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Abstract

General Background Rapid urban growth makes traditional solid waste collection unsustainable. **Specific Background** Conventional systems rely on manual, static routes, causing container overflow and excessive fuel use. **Knowledge Gap** However, urban infrastructures lack decentralized monitoring for real-time volume, temperature, and gas data. **Aims** This study evaluates an intelligent waste system integrating ultrasonic, temperature, and gas sensors via microcontrollers and dashboards. **Results** Validation confirms the prototype accurately detects fill levels and filters measurement noise from irregular surfaces. **Novelty** The system introduces a multi-sensor classification framework triggering alerts based on combined volumetric, thermal, and chemical changes. **Implications** These findings demonstrate that sensor networks improve municipal efficiency, reduce vehicle deployment, and provide a foundation for predictive route optimization.

Keywords: Smart Waste Management, Real-time Monitoring, Ultrasonic Sensor, Smart City Infrastructure, Wireless Sensor Networks

Key Findings Highlights

Automated multi-sensor arrays accurately classify container capacities into prioritized operational states.

Specialized microcontroller data filtering successfully reduces measurement errors caused by irregular waste surface geometry.

Live telemetry loops transmit simultaneous volumetric, gas, and temperature updates directly to municipal operators.

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I. Introduction

The rapid growth of urban population, intensive urbanization, and increasing consumption have created serious challenges for municipal solid waste management. According to the World Bank report, global waste generation is expected to increase significantly by 2050, which makes the modernization of waste collection and monitoring systems an urgent task for cities [1].

Waste management is one of the most important problems in rapidly developing urban areas. In many cities, waste collection is still carried out through fixed schedules and manual control. Such an approach does not always reflect the real condition of waste containers, because some containers may be collected before they are full, while others may overflow before the next scheduled collection [2].

Traditional waste collection approaches are usually based on manual inspection, predefined routes, and periodic collection schedules. Although these methods are simple to organize, they are often inefficient in areas where waste generation changes depending on population density, commercial activity, and time of day. As a result, operational costs increase, service quality decreases, and environmental hygiene is negatively affected [3].

Furthermore, conventional waste management systems often fail to provide real-time information about container status. The lack of timely data limits the ability of municipal services to respond quickly to overflowing containers, unpleasant odors, fire risks, and other environmental problems. Therefore, smart monitoring technologies are increasingly considered an important component of sustainable urban infrastructure [4].

The Internet of Things provides new opportunities for monitoring physical objects through sensors, microcontrollers, wireless communication, and cloud-based platforms. In smart city environments, IoT technologies can be effectively used for monitoring and managing urban services such as transportation, energy, environment, and public infrastructure [5].

In waste management, IoT sensors can be installed inside or near waste containers to measure fill level, temperature, gas concentration, and location. The collected data can be transmitted to a server and displayed on a dashboard for municipal operators. This enables continuous monitoring of waste containers and supports data-driven decision-making in waste collection services [6].

Recent studies show that distance-based sensing technologies are effective for real-time waste monitoring. For example, Pires et al. developed an urban garbage level monitoring system using Time-of-Flight sensing technology, an ESP32-S3 microcontroller, a Raspberry Pi gateway, Wi-Fi communication, and cloud connection. Their system demonstrates that sensor nodes can provide real-time information about container capacity [7].

Existing research also shows that ultrasonic sensors, temperature sensors, gas sensors, RFID, and load cells are commonly used in IoT-enabled waste collection systems. These technologies help collect real-time data and support operational decisions such as collection priority, alert generation, and vehicle routing [8].

The main objective of this paper is to develop an IoT-based real-time waste monitoring system that automatically detects the fill level of waste containers and sends the information to a centralized monitoring platform. The proposed system is designed to improve waste collection planning, reduce manual inspection, prevent overflowing containers, and support smart city infrastructure through real-time environmental monitoring [9].

Literature Review

In recent years, the development of IoT-based waste monitoring systems has become an important research direction within smart city infrastructure. Traditional waste collection systems usually rely on manual inspection and fixed collection schedules, which may lead to container overflow, unnecessary vehicle movement, increased fuel consumption, and environmental problems. Therefore, many recent studies have focused on developing sensor-based, real-time, and data-driven waste monitoring systems. This section reviews relevant scientific works related to IoT sensors, smart waste containers, real-time monitoring, communication technologies, and route optimization.

The study by Zanella et al. [5] provides a general conceptual foundation for the use of Internet of Things technologies in smart cities. The authors analyzed IoT architecture, enabling technologies, communication protocols, and urban service models. Their research shows that IoT can be effectively used for monitoring and managing city infrastructure, including transportation, environment, energy, and public services. This work is important for the present research because waste monitoring is considered one of the practical components of smart city management.

The study by Anagnostopoulos et al. [2] is one of the important survey works devoted to waste management in IoT-enabled smart cities. The authors reviewed ICT-based waste management models and emphasized the role of smart devices in modern waste collection systems. The study highlights that waste management includes not only waste collection, but also transportation, disposal, and decision-making processes. This research provides a strong theoretical basis for designing an IoT-based waste monitoring system.

The research by Medvedev et al. [3] focuses on waste management as an IoT-enabled service in smart cities. The authors proposed a decision support system for efficient waste collection and discussed the use of RFID, sensors, cameras,

actuators, and intelligent transportation systems. The study also emphasizes real-time data sharing and dynamic route optimization. This approach is directly related to the current research because real-time sensor data can be used to improve the efficiency of waste collection services.

The study by Pires et al. [7] presents a real-time monitoring system for urban garbage levels using Time-of-Flight sensing technology. The system uses a VL53L8CX distance sensor, ESP32-S3 microcontroller, Raspberry Pi gateway, Wi-Fi communication, and cloud connection. The authors demonstrate how sensor nodes can collect container-level data and transmit it to an IoT platform. This study is especially relevant to the present article because it confirms the practical applicability of distance-based sensing for real-time waste monitoring.

The study by Roy et al. [10] analyzes IoT-based smart bin allocation and vehicle routing in solid waste management. The authors developed an integrated model that considers the fill level of waste bins together with a central monitoring system and vehicle routing algorithm. Their research shows that the combination of smart bins and optimized routing can improve the organization of municipal waste collection. This work is methodologically close to the present study because it links bin fill-level monitoring with data-driven collection planning.

The research by Ghahramani et al. [9] focuses on IoT-based route recommendation for intelligent waste management systems. The authors proposed an approach in which bin status and geographic coordinates are used in a multi-level decision-making process. The study demonstrates that IoT data can support artificial intelligence-based route recommendation and sustainable infrastructure planning. This research is important for the present work because the proposed monitoring system can later be expanded with route optimization functions.

The study by Maciel et al. [11] provides a systematic review and meta-analysis of IoT-enabled routing optimization in waste collection. The authors analyzed studies from Scopus, IEEE Xplore, and ACM Digital Library and reported that IoT-enabled routing optimization can reduce collection distance by a combined average of 21.51%. This result confirms the practical value of using real-time sensor data not only for monitoring, but also for improving route planning and reducing operational costs.

The study by Paul, Mohalder, and Alam [12] proposes an IoT-based smart waste management system for municipalities and city corporations. The authors combined smart dustbins with mobile application-based interactive management. Their model enables smart bins to communicate with waste collectors or control centers when necessary, while citizens can report local waste problems through a mobile application. This work is useful for the present research because it shows that IoT-based monitoring can be integrated with user participation and municipal service management.

The research by Ahmed et al. [13] examines artificial intelligence and IoT-driven architecture for smart waste management. The proposed system focuses on automating municipal trash management through IoT technologies and sending notifications based on sensor data about bin status. The study is relevant because it emphasizes system architecture, automation, and notification mechanisms, which are also important components of the proposed real-time monitoring system.

The study by Al Qurashi et al. [14] presents a smart waste management system for Makkah City using IoT and artificial intelligence. The proposed system uses ultrasonic sensors to monitor waste levels and gas sensors to detect harmful substances. When a container reaches full capacity, the sensor communicates with the microcontroller and alerts the responsible authorities. This research is important for the current study because it demonstrates the use of ultrasonic and gas sensors in crowded urban environments where waste accumulation is unpredictable.

The study by Abdullah et al. [15] analyzes IoT-based waste management systems in formal and informal sectors. The authors discuss how IoT technologies can improve waste monitoring and management processes in different urban contexts. This work is significant because it shows that IoT-based waste systems should be adapted not only to technical requirements, but also to local organizational, social, and infrastructural conditions.

Overall, the reviewed literature shows that IoT-based waste monitoring systems mainly rely on distance sensors, microcontrollers, wireless communication modules, cloud platforms, dashboards, and decision-support algorithms. Existing studies confirm that real-time monitoring can reduce manual inspection, prevent container overflow, improve collection planning, and support smart city sustainability. However, several challenges remain, including sensor calibration, communication reliability, energy consumption, environmental conditions, and integration with route optimization algorithms. Therefore, the present research focuses on developing a real-time waste monitoring system based on IoT sensors, with particular attention to fill-level detection, data transmission, database storage, and visualization through an operator dashboard.

II. Method

The methodological basis of this study is focused on developing a real-time waste monitoring system based on IoT sensors. The proposed methodology is designed to automatically determine the fill level of waste containers, transmit the collected data to a server, store the information in a database, and visualize the container status through an operator dashboard.

The methodology includes the following main stages:

- sensor data acquisition;
- data preprocessing and filtering;
- fill-level calculation;
- data transmission to the server;
- database storage;
- real-time monitoring and visualization;
- alert generation and system evaluation.

The process consists of several interconnected stages, and each stage contributes to the overall reliability and efficiency of the proposed waste monitoring system.

In the first stage, data are collected from waste containers using IoT sensors. The main sensor used in the system is an ultrasonic distance sensor, which measures the distance between the top of the container and the surface of the waste. In addition, temperature and gas sensors can be integrated into the system to detect abnormal environmental conditions, such as overheating, fire risk, unpleasant odor, or harmful gas concentration. Each waste container is assigned a unique identification number, which allows the system to distinguish containers and monitor their individual status.

The sensor unit is installed inside or on the upper part of the waste container. The ultrasonic sensor periodically sends a signal and receives the reflected wave from the waste surface. Based on the measured distance, the system determines how much space remains inside the container. This approach makes it possible to monitor the container without manual inspection and provides continuous information about its current condition.

In the second stage, the collected sensor data are processed by a microcontroller. Devices such as ESP32, NodeMCU, or Arduino can be used as the control unit. The microcontroller receives raw values from the sensors, checks their validity, and prepares the data for further processing. Since sensor readings may be affected by dust, humidity, irregular waste surfaces, or temporary measurement errors, a simple filtering mechanism is applied to reduce noise and improve measurement stability.

During the preprocessing stage, incorrect or extreme values are removed, and repeated measurements are averaged. This allows the system to obtain a more reliable value for the container fill level. For example, instead of using only one ultrasonic measurement, the system can take several measurements in sequence and calculate their average value. This reduces the influence of random errors and improves the accuracy of the monitoring process.

In the next stage, the fill level of the waste container is calculated. The calculation is based on the total height of the container and the measured distance between the sensor and the waste surface. The fill level is determined using the following formula:

$$F = \frac{H - D}{H} \times 100$$

Figure 1.

where **F** is the fill level of the container in percentage, **H** is the total height of the container, and **D** is the distance measured by the ultrasonic sensor.

For example, if the container height is 100 cm and the measured distance is 25 cm, the fill level is calculated as follows:

$$F = \frac{100 - 25}{100} \times 100 = 75\%$$

Figure 2.

This means that the container is 75% full and should be included in the waste collection list. Based on the calculated value, the system classifies the container status into different categories.

Fill level	Status	System decision
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0-49%	Normal	Monitoring continues
50-74%	Medium	More frequent observation is required
75-89%	Warning	Container is added to the collection list
90-100%	Critical	Immediate alert is generated

Table 1.

After calculating the fill level, the microcontroller forms a data packet. The packet includes the container ID, fill level, temperature value, gas value, location coordinates, status, and timestamp. This data packet is then transmitted to the server using a wireless communication module. Depending on the deployment environment, Wi-Fi, GSM, LoRa, or NB-IoT technologies can be used. Wi-Fi is suitable for small-scale and urban areas with stable internet access, while GSM, LoRa, and NB-IoT are more appropriate for wider city infrastructure and remote locations.

In the server stage, the transmitted data are received, checked, and stored in a database. The database stores all important information related to the waste containers, including container number, location, fill level, environmental sensor values, alert status, and last update time. This allows the system to maintain historical records and analyze changes in container conditions over time.

The monitoring dashboard is the main visualization component of the proposed system. It provides real-time information to municipal operators or waste management staff. Through the dashboard, users can observe the current status of each container, identify containers that are close to full capacity, and respond to critical conditions. The dashboard may display containers using different status indicators, such as normal, medium, warning, and critical. This makes the decision-making process faster and more convenient.

The proposed system also includes an alert generation mechanism. If the fill level exceeds the defined threshold, the system automatically generates a warning. If the fill level reaches a critical value, an urgent notification is sent to the responsible operator. Similarly, if the temperature or gas value exceeds the safe limit, the system sends an environmental safety alert. This mechanism helps prevent container overflow, fire risk, and possible sanitary problems.

In addition, the server-side component can be designed to support data analysis and reporting functions. By collecting historical data from each waste container, the system can identify usage patterns, peak waste generation periods, and areas with high waste accumulation. This information can be useful for municipal authorities in planning collection schedules, allocating vehicles, and improving the overall efficiency of waste management operations.

Another important feature of the proposed system is its scalability. New waste containers can be added to the system by registering their unique identification numbers and location coordinates in the database. This makes the system suitable not only for small pilot areas, but also for larger urban environments. As the number of monitored containers increases, the system can continue to operate through a centralized server and structured database management.

The integration of real-time monitoring with historical data analysis also creates a basis for future predictive functions. For example, by analyzing previous fill-level records, the system may estimate when a specific container is likely to become full. This can help waste collection services move from reactive management to predictive and preventive management.

Furthermore, the proposed system can be integrated with GPS-based route optimization modules. In this case, containers that reach warning or critical levels can be automatically included in the collection route. As a result, waste collection vehicles can follow more efficient routes, reduce unnecessary travel distance, save fuel, and decrease carbon emissions.

Overall, the server, database, dashboard, and alert modules work together as a unified digital monitoring environment. This structure improves transparency, reduces manual control, and supports faster decision-making in municipal waste management. Therefore, the proposed system can serve as a practical technological solution for smart city infrastructure and sustainable environmental management.

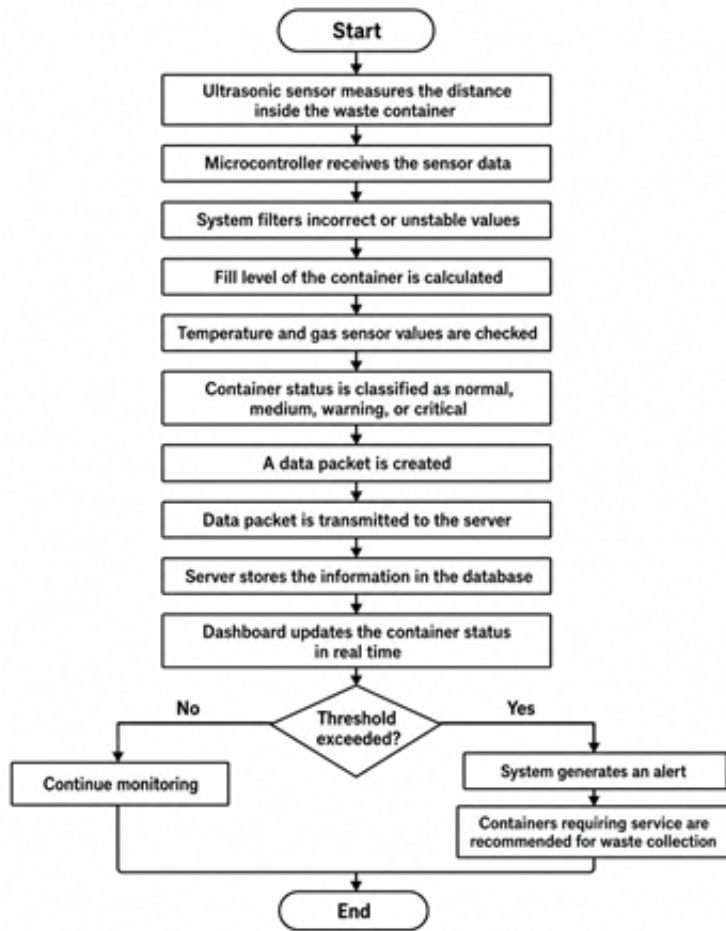


Figure 3.

Fig.1. General working algorithm of the proposed system

III. Result and Discussion

A series of prototype-based experiments were conducted to evaluate the performance of the proposed real-time waste monitoring system based on IoT sensors. During the experiments, waste containers with different fill levels were used to test the accuracy of the ultrasonic sensor, the stability of data transmission, and the effectiveness of the alert generation mechanism. The main purpose of the experiment was to determine how accurately the system could monitor container conditions and support timely waste collection decisions.

The obtained results showed that the proposed system was able to detect the fill level of waste containers with acceptable accuracy. The ultrasonic sensor successfully measured the distance between the sensor and the waste surface, and the microcontroller calculated the fill percentage based on the predefined container height. The system classified container conditions into normal, medium, warning, and critical levels. This classification allowed operators to quickly identify containers requiring collection.

To evaluate the system performance, several indicators were considered, including fill-level accuracy, data transmission delay, alert generation time, and monitoring stability. The results confirmed that the system could transmit sensor data to the server in real time and update the monitoring dashboard without significant delay. In particular, when the fill level exceeded the defined threshold, the system automatically generated an alert and recommended the container for waste collection.

The experimental results also demonstrated that the preprocessing and filtering stage improved the reliability of sensor readings. Since ultrasonic measurements can be affected by irregular waste surfaces, dust, humidity, and sensor placement, repeated measurements were averaged to reduce unstable values. This approach helped increase the accuracy of fill-level detection and reduced the possibility of false alerts.

Compared with the traditional waste collection approach, the proposed IoT-based system showed several advantages. In the

traditional model, containers are usually checked manually or collected according to a fixed schedule. This may result in unnecessary vehicle trips or delayed collection of full containers. In contrast, the proposed system provides real-time information about each container and allows waste collection to be organized based on actual container conditions.

Evaluation criterion	Traditional system	Proposed IoT-based system
Container status detection	Manual inspection	Automatic monitoring
Data update	Periodic or delayed	Real time
Collection planning	Fixed schedule	Based on fill level
Overflow prevention	Limited	High
Resource efficiency	Low	Improved
Operator decision-making	Based on assumptions	Based on sensor data

Table 2.

The results indicate that real-time monitoring can significantly improve the efficiency of municipal waste management. By identifying containers that are nearly full or critical, the system helps reduce unnecessary inspections, prevent overflow, and improve service quality. Moreover, the use of temperature and gas sensors increases environmental safety by allowing the system to detect abnormal conditions inside the container.

Overall, the results and discussion confirm that the IoT sensor-based real-time waste monitoring system is an effective solution for smart waste management. The proposed approach supports automatic container monitoring, timely alert generation, and data-driven waste collection planning. In the future, the system can be further improved by integrating GPS-based route optimization, mobile applications, artificial intelligence-based fill-level prediction, and cloud-based analytics. This would increase the practical value of the system and support its wider application in smart city infrastructure.

IV. Conclusion

In this study, a real-time waste monitoring system based on IoT sensors was developed and analyzed. The proposed approach enables automatic detection of waste container fill levels using ultrasonic sensors, microcontrollers, wireless communication modules, a server, a database, and a monitoring dashboard. Compared with traditional waste collection methods, the system provides faster, more accurate, and more reliable information about container conditions.

The results showed that the proposed IoT-based system can effectively classify waste containers into normal, medium, warning, and critical states. This makes it possible to identify full or nearly full containers in time and prevent overflow. The automatic alert generation mechanism also helps municipal service operators respond quickly to critical situations and organize waste collection based on real-time data rather than fixed schedules.

Moreover, the use of temperature and gas sensors increases the environmental safety of the system. These sensors allow the detection of abnormal conditions inside containers, such as overheating or harmful gas concentration. The preprocessing and filtering of sensor data also improve the reliability of measurements and reduce the risk of false alerts.

In conclusion, the proposed IoT sensor-based real-time waste monitoring system has significant scientific and practical value for improving smart waste management and supporting smart city infrastructure. The system can reduce unnecessary vehicle trips, improve municipal service efficiency, prevent container overflow, and strengthen environmental monitoring. In the future, the system can be further improved by integrating GPS-based route optimization, mobile applications, cloud platforms, and artificial intelligence-based prediction models.

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