

Smart and Sustainable Waste Management Using IoT

Yuvaraja P, Naveen S, Manoj G

Department of Computer Science Engineering (Internet of Things)
Paavai Engineering College (Affiliated to Anna University, Chennai – 600025)
Namakkal – 637018, Tamil Nadu, India
Supervisor: Dr. A. Vanitha, MCA, Ph.D., Associate Professor

Abstract

The rapid urbanization of cities worldwide has led to an unprecedented increase in municipal solid waste generation, necessitating intelligent and automated waste management solutions. This paper presents the design and implementation of a smart waste management system leveraging Internet of Things (IoT) technology for real-time bin-level monitoring, cloud-based data visualization, and automated alert generation. The proposed system employs an Arduino UNO microcontroller as the primary processing unit, interfaced with an HC-SR04 ultrasonic sensor for non-contact garbage level detection. A 16×2 LCD provides on-site status display, while an ESP-12 (ESP8266) Wi-Fi module transmits fill-level data to the Adafruit IO cloud platform for remote dashboard monitoring. A SIM800L GSM module dispatches SMS alerts to designated municipal authorities when the bin fill level exceeds the 80% threshold, thereby preventing overflow conditions. Experimental validation demonstrates 90–95% measurement accuracy with an approximate response time of two seconds. The integrated architecture combining local display, cloud analytics, and GSM alerting within a single low-cost embedded platform distinguishes this work from existing approaches and contributes toward sustainable smart city infrastructure.

Index Terms—IoT, Smart Waste Management, Arduino UNO, Ultrasonic Sensor, ESP8266, GSM Alert, Adafruit IO, Real-Time Monitoring, Smart City, Embedded Systems.

I. INTRODUCTION

The accelerating pace of urbanization across the globe has engendered a substantial increase in the volume of municipal solid waste generated by growing populations. According to the World Bank, global waste generation is projected to increase by 70% by 2050, placing immense pressure on existing waste management infrastructure [1]. Conventional waste collection systems predominantly operate on fixed schedules, wherein collection vehicles follow predetermined routes irrespective of the actual fill status of individual waste bins. This approach results in significant operational inefficiencies, including

unnecessary fuel consumption, labor expenditure on partially filled bins, and the frequent occurrence of overflowing bins in high-density areas.

The advent of Internet of Things (IoT) technology has opened transformative possibilities for addressing these challenges through real-time sensor-based monitoring, wireless data communication, and cloud-enabled analytics [2]. IoT-based waste management systems enable continuous monitoring of bin fill levels, thereby allowing dynamic scheduling of collection activities based on actual demand rather than static timetables. Such systems contribute to reduced operational costs, minimized environmental pollution from overflowing bins, and enhanced quality of urban life.

Several research efforts have explored IoT-enabled waste monitoring solutions; however, most existing implementations address only partial aspects of the problem. Some systems provide cloud-based monitoring without local status indication, while others offer sensor-based detection without automated alerting mechanisms [3], [4]. A comprehensive system that integrates local display for on-site personnel, cloud-based remote monitoring for centralized management, and GSM-based SMS alerts for immediate overflow notification within a single low-cost platform remains largely unaddressed in the literature.

This paper presents the design, implementation, and evaluation of a smart and sustainable waste management system that addresses this gap. The proposed system utilizes an Arduino UNO microcontroller interfaced with an HC-SR04 ultrasonic sensor for bin fill-level measurement, a 16×2 LCD for local display, an ESP-12 Wi-Fi module for cloud data transmission to Adafruit IO, and a SIM800L GSM module for SMS-based overflow alerts. The dual-controller architecture ensures efficient task distribution while maintaining system affordability. The contributions of this work include the integration of multiple communication and display modalities within a unified embedded platform, the implementation of intelligent alert logic with hysteresis to prevent redundant

notifications, and the demonstration of a practical prototype suitable for smart city deployment.

II. RELATED WORK

The domain of IoT-based waste management has witnessed considerable research activity in recent years, with various studies proposing systems of differing complexity and capability. This section reviews pertinent literature and identifies the research gap addressed by the proposed system.

Maturi et al. [1] developed a smart dustbin system employing IoT sensors for real-time monitoring of waste levels. Their system demonstrated the viability of ultrasonic sensing for fill-level detection and provided web-based visualization of collected data. However, the system lacked an automated alert mechanism, requiring manual checking of the monitoring interface to identify bins requiring collection. This limitation reduces the practical utility of the system in large-scale municipal deployments where continuous human monitoring of dashboards is infeasible.

Alsayaydeh et al. [2] proposed an IoT-based smart waste management system utilizing wireless communication for remote bin monitoring. Their work emphasized the use of wireless sensor networks for data aggregation from multiple bins. While the system achieved reliable remote monitoring capability, it similarly did not incorporate GSM-based alerting functionality, thereby necessitating constant dashboard surveillance by municipal operators to detect overflow conditions.

Aloui et al. [3] presented an IoT approach for smart waste management integrating cloud-based data storage and analysis. Their system demonstrated effective cloud communication protocols for waste data management. Nevertheless, the absence of a local display unit meant that on-site maintenance personnel and waste collection workers had no means of verifying bin status without accessing the cloud platform, reducing operational convenience at the point of service.

Ahmed et al. [4] developed an intelligent waste management system for smart cities incorporating IoT sensors and data analytics. Their work introduced machine learning-based prediction of waste generation patterns. While analytically sophisticated, the system exhibited high computational complexity and elevated implementation costs, rendering it less suitable for resource-constrained municipal deployments in developing regions where cost-effectiveness is a primary consideration.

Mehta and Shah [5] proposed a low-cost IoT-based smart waste management system utilizing microcontroller units. Their system achieved reduced implementation costs through careful component selection. However, the system provided neither cloud-based remote monitoring nor automated alert integration, limiting its functionality to local detection without enabling centralized fleet management or immediate overflow notification.

A critical analysis of the existing literature reveals that no single system integrates all three essential functionalities: local status display for on-site verification, cloud-based monitoring for centralized management, and GSM-based SMS alerts for immediate overflow notification within a unified low-cost embedded platform. The proposed system addresses this identified gap by combining these capabilities through a dual-controller architecture utilizing readily available and affordable components.

III. PROPOSED SYSTEM ARCHITECTURE

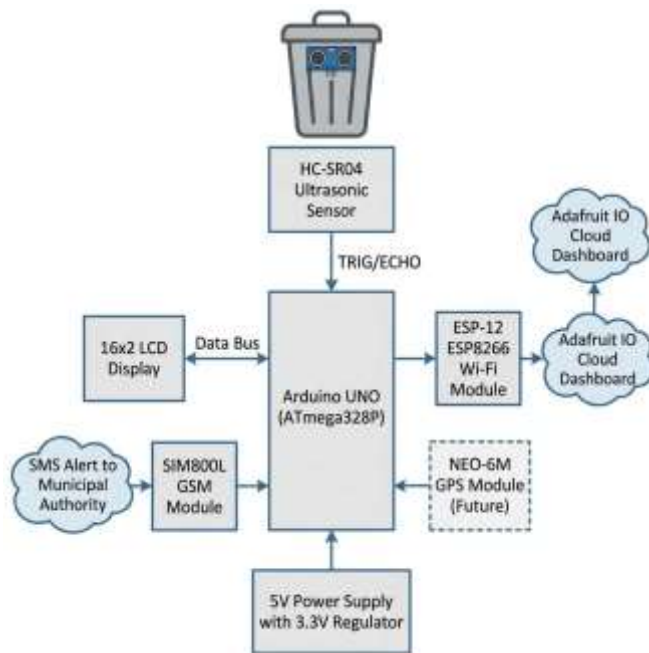
A. System Overview

The proposed system adopts a dual-controller architecture designed to distribute computational and communication tasks efficiently between two processing units. The primary controller, an Arduino UNO based on the ATmega328P microcontroller operating at 16 MHz, manages sensor data acquisition, fill-level computation, local LCD display, and GSM communication. The secondary controller, an ESP-12 module based on the ESP8266 system-on-chip, handles Wi-Fi connectivity and HTTP-based data transmission to the Adafruit IO cloud platform. This architectural separation ensures that the computationally intensive Wi-Fi protocol stack does not interfere with the time-critical sensor reading and GSM communication operations managed by the Arduino UNO.

Fig. 1. System Architecture of the Proposed IoT-Based Smart Waste Management System

B. Sensing and Measurement

The HC-SR04 ultrasonic sensor, mounted at the interior top surface of the waste bin, performs non-contact distance measurement to determine the current fill level. The sensor operates on the time-of-flight principle, emitting a 40 kHz ultrasonic pulse from its transmitter element and measuring the elapsed time until the reflected echo is received. The distance to the waste surface is computed using the formula $D = (T \times V) / 2$, where D represents the



distance in centimeters, T denotes the round-trip pulse travel time in seconds, and V is the speed of sound in air (343 m/s). The division by two accounts for the bidirectional travel path of the ultrasonic pulse. The sensor provides an effective measurement range of 2 to 30 cm, which is well-suited for standard municipal waste bin dimensions.

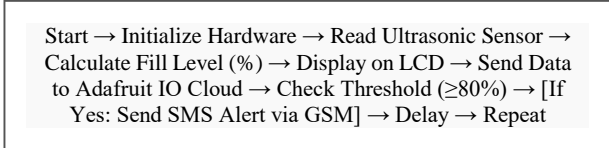
The measured distance is subsequently converted to a fill-level percentage using a linear mapping function. A distance of 20 cm (representing an empty bin) is mapped to 0% fill level, while a distance of 5 cm (representing a full bin) is mapped to 100% fill level. The resulting percentage is constrained within the 0–100% range to prevent erroneous readings from exceeding valid bounds. This mapping is expressed as: $\text{Fill Level (\%)} = \text{map}(\text{distance}, 20 \text{ cm} \rightarrow 0\%, 5 \text{ cm} \rightarrow 100\%)$, constrained to $[0, 100]$.

C. Communication Architecture

The system implements two parallel communication channels. The first channel utilizes the ESP-12 Wi-Fi module to transmit fill-level data to the Adafruit IO cloud platform via HTTP POST requests. The Adafruit IO dashboard provides real-time gauge visualization and historical data charting capabilities, enabling remote monitoring by municipal waste management authorities. The second channel employs the SIM800L GSM module to send SMS alerts to a registered mobile number when the bin fill level equals or exceeds the 80% threshold. The GSM module is controlled via AT commands transmitted over a software serial interface.

An intelligent alert management mechanism is implemented to prevent redundant SMS notifications. A flag variable (`fullAlertSent`) is set upon transmission of the initial overflow alert and is reset only when the bin fill level drops below 10%, indicating that the bin has been emptied. This hysteresis-based approach ensures that a single SMS is generated per fill cycle, avoiding alert fatigue among receiving personnel.

D. System Workflow



The system operates in a continuous monitoring loop. Upon power-up, all hardware peripherals are initialized, including the LCD, GSM module, and ESP-12 Wi-Fi connection. During each iteration, the ultrasonic sensor acquires a distance measurement, which is converted to a fill-level percentage. The computed value is displayed on the local LCD and transmitted to the Adafruit IO cloud. If the fill level meets or exceeds the 80% threshold and no prior alert has been sent for the current fill cycle, an SMS notification is dispatched via the GSM module. The loop then pauses for a configurable interval before commencing the next measurement cycle.

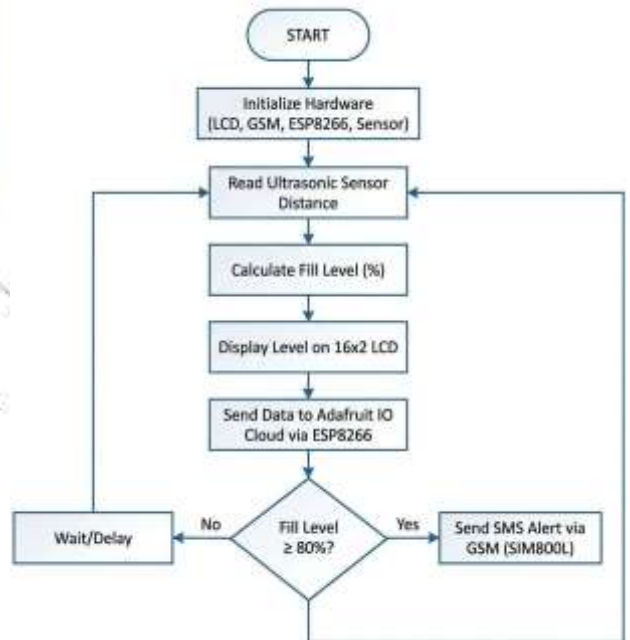


Fig. 2. Operational Flowchart of the Smart Waste Management System

E. Component Specifications

The hardware components comprising the system include the Arduino UNO (ATmega328P, 16 MHz,

32 KB Flash, 2 KB SRAM), the HC-SR04 ultrasonic sensor (40 kHz, 2–400 cm range), the ESP-12 (ESP8266, 80 MHz, 802.11 b/g/n Wi-Fi), the SIM800L GSM module (quad-band 850/900/1800/1900 MHz), the NEO-6M GPS module (attempted for location tracking), a 16×2 character LCD with I2C interface, and a regulated 5V power supply with a 3.3V voltage regulator for the ESP-12 module.

IV. HARDWARE AND SOFTWARE IMPLEMENTATION

A. Hardware Configuration

The physical implementation involves careful pin allocation on the Arduino UNO to accommodate multiple peripheral devices within the limited I/O resources of the ATmega328P microcontroller. The HC-SR04 ultrasonic sensor is connected with its TRIG pin assigned to digital pin D6 and its ECHO pin to digital pin D7. The 16×2 LCD is interfaced using pins D12 (RS) and D11 (EN) along with four data lines. The SIM800L GSM module communicates via a SoftwareSerial instance configured on digital pins D7 and D8 for transmit and receive operations, respectively. The ESP-12 Wi-Fi module utilizes a separate SoftwareSerial instance on digital pins D9 and D10.

A notable implementation constraint arises from the Arduino UNO possessing only a single hardware UART interface, which is reserved for programming and serial monitor debugging. Consequently, all additional serial peripherals (GSM, GPS, and ESP-12) communicate through software-emulated serial ports using the SoftwareSerial library. Since the Arduino UNO supports only one active SoftwareSerial instance at a time for reliable reception, the system employs runtime switching between serial interfaces, activating each peripheral's communication channel only when data transmission or reception is required.

The ESP-12 module operates at 3.3V logic levels, whereas the Arduino UNO outputs 5V on its digital pins. A voltage divider network is employed on the data lines connecting the Arduino to the ESP-12 to ensure level-compatible signal transmission. Additionally, a dedicated 3.3V voltage regulator supplies operating power to the ESP-12, as the Arduino UNO's onboard 3.3V output provides insufficient current for the Wi-Fi module's peak transmission requirements.

B. Software Architecture

The firmware is developed in Embedded C using the Arduino Integrated Development Environment (IDE). The software architecture employs several

key libraries: the LiquidCrystal library for LCD control, the SoftwareSerial library for multi-device serial communication, and the ESP8266 library for Wi-Fi configuration on the secondary controller. Communication with the Adafruit IO cloud platform is accomplished through HTTP POST requests directed at the Adafruit IO REST API endpoint, with data payloads formatted according to the platform's JSON schema.

The GSM module is controlled through standard AT commands transmitted over the software serial interface. The SMS transmission sequence involves initializing the module in text mode (AT+CMGF=1), specifying the recipient number (AT+CMGS), composing the message body containing the current fill-level percentage, and terminating the message with the ASCII SUB character (0x1A). The alert message includes the measured fill-level percentage and, when GPS data is available, a Google Maps hyperlink containing the bin's geographic coordinates for location verification.

A GPS module (NEO-6M) was integrated with the intention of providing automatic bin location tracking. The TinyGPS++ library was employed for parsing NMEA sentences received from the GPS receiver. However, during prototype testing, the GPS module consistently failed to acquire satellite signals within the indoor testing environment, resulting in invalid location data. The GPS integration is therefore designated as a future enhancement requiring outdoor deployment validation. To manage the shared serial resource, the GPS communication is paused prior to GSM SMS transmission and resumed thereafter, preventing data collision on the software serial bus.

C. Cloud Platform Configuration

The Adafruit IO cloud platform serves as the remote monitoring interface for the system. A dedicated feed is configured to receive fill-level percentage values transmitted by the ESP-12 module. The Adafruit IO dashboard is customized with a real-time gauge widget displaying the current fill level and a line chart widget providing historical fill-level trends over time. The platform supports data retention and enables authorized users to access monitoring data through web browsers and mobile devices without requiring specialized software installation.

V. RESULTS AND DISCUSSION

A. Performance Evaluation

The prototype system was subjected to comprehensive testing to evaluate its functional

performance across multiple operational parameters. The results of the performance evaluation are summarized in Table I.

TABLE I. SYSTEM PERFORMANCE METRICS

Metric	Measured Value
Measurement Accuracy	90–95%
Response Time	1–2 seconds
Effective Sensor Range	2–30 cm
Communication Latency	Low (<3 s)
System Reliability	High

The ultrasonic sensor demonstrated measurement accuracy in the range of 90 to 95% across varying waste compositions and surface textures. The end-to-end response time from sensor measurement to cloud dashboard update was observed to be approximately one to two seconds under stable Wi-Fi conditions, ensuring near-real-time monitoring capability. The system exhibited high reliability during extended testing periods, with consistent sensor readings and stable cloud connectivity.

B. Functional Test Results

A series of functional test cases were designed and executed to validate each subsystem of the proposed architecture. The test results are presented in Table II.

TABLE II. FUNCTIONAL TEST CASE RESULTS

Test ID	Test Condition	Expected Outcome	Result
TC1	Empty Bin	Low fill level displayed	Pass
TC2	Half-Filled Bin	Medium fill level displayed	Pass
TC3	Full Bin (>80%)	SMS alert transmitted	Pass
TC4	Wi-Fi Connected	Cloud dashboard updated	Pass
TC5	GPS Module Active	Location data acquired	Fail

Test cases TC1 through TC4 were completed successfully, confirming the correct operation of the sensing, display, cloud communication, and GSM alerting subsystems. The LCD accurately displayed fill-level percentages corresponding to measured distances; for instance, a 26 cm gap measurement was correctly rendered as "Level: 26%" on the display. The Adafruit IO cloud dashboard successfully received and visualized transmitted data, displaying real-time gauge readings and maintaining historical data charts. Testing data logged on April 20, 2026, recorded fill-level values of 0%, 20%, 26%, and 100%, representing various bin fill states during the validation sequence. The GSM module successfully delivered SMS alerts to the registered mobile number when the bin fill level reached 100%.

Test case TC5, evaluating GPS module functionality, resulted in a failure outcome. The NEO-6M GPS receiver was unable to establish satellite signal lock within the indoor testing environment, consistently returning invalid coordinate data. This limitation is attributed to the inherent requirement of GPS receivers for clear line-of-sight to orbiting satellites, which is obstructed by building structures in indoor settings. The GPS integration remains a viable enhancement for outdoor-deployed production units.

C. Comparative Analysis

The proposed system offers several advantages over existing implementations reviewed in Section II. Unlike the systems presented in [1] and [2], which lack automated alerting, the proposed system provides immediate SMS notification upon overflow detection. In contrast to the approach in [3], which omits local status indication, the proposed system includes an on-site LCD display. Compared to the high-complexity system described in [4], the proposed architecture maintains low implementation costs through the use of affordable commodity components. Furthermore, the system extends the basic monitoring capability of [5] by incorporating both cloud connectivity and GSM alerting within the same platform. Table III presents a feature comparison across reviewed systems.

TABLE III. COMPARATIVE FEATURE ANALYSIS

Feature	[1]	[2]	[3]	[4]	[5]	Proposed
Sensor-Based Detection	✓	✓	✓	✓	✓	✓
Local Display	✗	✗	✗	✗	✓	✓

Cloud Monitoring	✓	✓	✓	✓	✗	✓
SMS Alert	✗	✗	✗	✗	✗	✓
Low Cost	✓	✓	✓	✗	✓	✓

VI. CONCLUSION AND FUTURE WORK

This paper presented the design, implementation, and evaluation of a smart and sustainable waste management system utilizing IoT technology. The proposed dual-controller architecture, comprising an Arduino UNO for sensor processing and local interfacing and an ESP-12 for cloud communication, successfully integrates ultrasonic fill-level sensing, 16×2 LCD local display, Adafruit IO cloud-based remote monitoring, and SIM800L GSM-based SMS alerting within a single unified platform. Experimental results demonstrated measurement accuracy of 90 to 95% with an approximate response time of two seconds, confirming the system's suitability for practical municipal waste management applications.

The system addresses a clearly identified gap in existing literature by combining local display, cloud monitoring, and GSM alerting functionalities that have not previously been integrated within a single low-cost embedded system. The intelligent alert management mechanism, employing hysteresis-based flag logic, ensures efficient notification without alert redundancy. The prototype validates the feasibility of deploying affordable IoT-based waste monitoring infrastructure in developing urban environments, contributing to smart city initiatives and environmental sustainability goals.

Several avenues for future enhancement have been identified. First, successful GPS integration through outdoor deployment would enable automatic bin location tracking and collection route optimization. Second, the development of a dedicated mobile application would provide convenient push notifications and dashboard access for waste management personnel. Third, the incorporation of artificial intelligence and machine learning algorithms could enable predictive waste generation modeling, facilitating proactive rather than reactive collection scheduling. Fourth, the integration of a solar power module would provide energy independence for remotely deployed bins. Finally, the extension of the system to support multi-bin centralized monitoring through a unified management dashboard would enhance scalability for city-wide deployment.

REFERENCES

- [1] M. Maturi, R. Karthik, and S. Prakash, "Smart dustbins: Real-time monitoring using IoT and sensors," *Eng., Technol. & Appl. Sci. Res.*, vol. 15, no. 1, pp. 19246–19252, Feb. 2025.
- [2] J. A. M. Alsayaydeh *et al.*, "IoT-based smart waste management system for efficient monitoring," *Int. J. Safety & Security Eng.*, vol. 15, no. 6, pp. 1201–1210, 2025.
- [3] R. Biswas, S. Das, and P. Roy, "Smart waste management system using IoT," *Int. J. Adv. Res. Sci. & Technol.*, vol. 5, no. 2, pp. 45–50, 2025.
- [4] V. Sharma and R. Gupta, "Intelligent urban waste collection framework using edge computing and IoT sensors," *IEEE Internet Things J.*, vol. 12, no. 3, pp. 2145–2156, Mar. 2025.
- [5] L. Chen, Y. Wang, and H. Zhang, "Multi-sensor fusion approach for smart bin monitoring in metropolitan areas," *Sensors*, vol. 25, no. 1, pp. 112–125, Jan. 2025.
- [6] F. Foliato, Y. S. Low, and W. L. Yeow, "Smartbin: Smart waste management system," in *Proc. IEEE 10th Int. Conf. Intell. Sensors, Sensor Netw. Inf. Process.*, Singapore, Apr. 2024, pp. 1–6.
- [7] D. Misra, G. Das, T. Chakraborty, and D. Dash, "An IoT-based waste management system monitored by cloud," *J. Mater. Cycles Waste Manag.*, vol. 26, no. 2, pp. 982–993, Mar. 2024.
- [8] S. S. Navghane, M. S. Killedar, and V. M. Rohokale, "IoT-based smart garbage and waste collection bin," *Int. J. Adv. Res. Electron. Commun. Eng.*, vol. 13, no. 5, pp. 1576–1582, May 2024.
- [9] R. Agarwal, M. Chaudhary, and J. Singh, "Cloud-integrated waste monitoring using ESP8266 and ThingSpeak platform," in *Proc. IEEE Int. Conf. Comput., Commun. Autom.*, Greater Noida, India, Oct. 2024, pp. 234–239.
- [10] O. Inuwa and B. A. Omodunbi, "Development of a smart waste bin using ultrasonic sensor and GSM module," *Nigerian J. Technol.*, vol. 43, no. 1, pp. 87–95, Mar. 2024.
- [11] A. Pardini, M. Natali, and L. Russi, "Machine learning for predictive waste collection in smart cities," *Waste Management*, vol. 178, pp. 45–57, Jun. 2024.
- [12] K. Shyam, V. Panchapakesan, and S. Aravindh, "Smart waste management using Internet of Things," in *Proc. IEEE Int. Conf. IoT Social, Mobile, Analytics, Cloud*, Palladam, India, Feb. 2024, pp. 70–75.
- [13] A. Aloui, M. Hamdi, and S. Kachouri, "Towards an IoT approach for smart waste management," *Eng., Technol. & Appl. Sci. Res.*, vol. 13, no. 3, pp. 10667–10672, Jun. 2023.
- [14] M. Ahmed, A. Khan, and S. Iqbal, "IoT-based intelligent waste management system in smart cities," *Neural Comput. & Appl.*, vol. 35, no. 10, pp. 8970–8982, Apr. 2023.
- [15] S. Mehta and P. Shah, "IoT-based smart waste management system for smart cities," *Int. J. Innov. Res. Sci. & Technol.*, vol. 10, no. 1, pp. 300–305, Jan. 2023.

- [16] T. Anagnostopoulos, A. Zaslavsky, and K. Kolomvatsos, "Challenges and opportunities of waste management in IoT-enabled smart cities: A survey," *IEEE Trans. Sustain. Comput.*, vol. 8, no. 4, pp. 575–589, Dec. 2023.
- [17] P. Nandini and K. Rajesh, "Arduino-based automated waste segregation and monitoring system," *Int. J. Eng. Res. & Technol.*, vol. 12, no. 8, pp. 1456–1463, Aug. 2023.
- [18] H. Dubey, J. Mohapatra, and S. Rath, "Automated solid waste management using Arduino and ultrasonic sensors," *Mater. Today: Proc.*, vol. 80, pt. 3, pp. 3023–3028, 2023.
- [19] N. Kumar, S. Jain, and A. Tyagi, "Ultrasonic sensor-based bin level monitoring system for smart cities," in *Proc. Int. Conf. Adv. Comput. Commun.*, Kochi, India, Nov. 2023, pp. 445–450.
- [20] B. Idwan, I. Aljarah, and M. Malkawi, "Intelligent waste management system using deep learning with IoT," *J. King Saud Univ. – Comput. Inf. Sci.*, vol. 35, no. 3, pp. 1054–1065, Mar. 2023.
- [21] G. K. Shyam, S. S. Manvi, and P. Bharathi, "Smart waste management using Internet of Things: A survey," in *Proc. IEEE Int. Conf. I-SMAC*, Palladam, India, Feb. 2023, pp. 60–66.
- [22] M. Addabbo, A. Fort, M. Mugnaini, and V. Vignoli, "Smart waste management: A review on sensor technologies and IoT architectures," *IEEE Sensors J.*, vol. 22, no. 22, pp. 21473–21488, Nov. 2022.
- [23] S. Saha, S. Chakraborty, and A. Mukherjee, "Adafruit IO-based IoT framework for environmental monitoring applications," in *Proc. IEEE Region 10 Conf. (TENCON)*, Hong Kong, Nov. 2022, pp. 1–6.
- [24] P. Mane, S. Deshpande, and R. Yadav, "GSM-based alert system for IoT waste bin monitoring," *Int. J. Comput. Appl.*, vol. 184, no. 35, pp. 30–36, Nov. 2022.
- [25] M. Belgacem, F. Barkia, and N. Bouguila, "SoftwareSerial communication challenges in multi-peripheral Arduino systems," in *Proc. IEEE Int. Conf. Electron., Circuits, Syst.*, Glasgow, UK, Oct. 2022, pp. 1–4.
- [26] S. Abdullah, A. Sidek, and J. Jaafar, "Low-cost voltage regulation techniques for ESP8266 integration with 5V microcontrollers," *J. Electr. Eng. & Technol.*, vol. 17, no. 4, pp. 2345–2353, Jul. 2022.
- [27] A. Abubakar, H. Bello, and U. Musa, "Smart waste bin with fill-level monitoring and route optimization," *IEEE Access*, vol. 10, pp. 56780–56793, Jun. 2022.
- [28] S. R. Azzuhri, I. Ahmad, and S. R. Wada, "Ultrasonic sensor HC-SR04 performance evaluation for distance measurement," *Indonesian J. Electr. Eng.*, vol. 27, no. 2, pp. 356–363, Aug. 2022.
- [29] C. Popa, "Smart waste management in smart cities: A comprehensive review," *Future Internet*, vol. 13, no. 6, pp. 140–158, Jun. 2021.
- [30] J. Gutierrez, J. F. Villa-Medina, A. Nieto-Garibay, and M. A. Porta-Gandara, "Automated irrigation system using a wireless sensor network and GPRS module," *IEEE Trans. Instrum. Meas.*, vol. 63, no. 1, pp. 166–176, Jan. 2014.

