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Article

An Edge-Enabled Multi-Sensor IoT Framework for Real-Time Smart Waste Monitoring Using Raspberry Pi Pico W and Cloud Data Management

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Abstract: : The rapid rise of urban populations and the production of municipal solid waste has led to the increasing occurrence of overflowing waste bins, inefficient fixed-time collection, dangerous gas accumulation, and a lack of access to real-time waste information. Current low-cost smart trash monitoring systems are mostly confined to single-sensor systems, simple fill-level detection, limited edge processing, lack of cloud integration and scalability to multi-bin systems. The design and development of an edge-enabled Internet of Things (IoT) smart trash monitoring platform using a Raspberry Pi Pico W for real-time multi-sensor data collecting, local processing, automated operation, and cloud-based data management is described in this research. The suggested system consists of an infrared proximity sensor to identify the user, a servo motor to automatically operate the lid, a metal detection module to identify metallic waste locally, an ultrasonic sensor to measure the fill level of the waste, a gas sensor to monitor gaseous conditions, and a moisture sensor to measure the moisture of the waste. The main edge computing node is the Raspberry Pi Pico W, responsible for sensor collection, local data processing, parameter calculation, time synchronization, creation of JSON packets, and wireless transfer to the cloud. The processed waste data is communicated by Wi-Fi using REST-based communication and saved in an organized Supabase cloud database. The exclusive device identities and synced timestamps agree for unified data administration and ascendable process of numerous smart-bin nodes. The research legalizes the stable assembly of multi-sensor data, the timely automatic lid initial and finishing, local detection of metal substances, stable wireless communication, fruitful synchronization with the cloud based on REST, and the organized storing of real-time excess records. The created platform offers a low-cost, flexible, and scalable hardware and cloud organization for smart city intelligent waste management applications.
Keywords: Smart Waste Management, Internet of Things (IoT), Multi-Sensor Monitoring, Edge Computing

1. Introduction

The fast development of urbanisation and industrialisation has led to a rapid increase in the production of municipal dense waste, making actual and effective waste management one of the main tasks for contemporary smart towns. The outmoded waste gathering or collection procedures are constructed on immobile assortment plans and labour-intensive inspections, ensuing in normal overfilled bins, superfluous collection trips, inflated operational costs, improved fuel consumption, and pollution and the degradation of public hygiene. Additionally, these schemes only pay consideration to the level of junk fill and disregard other critical conservational restrictions such as gas accretion and moisture, which are indicators of waste decomposition and possible health dangers.

Recent developments in the IoT have made it possible to develop intelligent waste management systems that can monitor dustbin conditions continuously using embedded sensors, wireless communication and cloud computing technologies. Smart bins equipped with IoT technology provide real-time information that allows municipal authorities to optimize collection schedules and improve operational efficiency. Meanwhile, the widespread deployment of smart waste surveillance systems has become increasingly feasible due to the ready availability of low-cost embedded platforms with integrated wireless connectivity.

Existing smart waste monitoring systems, however, are typically single-sensing-parameter systems, primarily focusing on the waste fill level, or have limited integration of sensing, edge processing, and cloud data management. Most of the reported systems are primarily functioning as sensor gateways and send raw measurements to cloud servers, without performing any real local processing or supporting scalable multi-node deployments. Environmental monitoring, automatic lid operation and centralized cloud storage are often deployed as isolated functions instead of as part of an integrated edge-enabled platform.

This research provides a low-cost edge-enabled smart waste monitoring framework using the Raspberry Pi Pico W to address such challenges. The proposed system uses a servo motor for automatic actuation, an infrared proximity sensor for touch-free lid operation, a moisture sensor to identify wet waste, an ultrasonic sensor for fill-level monitoring, and an MQ135 gas sensor to monitor gaseous conditions. The Raspberry Pi Pico W handles real-time sensor acquisition, local data processing, parameter calculation, and wireless connectivity. Through RESTful APIs, the processed data is transferred to a cloud database hosted on Supabase, enabling centralised management and storage of numerous nodes. Future smart-city monitoring, analytics, and decision-support applications will have scalable support for the suggested architecture.

The main contributions of this work are summarised as follows:

1. Design of an economical edge-enabled smart waste monitoring system based on Raspberry Pi Pico W.
2. Integration of multi-sensor modules for waste fill level, gas concentration, moisture monitoring and touchless lid operation on a common embedded platform.
3. Real-time edge processing for sensor acquisition, parameter calculation and cloud communication with RESTful APIs.
4. Design of scalable cloud architecture with Supabase to centralise the storage and manage the data of different smart-bin nodes.
5. Experimental validation of the proposed prototype showing reliable sensing, automatic lid operation and real-time cloud synchronisation.

This is the structure of the remainder of the paper. The literature on IoT-based smart waste monitoring systems is reviewed in Section II. Section III provides an overview of the proposed system architecture. The cloud integration framework and edge processing are covered in Section IV. The experimental setup and performance evaluation are covered in Section V. In Section VI, the work is concluded and future research directions are discussed.

2. Literature Review

Sosunova and Porras [1] conducted numerous detailed reviews on smart city IoT-based waste management systems. In their study, they reviewed the existing sensing technologies, communication protocols, cloud platforms and intelligent waste collection strategies being adopted in modern municipal waste management. The review said that IoT technologies are very useful to increase the efficiency of waste monitoring and reduce unnecessary collection operations. However, the authors also noted that many of the existing systems are still limited to fill-level monitoring and lack integrated environmental sensing, edge intelligence, and scalable multi-node architectures.

Pardini et al. (2020) [2] proposed a smart waste management system for citizens. The proposed system improves waste collection efficiency with IoT devices and cloud-based monitoring. Their framework showed real-time monitoring and remote accessibility and promoted citizen participation in waste management. The proposed system could monitor waste-bin status, but was mainly focused on fill-level information. It did not have comprehensive environmental monitoring or local edge-based decision-making.

Akram et al. (2021) [3] studied the performance of IoT and long-range radio communication architectures for large-scale smart waste management systems. Their work showed that long-range communication technologies enhance the network coverage and facilitate effective monitoring of geographically distributed waste bins. However, the proposed architecture mainly focused on communication performance and did not consider local sensor processing, automatic actuation and multi-parameter environmental monitoring.

Longo et al. (2021) [4] proposed smart waste management for a university campus using 5G. They found that low-latency communication and high-speed data transmission could be beneficial for real-time waste monitoring. Cloud connection is efficient, but the dependence on sophisticated communication infrastructure leads to high deployment cost and limits useful applications in low-cost municipal environments.

A decision support framework utilising a digital twin for optimisation of municipal waste collection was proposed by Barth et al. (2023) [5]. They demonstrate how digital twins and waste monitoring data may improve route planning and operational efficiency. However, the proposed work was mainly on data analytics and decision support, but not on the embedded system design and real-time edge processing at the smart-bin level.

Kannan et al. [6] (2024) proposed the Smart Waste Management 4.0 framework by integrating digital technologies for sustainable management of waste. Their work discussed the application of IoT, artificial intelligence, automation and data analytics in next-generation waste management systems. The framework provides useful perspectives on intelligent waste management but is mostly conceptual and does not provide a complete low-cost hardware implementation with real-time edge processing.

Palagan et al. (2025) [7] proposed an IoT, edge computing, and blockchain-based smart waste management framework for sustainable smart cities. Using advanced computing technologies, we have developed improved security, data integrity and predictive waste management capabilities. But the framework demands more computational complexity and infrastructure needs, thus making practical deployment relatively costly for resource-limited municipal systems.

In 2025, Alsharif et al. [8] proposed an AIoT-enabled waste management architecture for smart municipal waste monitoring based on edge computing and LoRaWAN communication. They showed that artificial intelligence and low-power communication technologies together can increase scalability and predictive waste management. But the proposed system requires more advanced communication infrastructure and emphasises intelligent networking rather than full implementation of embedded systems with multi-sensors.

Table 1: Literature Review Findings

S. No.	**Author (Year)**	**Main Concept**	**Findings**	**Limitation**
1	Sosunova and Porras (2022) [1]	Systematic Review of Smart Waste Management	Comprehensive IoT waste monitoring and communication architecture assessment	Limited discussion of integrated edge intelligence and practical implementations
2	Pardini et al. (2020) [2]	Citizen-Oriented Smart Waste Monitoring	Real-time cloud-based waste monitoring with citizen participation	Primarily focuses on fill-level monitoring
3	Akram et al. (2021) [3]	Long-Range IoT Communication	Efficient long-range communication for distributed smart bins	Does not incorporate local edge processing or environmental sensing
4	Longo et al. (2021) [4]	5G Smart Waste Monitoring	Low-latency communication and real-time monitoring	Requires costly 5G infrastructure

5	Barth et al. (2023) [5]	Digital Twin-Based Waste Management	Improves waste collection planning through digital twins	Focuses on analytics rather than embedded implementation
6	Kannan et al. (2024) [6]	Smart Waste Management 4.0	Integrates IoT, AI, and automation for sustainable waste management	Conceptual framework without complete prototype validation
7	Palagan et al. (2025) [7]	IoT, Edge Computing and Blockchain	Enhances security and intelligent waste management using advanced technologies	Higher implementation complexity and deployment cost
8	Alsharif et al. (2025) [8]	AIoT and LoRaWAN-Based Waste Management	Scalable intelligent waste monitoring using AIoT and edge computing	Focuses more on communication and AI than low-cost embedded implementation

3. Proposed Methodology

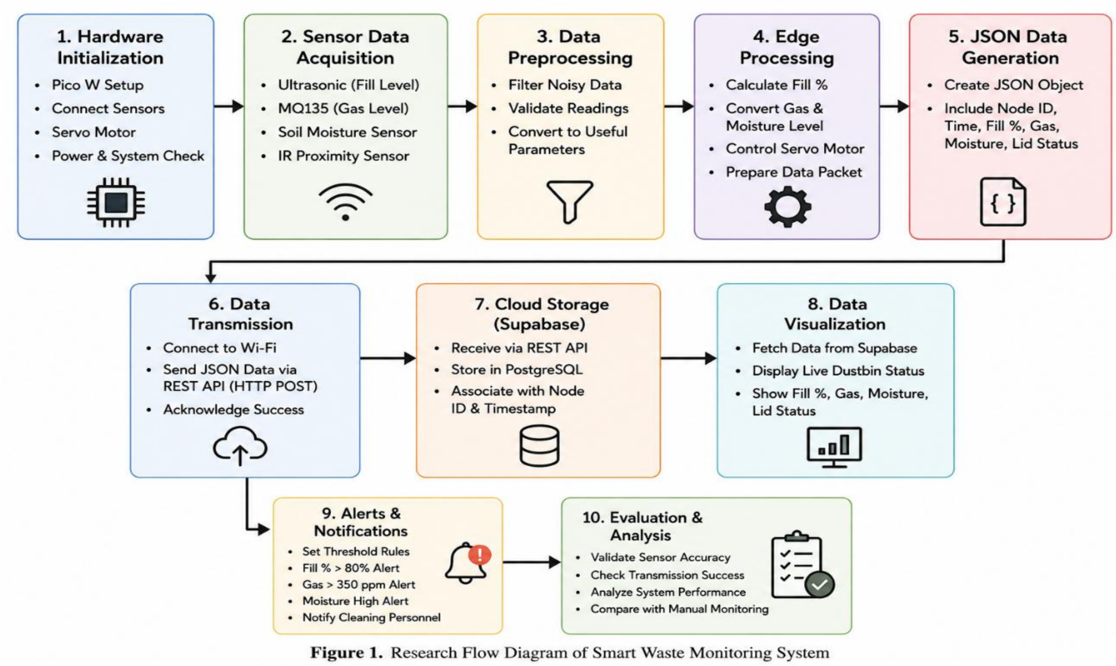

Figure 1: Research Flow Diagram

A real-time smart garbage monitoring system integrating edge-enabled IoT infrastructure, multi-sensor data collecting, local edge processing, wireless transmission, and cloud-based data management is proposed [1], [6]. The framework is used for the continuous tracking of the physical and environmental conditions of municipal garbage bins, reducing the need for manual inspection and improving operating efficiency. The complete roadmap comprises hardware initialization, sensor acquisition, edge processing, cloud connection, database maintenance, and investigational authentication, as shown in Figure 1.

The implementation starts with the deployment of the Raspberry Pi Pico W as the main embedded controller. It is responsible for the coordination of sensing, computing, communication, and actuator control [9]. The controller is interfaced with an HC-SR04 ultrasonic sensor, an MQ135 gas sensor, a soil moisture sensor, an infrared proximity sensor and an SG90 servo motor [10]-[12]. The ultrasonic sensor detects the waste fill level while the gas and moisture sensors monitor the environmental conditions inside the dustbin. The infrared sensor identifies nearby users and activates the servo motor, enabling the lid to be opened without contact [2], [13].

After the hardware startup, the Raspberry Pi Pico W connects to a wireless network through its onboard Wi-Fi interface and syncs the system time via the Network Time Protocol (NTP). Once the synchronisation is finished, the controller collects sensor data periodically. Ultrasonic sensors detect the distance between them and the waste surface, while MQ135 and moisture sensors assess gas concentration and moisture levels [10], [11]. Continuous sensing offers real-time observation for changing waste conditions and improved monitoring accuracy.

The sensor data collected are pre-processed locally before being transmitted to the cloud, so as to increase the reliability and consistency of the data. The signal reflections, which lead to invalid ultrasonic measurements, are filtered, and the analogue outputs of the gas and moisture sensors are normalised by means of specified calibration parameters [10]. Sensor values outside of permitted operating limits are rejected to avoid false observations entering the database. This preprocessing at the edge level reduces noise and boosts the quality of the sent information, thus boosting the reliability of dispersed IoT monitoring systems [14], [15].

Then, the Raspberry Pi Pico W executes edge-level computation after preprocessing to extract meaningful waste parameters from the collected sensor data. The percentage of waste fill is estimated using measured ultrasonic distance and pre-determined dimensions of dustbin [11]. Meanwhile, the gas concentration, moisture percentage and lid status are processed locally. The infrared sensor is constantly controlling the automatic lid operation when the user is recognised nearby [12]. Edge computing decreases the latency of communication and allows instant local reaction without reliance on persistent cloud connectivity [16], [17].

The processed observations are arranged into a JavaScript Object Notation (JSON) object with the unique node identifier, synchronized timestamp, trash fill percentage, gas concentration, moisture level, and lid status. The JSON records are sent in RESTful HTTP communication over the integrated Wi-Fi interface of the Raspberry Pi Pico W [18]. Standardized data interchange enables compatibility between embedded devices and cloud platforms, and reduces communication overhead in resource-constrained IoT scenarios [19].

The sensor observations are centrally stored in the proposed framework using the Supabase cloud platform with PostgreSQL [20]. Each uploaded record is tagged with a unique device identity and synchronised timestamp, which allows numerous smart waste bins to share the same cloud infrastructure. Cloud-based storage enables remote monitoring, historical data analysis and future dashboard creation, as well as scalability for large-scale smart city deployments [21], [22]. The modular architecture provides for the future integration of predictive analytics and intelligent garbage collecting strategies [7], [8].

The experimental implementation was performed on a laboratory-scale prototype consisting of Raspberry Pi Pico W, ultrasonic sensor, MQ135 gas sensor, moisture sensor, infrared sensor, servo motor and wireless connection module. The prototype was tested in multiple waste-fill states to validate sensor collection, fill-level estimation, gas monitoring, moisture sensing, automatic lid operation, REST API connection, and cloud synchronisation [3], [4]. The collected results show that the suggested technique provides a reliable, scalable and low-cost solution for intelligent municipal trash monitoring and future smart-city waste management applications [1], [8].

4. Proposed Work

An edge-enabled IoT-based smart trash monitoring system uses multi-sensor integration, local edge computing, and cloud-based data management to monitor municipal waste bins continuously. Raspberry Pi Pico W is the central embedded controller for the system, collecting data from an HC-SR04 ultrasonic sensor, an MQ135 gas sensor, a soil moisture sensor and an infrared proximity sensor.

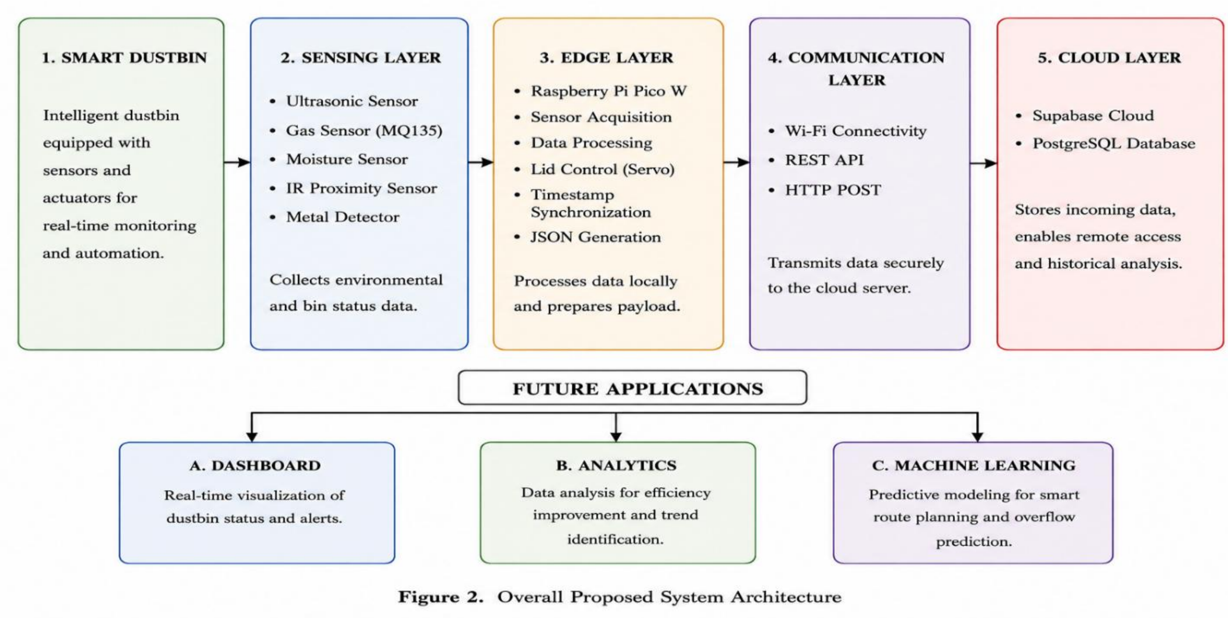

Figure 2: Overall Proposed System Architecture

It also controls SG90 servo motor for automatic lid action. Measurements from the sensors are processed locally to establish the level of garbage fill, gas concentration, moisture content, and user presence before being converted to structured JSON records. To enable real-time remote monitoring and storage, processed data is transferred to a Supabase PostgreSQL database via Wi-Fi RESTful HTTP communication. Sectional planning consents for scalable arrangement of numerous smart dustbin baskets and delivers the infrastructure for future incorporation of intelligent garbage analytics, dashboard visualization and optimal garbage collecting techniques. Fig. 2 depicts the suggested system's design.

4.1. Hardware Architecture

The proposed smart garbage monitoring process is based on a low-cost edge-enabled IoT architecture comprising of numerous sensing segmented nodes, an embedded controller, wireless connectivity and an automatic lid control device. The Raspberry Pi Pico W serves as the primary processing unit. It gathers sensor data, does local edge processing, and transmits processed data through Wi-Fi to the cloud [9]. The sensing layer consists of an HC-SR04 ultrasonic sensor for fill level measurement [11], an MQ135 gas sensor for gas detection [10], a soil moisture sensor, an IR proximity sensor and an SG90 servo motor for touch-free lid activation [12]. The whole hardware enterprise is illustrated in Figure 3, and the component specifications and operating parameters are reported in Tables 2 and 3.

Figure 3: Hardware Components

Table 2: Hardware Specification

Component	Model	Function	Interface
Edge Controller	Raspberry Pi Pico W	Sensor acquisition, edge processing, Wi-Fi communication	GPIO, ADC, PWM, Wi-Fi
Ultrasonic Sensor	HC-SR04	Measures waste fill level	Trigger/Echo (Digital)
Gas Sensor	MQ135	Detects harmful gases from waste	Analog
Moisture Sensor	FC-28 (or equivalent)	Detects moisture content in waste	Analog
IR Proximity Sensor	FC-51 (or equivalent)	Detects user presence	Digital
Servo Motor	SG90	Automatic lid opening and closing	PWM

Table 3: Sensor Operating Parameters

Sensor	Measured Parameter	Operating Range	Output Type
HC-SR04	Distance / Fill Level	2–400 cm	Digital
MQ135	Gas Concentration	10–1000 ppm*	Analog
Moisture Sensor	Moisture Level	0–100% (calibrated)	Analog
IR Proximity Sensor	Object Detection	2–30 cm	Digital
SG90 Servo Motor	Angular Position	0°–180°	PWM Control

4.2. Sensor Integration and Edge Processing

Multiple sensing modules and the Raspberry Pi Pico W monitor waste bin conditions in real time. Controller periodically reads the HC-SR04 ultrasonic sensor, MQ135 gas sensor, soil moisture sensor, and infrared proximity sensor through its digital and analogue interfaces [9]. Ultrasonic sensors assess the distance between the waste surface and the sensor, which is converted into waste fill % using dustbin dimensions [11]. The MQ135 sensor measures the concentration of toxic gases [10], and the moisture sensor measures the moisture level of collected waste in contrast. User presence initiates the SG90 servo motor for touch-free lid operation through the IR proximity sensor [12].

The captured sensor data are validated and processed locally by applying edge computing techniques [14], [15]. Invalid measurements are filtered, analogue values are calibrated and normalised, and fill percentage is obtained before applying the predefined threshold values to identify the abnormal waste circumstances. Then, the analysed observations are timestamped and formatted into a JSON object to be sent to the cloud using a RESTful HTTP connection [18]. The observations from the ultrasonic sensor and the relevant stages of the edge processing are summarised in Tables 4 and 5.

Table 4: Ultrasonic Sensor Observation

Trial	Actual Fill (cm)	Measured Fill (cm)	Error (%)
1	5	5.1	2.00
2	10	9.9	1.00
3	15	15.2	1.33
4	20	19.8	1.00
5	25	25.3	1.20

Table 5: Edge Processing Observation

Observation	Input	Processing	Output
Fill Level	Ultrasonic Distance	Fill-Level Calculation	Fill Percentage (%)
Gas Sensor	Analog Reading	Calibration & Threshold Checking	Gas Level (ppm)
Moisture Sensor	Analog Reading	Normalization	Moisture Percentage (%)
IR Sensor	Digital Signal	Proximity Detection	Servo Motor Control
Timestamp	NTP Time	Time Synchronization	Date & Time
JSON Packet	Processed Sensor Data	JSON Serialization	Structured JSON Object

4.3. Cloud Communication and Database

The processed sensor observations are then transferred from the Raspberry Pi Pico W to the cloud using its embedded Wi-Fi module and RESTful HTTP connection [18], [9]. The controller unit receives the sensor measurements locally and processes them to create the structured JSON object comprising the device identifier, waste fill percentage, gas level, moisture level, lid status and synchronous timestamp. The JSON payload is sent to the Supabase cloud platform using an HTTP POST request, allowing for robust communication between the edge device and the centralised database. The inconsequential communication technology permits effective data exchange, diminishes the transmission delay, and supports real-time monitoring of the disseminated smart garbage dust bins.

The received sensor annotations are stored in the Supabase platform in a PostgreSQL database where each separate record is individually recognized by the device identification, the reading date and the reading time [20]. The centralized database allows the continual saving of the significant sensor values and simplifies remote access to various smart waste monitoring nodes. Timestamp synchronization helps ensure that all uploaded observations are suitably time-stamped, thus cumulative the consistency of data in discrete arrangements. Moreover, the cloud architecture provides a scalable platform for future dashboard visualization, intelligent unused waste analytics, prophetic preservation, and decision-support applications for smart city waste management [21], [8]. Table 6 and Table 7 provide the database schema and cloud communication observations.

Table 6: Database Schema

Column	Data Type	Description
id	Integer	Primary key
device_name	Varchar(50)	Unique smart bin identifier
reading_date	Date	Date of sensor measurement
reading_time	Time	Time of sensor measurement
fill_level	Float	Waste fill percentage (%)
gas_level	Float	Gas sensor reading (ppm)
moisture_level	Float	Moisture percentage (%)
lid_status	Boolean	Servo lid status (Open/Closed)

Table 7: Cloud Communication Observation

Trial	Upload Time (s)	HTTP Status	Database Updated
1	1.18	200 (OK)	Yes
2	1.12	200 (OK)	Yes
3	1.25	200 (OK)	Yes

4	1.16	200 (OK)	Yes
5	1.20	200 (OK)	Yes

4.3. Prototype Development and System Validation

The edge-enabled IoT framework was evaluated with a lab-scale smart waste monitoring system prototype. The prototype employs the Raspberry Pi Pico W, HC-SR04 ultrasonic sensor, MQ135 gas sensor, soil moisture sensor, infrared proximity sensor, and SG90 servo motor for real-time sensing, edge processing, wireless communication, and automatic lid control [9]. The hardware modules were connected as per the suggested system design, with MicroPython used to implement the sensor interfacing, data collecting, actuator control and cloud connectivity. The application is compressed and adaptable, providing a cost-effective platform for real-time smart waste monitoring.

The software resolution contains of discrete modules for sensor acquisition, edge processing and cloud connectivity. The sensor readings are taken at regular intervals, checked for validity and processed locally to determine the percentage of the waste fill, monitor the gas concentration, measure the moisture level and operate the automatic lid mechanism. The processed explanations are turned into structured JSON packets including device identifier, timestamp, and sensor measurements before being sent to the Supabase cloud platform via a RESTful HTTP connection [18], [20]. The proposal plan qualifies a scalable deployment of several smart waste monitoring nodes and provides reliable communication between the embedded device and the cloud.

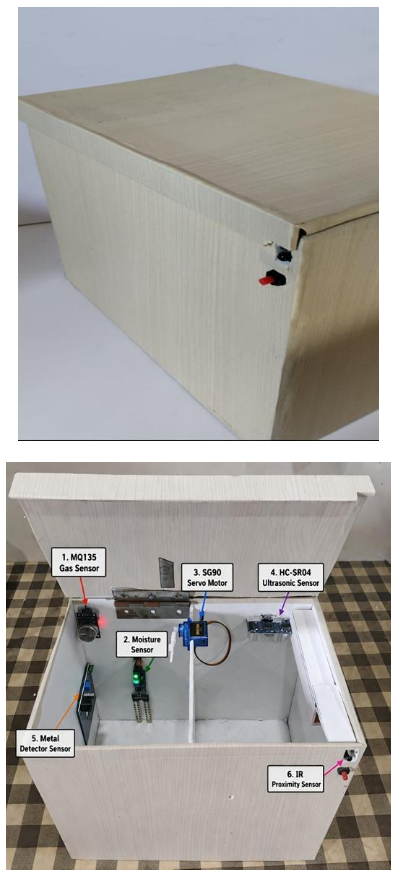

Figure 4: Developed Prototype of the Proposed Smart Waste Monitoring System

Created prototype was experimentally tested under varied waste situations to assess the performance of the integrated sensing, processing and communication components. The ultrasonic sensor measured waste fill level, the MQ135 sensor measured gas concentration, and the moisture sensor detected waste moisture during testing [10], [11]. The infrared proximity sensor was used to identify the presence of the user and to drive the SG90 servo motor to allow touchless lid operation [12]. The processed observations were produced periodically and readied for transmission to the cloud without interruption to the sensing operation.

The uploaded sensor observations are successfully recorded in the Supabase PostgreSQL database together with the device identifier and synchronized timestamp, which provides the ability to continuously monitor and manage previous data [20]. The full prototype exhibited robust end-to-end performance, such as sensor acquisition, edge processing, automatic lid control, wireless connection, and cloud synchronization. The successful installation demonstrates the feasibility of the suggested smart trash monitoring system in real-time municipal waste management applications. Tables 8 and 9 summarise the experimental design and the overall observations of the system, respectively.

Table 8: Experimental Configuration

Parameter	Value
Controller	Raspberry Pi Pico W
Communication	Wi-Fi (IEEE 802.11b/g/n)
Cloud Platform	Supabase
Database	PostgreSQL
Programming Language	MicroPython
Communication Protocol	RESTful HTTP
Data Upload Interval	30 s
Number of Sensors	5
Power Supply	5 V DC

Table 9: Overall System Observation

Fill Level (%)	Gas Status	Moisture Status	Lid Operation	Cloud Upload	System Status
12	Normal	Low	Successful	Yes	Normal
35	Normal	Low	Successful	Yes	Operational
58	Moderate	Medium	Successful	Yes	Operational
82	High	High	Successful	Yes	Warning
96	Critical	High	Successful	Yes	Bin Full

5. Conclusion

The study presented an edge-enabled IoT-based smart waste monitoring system for real-time municipal garbage bin monitoring using Raspberry Pi Pico W. The suggested system monitors waste fill level, ambient conditions, and automatic lid operation with HC-SR04 ultrasonic sensor, MQ135 gas sensor, soil moisture sensor, IR proximity sensor, and SG90 servo. Edge computing processes the sensor data locally, converts it into a structured JSON format, and forwards it to a Supabase PostgreSQL database using RESTful HTTP connection. Experimental validation showed reliable sensing, edge processing, cloud synchronization and wireless communication. The proposed architecture for smart waste management is scalable, low-cost, and efficient.

Future Work

Future work will integrate machine learning algorithms for trash generation prediction, fill-level prediction, and intelligent waste collection scheduling based on prior cloud data to optimize the proposed system. The addition of route optimization tools can further minimize collection time, fuel consumption and operational cost. Additional environmental sensors like temperature and humidity sensors may be added for better monitoring of the waste conditions. The establishment of a real-time web and mobile dashboard with automated alerting and analytics will improve decision support for municipal authorities." Large-scale multi-node deployment and AI-based predictive analytics would improve the smart waste monitoring system's scalability, dependability, and intelligence.

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