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International Journal on Advanced Computer Engineering and Communication Technology

ISSN: **2278-5140**

Volume 14 Issue 03s, 2025

Intelligent Waste Management System using Internet of Things (IoT)

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Peer Review Information

Submission: 05 Nov 2025

Revision: 25 Nov 2025

Acceptance: 17 Dec 2025

Keywords

Smart Dustbin, IoT, Arduino, Bluetooth Control, Rack-and-Pinion Mechanism, Sustainable Development Goals (SDGs)

Abstract

Rapid urbanization and population growth have made municipal solid waste management a pressing challenge, especially in regions where infrastructure development lags behind demand. This paper introduces an Intelligent Waste Management System that integrates Internet of Things (IoT) technologies with mechanical automation. The system consists of a smart bin equipped with a rack-and- pinion mechanism for waste sealing, an Arduino-based controller for automation, and a Bluetooth-enabled Android application for remote monitoring and control. Its main features include contactless waste disposal, automated wrapping and ejection of filled cartons, and capacity alerts through a buzzer and mobile notifications. Unlike conventional smart bins that only measure waste levels, the proposed system combines physical automation with user-friendly mobile integration, offering a more reliable and efficient solution.

The design contributes to the Sustainable Development Goals (SDGs)[1], particularly Goal 11 (Sustainable Cities and Communities) and Goal 12 (Responsible Consumption and Production), by promoting hygienic and environmentally responsible practices.

Introduction

The rapid growth of urban populations has placed increasing pressure on municipal solid waste management systems, particularly in developing regions where infrastructure often cannot keep up with demand. Traditional waste handling methods, which depend on manual collection and plastic liners, frequently result in overflowing bins, unhygienic conditions, and operational inefficiencies. These issues not only create health hazards but also contribute to environmental degradation. As cities move toward smart and sustainable infrastructure, the demand for automated and intelligent waste management solutions has become more urgent. Recent progress in the Internet of Things (IoT) has led to the development of smart bins capable of monitoring fill levels and transmitting alerts through sensors and cloud dashboards. While useful, most of these systems stop short at detection, still requiring human involvement for collection and disposal. To overcome this limitation, the proposed Intelligent Waste Management System combines IoT-enabled monitoring with mechanical automation. The system includes motion detection for automatic lid operation, a rack-and-pinion mechanism for carton insertion and ejection, and an automated wrapping unit for hygienic containment. Its operational cycle consists of waste detection, mobile-based monitoring, carton wrapping, automated ejection, capacity alerts, and system reset. By combining IoT-based monitoring, automated mechanisms, and eco-friendly materials, the system provides a scalable and practical solution suitable for smart cities, educational institutions, workplaces, and other urban spaces.

Literature Survey

Effective smart waste-management research spans several domains: sensor-based monitoring, app-based control, mechanical automation, AI-driven classification, and integrated IoT reviews.The carton-based wrapping and ejection system presented in this work builds on these strands while addressing a practical gap: ensuring reliable, hygienic, and sustainable automated waste handling.

1. **Sensor-based monitoring and level detection**

Low-cost sensors and microcontrollers have been widely applied to detect bin fill levels and optimize collection cycles. Ultrasonic sensors are particularly common because they provide reliable distance measurements that can be translated into fill levels. Sreejith et al. [2] designed an Arduino-based smart bin using ultrasonic sensors to detect waste accumulation and trigger alerts, proving the feasibility of low-cost embedded sensing for urban applications. Similarly, Mohapatra and Shirapuri [3] demonstrated an Arduino-based smart dustbin using ultrasonic sensors and simple actuation, reinforcing the practicality of sensordriven monitoring.

2. **Mobile and Bluetooth/app-based control**

Smartphone integration has been explored to provide real-time status updates and remote control. Mohapatra and Shirapuri [3] showed that coupling Arduino systems with Bluetooth modules and MIT App Inventor interfaces enables users to monitor waste levels and control actuators locally. Such systems are costeffective for small-scale or campus-level deployments, where full GSM or Wi-Fi connectivity is not essential.

3. Mechanical automation, wrapping, and ejection

While most studies focus on monitoring and alerts, fewer address the mechanical aspects of packaging and ejecting waste. Wijaya et al. [4] developed a smart bin prototype with embedded sensors and microcontrollers, but manual intervention was still required for waste disposal. Surveys of smart dustbin systems indicate that while robotics and automation are possible, they are often expensive or impractical for fixed installations [5]. This highlights a gap in the literature: the need for affordable, low-cost mechanical handling solutions. The proposed carton-based wrapping and rack-and-pinion ejection directly addresses this challenge by replacing fragile garbage bags with rigid cartons.

4. Edge AI and IoT reviews in smart waste management Recent advances in smart waste management integrate edge AI with IoT, where models like *WasteNet* enable real-time waste classification on devices such as Jetson Nano (White et al. [6]; Arishi [7]). Reviews further highlight trade-offs in cost, energy, and scalability, stressing the need for modular, ML-driven IoT architectures for practical deployment (Arthur et al. [8]; Kannan et al. [9]).

5. Where this work fits

From the literature, it is evident that most smart bins concentrate on monitoring and notifications, with limited progress in automated handling. By introducing cartons as uniform, recyclable waste containers, this research closes a key gap: transforming the smart bin from a passive sensing device into an active, hygienic, and sustainable mechanical system.

System Design And Methodology

The proposed Intelligent Waste Management System is designed to integrate IoT-based monitoring, mechanical automation, and mobile application control into a cohesive and practical solution for modern urban environments. The system addresses limitations of traditional waste management methods and conventional smart bins, including the need for manual disposal, inconsistent waste containment, and hygiene concerns. By combining modular mechanical design with IoT-enabled electronics and a user-friendly interface, the system delivers a scalable, cost-effective, and environmentally sustainable approach to waste handling.

A. System Architecture

The intelligent waste management system is conceptualized as a hybrid architecture that merges three core subsystems: mechanical assembly, IoT-based electronics, and mobile application control. Each subsystem plays a vital role in ensuring smooth operation, hygienic waste handling, and real-time monitoring. The system has been optimized for both small-scale applications, such as office spaces and campuses, and larger urban deployments, aligning with the principles of smart cities.

The primary objectives of the system include:

1. Ensuring hygienic, contactless waste disposal.
2. Automating the insertion, wrapping, and ejection of waste containers.
3. Providing real-time monitoring and remote control via a mobile interface.
4. Supporting standardized waste containment using recyclable cartons to reduce

environmental impact.
As shown in Figure 1, the system consists of three core subsystems: mechanical assembly,IoT-based electronics, and mobile application interface.

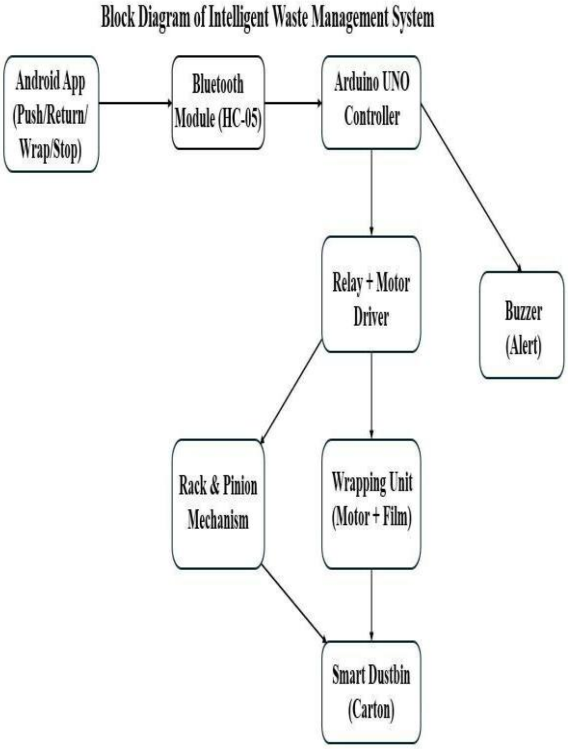

Figure 1. Block diagram of the Intelligent Waste Management System using IoT

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B. Mechanical Design

The mechanical subsystem forms the backbone of the proposed system, providing reliable and repeatable operations for waste handling. Key components of the mechanical design include:

1. **Dustbin Body**: The dustbin body is fabricated from 22-gauge
mild steel, with dimensions of 24″× 24″ × 24″. This cubic structure ensures durability,stability, and easy integration with mechanical components. The choice of steel provides long term robustness while maintaining a manageable weight for installation in diverse locations.

2. **Carton-Based Waste Containment**: The system uses standardized 14″ × 14″ × 14″ corrugated cardboard cartons as waste containers. Unlike plastic bags, cartons maintain their cubic shape during insertion, wrapping, and ejection. This eliminates misalignment, reduces tearing, and facilitates reliable automated handling.Additionally, cartons are recyclable, contributing to sustainability goals and minimizing environmental footprint.

3. **Rack-and-Pinion Mechanism**: Central to the mechanical subsystem is the rack-and-pinion assembly. Rotational motion from a DC motor is converted into linear motion to push and pull
cartons along predefined paths. The mechanism ensures precise positioning of cartons during insertion and ejection, reducing the likelihood of jams or operational failures. The rack-and-pinion design is compact, cost-effective, and easily integrated with Arduino-based motor control.

4. **Wrapping Mechanism**: A motor-driven rotating plate wraps full cartons with a biodegradable plastic film or alternative recyclable material. This mechanism ensures that waste is securely
contained, preventing leaks, odors, and potential contamination. The wrapping system operates automatically once a carton reaches capacity, minimizing human intervention and maintaining high hygiene standards.
5. **Safety and Feedback Components**: To enhance operational safety and monitoring, the mechanical design incorporates limit switches, sensors, and abuzzer system. Limit switches detect the extreme positions of the rack-and-pinion mechanism, preventing over-travel or mechanical damage. The buzzer provides auditory alerts when cartons are full or if a mechanical fault occurs.

C. Electronics and IoT Subsystem

The IoT-based electronics subsystem enables monitoring, control, and communication between the mechanical components and the mobile application.
Key elements include:
1. **Arduino Uno Microcontroller**: Serving as the central controller, the Arduino Uno receives input from sensors and mobile commands and drives actuators accordingly. Its versatility, low cost, and ease of programming make it ideal for prototyping and deployment in smart waste systems.
2. **Bluetooth Communication (HC-05 Module)**: The HC-05 Bluetooth module establishes a wireless connection between the Arduino and the Android mobile application. Bluetooth was chosen for its simplicity, reliability, and suitability for shortrange communication in offices or urban installations.

3. **DC Motors and Relays**: 12V DC motors are used to drive the rack-and-pinion system and wrapping mechanism. Relay modules control motor operation and provide electrical isolation

from the Arduino, ensuring safe operation. Motor speed and direction are carefully calibrated to achieve smooth carton movement without misalignment.

3. **Sensors and Feedback Devices**: Ultrasonic or IR sensors detect carton presence and bin fill levels.Buzzer alerts inform users when a carton is full or if operational issues arise. Sensor data is processed in real-time by the Arduino, allowing accurate and responsive control of mechanical components.

D. Mobile Application Interface

A Bluetooth-enabled Android application forms the user interface for the system, allowing remote monitoring and operation. The app is developed using MIT App Inventor and provides four primary commands:

1. **Push**: Inserts an empty carton into the bin.
2. **Return**: Reverses the rack-and-pinion mechanism in case of misalignment.
3. **Wrap**: Activates the wrapping unit to secure a full carton.
4. **Stop**: Halts ongoing operations immediately for safety or maintenance purposes.

The mobile interface ensures convenient interaction for users, eliminating the need to directly manipulate the mechanical system. Real-time feedback from sensors is displayed, keeping users informed about the bin's status.

E. Operational Workflow

The complete operational cycle of the intelligent waste management system involves:

1. Loading an empty carton into the bin.
2. Waste deposition through the top opening.
3. Detection of full capacity via sensors, triggering a buzzer alert.
4. Automatic activation of the wrapping mechanism to secure the waste.
5. Ejection of the sealed carton via the rack-and pinion system.
6. Insertion of a new empty carton, preparing the system for the next cycle.

This automated workflow ensures hygiene, minimizes manual labor, and maintains a structured collection process.

F. Key Advantages and Innovation

The proposed system overcomes limitations of conventional smart

bins by integrating mechanical automation, IoT monitoring, and mobile app control into a practical and scalable solution for modern cities. Contactless operation ensures hygienic handling, while standardized recyclable cartons simplify wrapping, storage, and collection, promoting sustainability. Automation through rackand-pinion and wrapping mechanisms reduces manual effort, and real-time mobile monitoring enhances usability and operational efficiency. Its modular design, combined with low-cost Arduinobased electronics, makes the system cost-effective and adaptable for both small- and large-scale deployments. Unlike previous approaches that focused solely on sensing or AI-based waste classification, this design prioritizes operational reliability, hygiene, and environmental responsibility, effectively addressing key gaps in smart waste management.

Experimental Setup and Results

The prototype of the Intelligent Waste Management System was developed and tested under controlled laboratory conditions to evaluate its operational efficiency, mechanical reliability, and usability. The primary objective of testing was to verify the seamless integration of mechanical, electronic, and IoT components while validating the practical benefits over conventional smart bins.

A. Prototype Development

The dustbin body was constructed using 22-gauge mild steel sheets for durability and stability. The rack-and-pinion assembly was fabricated using lightweight steel and coupled with 12V DC motors for smooth motion. The wrapping mechanism consisted of a motor driven rotating plate capable of securing standard corrugated cartons with biodegradable wrapping material.

The electronics subsystem included an Arduino Uno microcontroller, an HC-05 Bluetooth module for wireless communication, relay modules for motor control, and a buzzer to signal full-capacity notifications. Ultrasonic sensors were employed to detect bin fill levels and ensure timely activation of the wrapping mechanism.

Fig. 2. Prototype of Intelligent Waste Management System (external view).

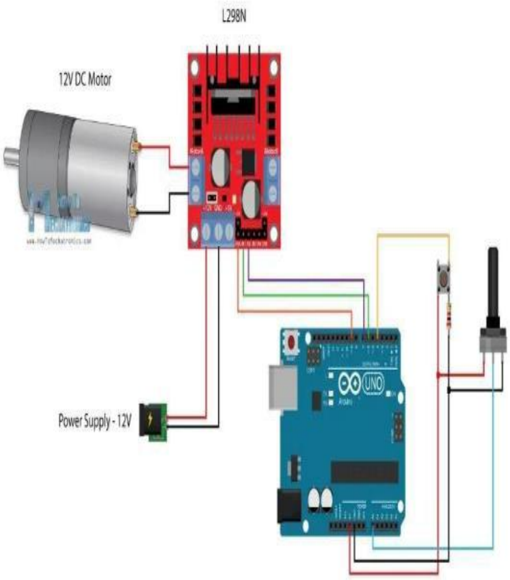

Fig. 3.Interfacing Arduino UNO with L298N Motor Driver Module

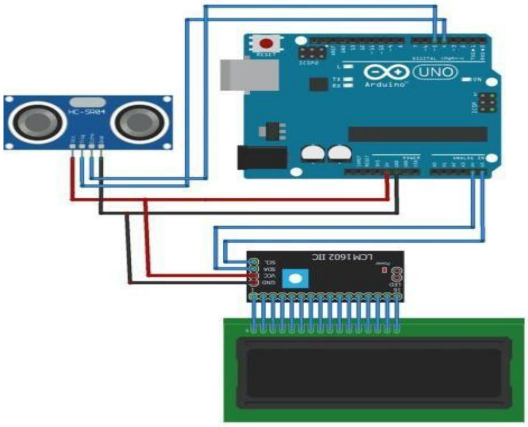

Fig.4. Interfacing Arduino UNO with HC-SR04 Ultrasonic Sensor and LCD display module.

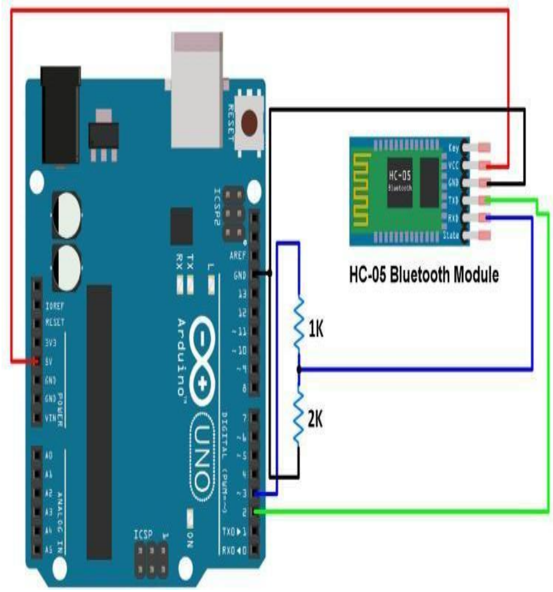

Fig.5. Interfacing Arduino UNO with HC-05 Bluetooth module for wireless serial communication.

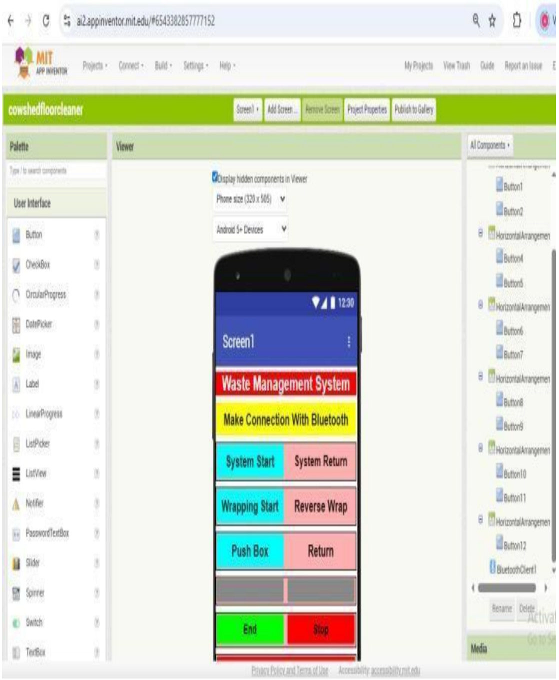

Fig.6. Android mobile application interface developed using MIT App Inventor for controlling the intelligent waste management system via Bluetooth.

G. Components Used

Component	Specification
Arduino UNO	Microcontroller board
HC-05	Bluetooth module

Component	Specification
12V DC Motor	12 V ,1 A for push/wrap mechanisms
Relay Module	1-channel or 2-channel to drive motor
Rack and Pinion	Mechanical linear actuator system
Metal Sheet	22 gauge for container body
Buzzer	Sound alert for full-carton notification
Android Application Developer Tool	Used to develop the Android control application
Plastic Wrap	Used in the wrapping unit
Cardboard Cartons	14" × 14" × 14" for collecting waste

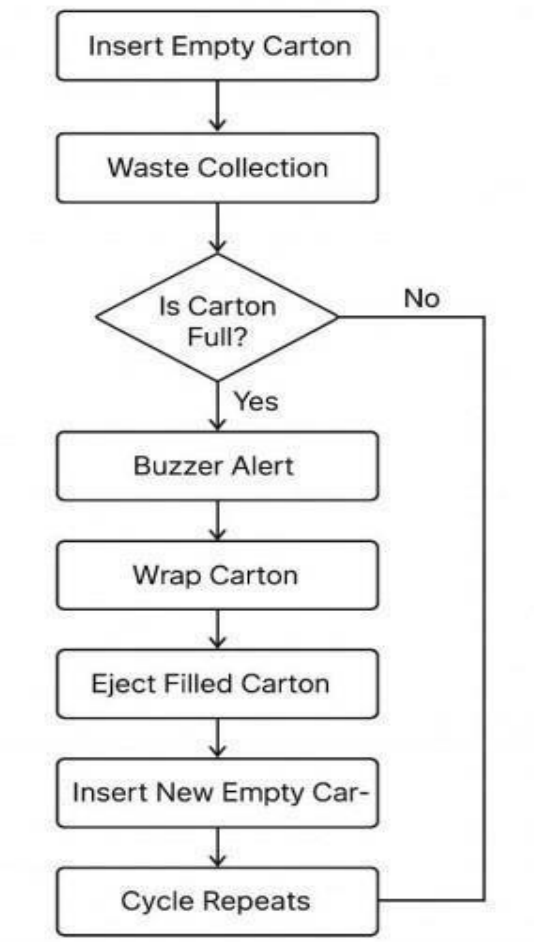

Fig.7. Intelligent Waste Bin Operation Flowchart

B. Testing Procedure

The prototype was subjected to repeated operational cycles to ensure reliability. The tests included:

1. Insertion of empty cartons and verification of proper alignment within the rack-and-pinion system.
2. Waste deposition and real-time monitoring of fill levels via sensors.
3. Activation of the wrapping mechanism upon reaching full capacity.
4. Ejection of sealed cartons and resetting for subsequent cycles.
5. Evaluation of response time and reliability of Bluetooth communication with the mobile app.

C. Results

The results demonstrated the effectiveness and reliability of the proposed system:

1. **Buzzer Alerts:** Triggered consistently when cartons reached maximum capacity, preventing overflow.
2. **Bluetooth Response:** Commands from the Android app were executed with an average latency of less than one second.
3. **Wrapping Efficiency:** The motor-driven plate effectively wrapped cartons, preventing leaks, odor, and spillage.
4. **Mechanical Reliability:** The rack-and-pinion system operated smoothly without misalignment or jamming, even under repeated cycles.
5. **Ease of Operation:** Users could control the system remotely, insert and eject cartons seamlessly, and monitor bin status in real-time.

These results confirm that the system performs reliably in terms of mechanical handling, IoT-based monitoring, and remote control, significantly improving upon conventional sensor-only smart bins.

Discussion

The Intelligent Waste Management System offers multiple advantages over traditional and existing smart bin solutions:

1. **Hygiene and Safety**: Contactless operation reduces human exposure to waste, minimizing health risks and aligning with SDG 3 (Good Health and Well-Being).
2. **Structured Waste Management**: Standardized 14″ × 14″ × 14″ cartons ensure organized and predictable waste containment.
3. **Automation**: Rack-and-pinion insertion and ejection combined with automated wrapping significantly reduce manual labor requirements.
4. **IoT Integration**: Real-time monitoring and mobile app control enable prompt intervention and efficient management.

5. **Sustainability**: Use of recyclable cartons minimizes environmental impact and aligns with SDG 12 (Responsible Consumption and Production).
6. **Cost-Effectiveness**: Arduino-based electronics and low-cost mechanical components reduce initial deployment costs while ensuring durability and scalability.

The modular design allows adaptation for larger-scale deployments, multi-bin configurations, or integration with additional sensors for specialized waste categories, such as biodegradable and recyclable streams. The system also provides a scalable platform for future AI integration, including automated waste classification and predictive collection scheduling.

Conclusion and Future Scope

The research presented in this paper has demonstrated the design, development, and practical implementation of an Intelligent Waste Management System that combines IoT-based monitoring, mechanical automation, and mobile application control. The system addresses critical limitations in conventional waste management practices and existing smart bin solutions, particularly in developing urban environments.

By integrating a **rack-and-pinion mechanism**, a **motorized wrapping unit**, and a **Bluetooth-enabled mobile application**, the system achieves **fully automated carton insertion, wrapping, and ejection**, minimizing the need for manual handling. The use of standardized corrugated cartons enhances structural reliability, improves hygiene, and supports sustainable practices through recyclability. The system's modular design ensures that it can be adapted for offices, campuses, and municipal settings, making it a flexible solution for diverse urban environments.

A. Key Contributions

The proposed system offers a complete solution for smart waste management by combining mechanical automation with IoT-based control. Unlike typical smart bins that only detect or alert, it integrates rack-and-pinion mechanics with an automated wrapping mechanism to handle waste efficiently. The design emphasizes hygienic, contactless operation, reducing human exposure and minimizing odor and spillage, supporting SDG 3 on good health and well-being. Sustainability is promoted through the use of recyclable cartons, which reduce plastic use, prevent leakage, and align with SDG 12 on responsible consumption. An Android-based mobile application enables real-time monitoring, alerts, and remote control, improving operational efficiency and preventing overflow, in line with SDG 11 for sustainable cities. The system is also cost- effective and scalable, using affordable Arduino electronics and low-cost mechanical components, with a modular design that allows multiple bins to be networked for citywide deployment.

B. Observations from Experimental Validation

Extensive prototype testing confirmed the system's effectiveness:

- The **rack-and-pinion mechanism** provided reliable insertion and ejection of cartons with minimal misalignment or mechanical failures.
- **Wrapping efficiency** was consistent, preventing leakage and controlling odor effectively.
- **Bluetooth communication** enabled real-time interaction with minimal latency (<1 second), proving the system's usability and responsiveness.
- **Audible alerts** via the buzzer consistently notified users upon full capacity, preventing overflow and reducing manual monitoring requirements.

These results demonstrate that the proposed system delivers both functional reliability and operational convenience, addressing key gaps in existing smart waste management technologies.

C. Implications for Urban Waste Management

The proposed system has important implications for modern waste management strategies:

1. **Reduction in Manual Labor**: Automation of waste handling significantly decreases the need for personnel to manage waste bins, reducing human effort and associated risks.
2. **Enhanced Hygiene in Public Spaces**: Contactless operation and hygienic wrapping improve sanitation in offices, schools, hospitals, and urban public areas.
3. **Improved Efficiency of Municipal Services**: Standardized, sealed cartons simplify collection, transport, and recycling, enhancing operational efficiency for municipal waste management authorities.
4. **Educational and Demonstration Value**: The system serves as a practical example for educational institutions to demonstrate integration of IoT, embedded systems, mechanical design, and sustainable engineering practices.

D. Future Directions

While the proposed system shows considerable promise, there remain several opportunities for future enhancement to improve efficiency and sustainability in urban waste management. A key direction is the integration of artificial intelligence through computer vision and edge AI, which would allow automatic segregation of biodegradable, recyclable, and non-recyclable waste, thereby reducing manual effort and improving recycling efficiency. In addition, connecting bins via GSM or Wi-Fi to a centralized cloud platform could enable real-time monitoring and analytics, providing predictive fill-level notifications and optimizing waste collection routes. To further strengthen sustainability, the incorporation of solar panels or other renewable energy sources could ensure energy-efficient and self-sustained operation, particularly in outdoor or public settings. Future systems may also adopt multi-bin coordination, where a network of intelligent bins collaborates to prioritize collection based on fill status, minimizing unnecessary trips. Design improvements such as lightweight structures and eco-friendly wrapping materials can reduce installation costs while lowering environmental impact. Finally, adapting the system for scalability in high-density urban areas will be essential, ensuring that it can handle large volumes of waste through multi-bin clusters and smart coordination. Together, these directions provide a roadmap for transforming the system into a city-scale sustainable solution.

E. Conclusion

The Intelligent Waste Management System proposed in this research offers a **comprehensive, automated, and sustainable solution** for urban and institutional waste challenges. By bridging the gap between sensor-based monitoring and mechanical handling, the system reduces human effort, enhances hygiene, and supports environmental sustainability.

Its contributions to **SDG 3, 11, and 12** highlight its alignment with global sustainable development initiatives, while the modular and low-cost design ensures feasibility for both small-scale and large-scale implementations. The research establishes a framework for future smart city deployments, combining IoT, embedded systems, mechanical automation, and sustainable materials.

With future integration of AI, cloud connectivity, renewable energy, and networked coordination, this system has the potential to **transform urban waste management**, making cities cleaner, more efficient, and more sustainable. It provides a practical model for municipalities, institutions, and smart city planners to adopt next-generation waste handling solutions.

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