UNIVERSITY OF BENIN, BENIN CITY.

DESIGN AND DEVELOPMENT OF AN IMPROVED SMART DUSTBIN SYSTEM

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CERTIFICATION

I hereby certify that the project work "DESIGN AND DEVELOPMENT OF AN IMPROVED SMART DUSTBIN SYSTEM" was carried out by:

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DEDICATION

This work is wholeheartedly dedicated to God Almighty, whose grace, wisdom, and strength guided every stage of this project. His presence has been our constant help and source of inspiration throughout this journey.

We also dedicate this project to our parents and families, whose unending love, sacrifices, and encouragement have been the foundation of our success. Their prayers and unwavering support have carried us through every challenge and milestone of our academic pursuit.

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ABSTRACT

The growing concern over ineffective waste management in rapidly urbanizing areas has continued to threaten environmental sustainability, public health, and urban aesthetics—particularly in developing nations such as Nigeria. Conventional waste collection methods, which rely on manual inspections, static collection schedules, and minimal automation, are increasingly inadequate for modern cities. These traditional systems often result in overflowing waste bins, unhygienic surroundings, and increased exposure of sanitation workers to hazardous waste. To mitigate these challenges, the adoption of smart waste management systems has become a practical solution, harnessing Internet of Things (IoT) technologies to enhance operational efficiency, reduce health risks, and support global sustainability goals.

This project presents the design and development of an improved smart dustbin system, which integrates sensors, automation, and wireless communication for efficient and hygienic waste collection. The system was engineered to address major limitations of existing smart waste bin models—such as lack of automation, low adaptability to environmental conditions, and poor sustainability—by introducing enhanced features that improve functionality, reliability, and user safety. The prototype incorporates ultrasonic sensors for detecting the fill level and load cell sensors for measuring the weight of accumulated waste. These sensors interface with an Arduino microcontroller, which interprets real-time data and initiates corresponding control actions.

A key innovation in this design is the dual alert and communication mechanism, facilitated by a GSM module (SIM900D) that transmits SMS notifications and also initiates automated phone calls to designated waste management personnel once the bin reaches its full capacity. In addition, the system integrates a GPS module that tracks the exact location of the bin, simplifying collection logistics and enabling efficient route planning. To further enhance automation, the system features a linear actuator that performs self-compaction, reducing the waste volume and increasing the storage capacity before the next collection. Importantly, once the waste bin reaches its maximum threshold, the lid is automatically locked, preventing further deposit of waste and ensuring cleanliness until the bin is emptied and reset for operation. This mechanism helps prevent overflow and reduces contact with potentially contaminated waste.

The system is powered by a 24W rechargeable lithium battery supported by a DC–DC converter, ensuring stable power supply and efficient energy usage. The software component was

developed using Embedded C/C++ on the Arduino IDE, enabling real-time sensor monitoring, threshold detection, and GSM/GPS communication control. Comprehensive testing was carried out to evaluate sensor accuracy, power efficiency, communication reliability, and the responsiveness of the compaction and locking mechanisms. Results from both hardware and software testing confirmed that the system achieved reliable waste level detection, efficient data transmission, timely alert notifications, and effective compaction cycles. The automatic locking feature also performed accurately, preventing waste input once the bin reached capacity.

By combining IoT technology, automation, and sustainable material selection, the improved smart dustbin system demonstrates a viable, scalable, and eco-friendly approach to modern waste management. Its ability to autonomously monitor fill levels, compress waste, lock when full, and communicate through both SMS and phone calls significantly enhances efficiency, hygiene, and sustainability. This prototype provides a foundation for large-scale implementation in residential, institutional, commercial, and municipal environments, contributing to cleaner cities and smarter waste management systems that align with sustainable development goals.

CHAPTER ONE

INTRODUCTION

1.1 Background Of Study

The rapid pace of urbanization, industrial growth, and population expansion across the world, particularly in developing nations such as Nigeria, has led to an exponential rise in the amount of solid waste generated daily. Traditional waste management practices, which rely heavily on manual monitoring and fixed collection routines, have proven inadequate in addressing the increasing volume and diversity of waste. These outdated methods often result in delayed collection, overflowing bins, foul odors, and the spread of communicable diseases due to unhygienic conditions.

To address these challenges, the integration of Internet of Things (IoT) technology into waste management systems has gained global attention. IoT-based systems utilize interconnected sensors and communication modules to collect real-time data on waste levels, environmental conditions, and bin locations. Such smart systems enable authorities to optimize collection routes, minimize human exposure, and reduce operational costs while promoting sustainability and efficiency in waste management.

Within the context of the University of Benin, an earlier project titled "Monitoring and Control of a Smart Waste Bin" was undertaken by Uzoekwe, Monye-Emina, Martins, Moses, Izuka, Kalu, and Jaja-Wachukwu (2025) under the supervision of Prof. P. O. Ebunilo. Their work successfully developed a prototype capable of detecting bin levels using an ultrasonic sensor and transmitting SMS alerts through a GSM module when the bin was full. While this project demonstrated the feasibility of IoT-based monitoring, it lacked certain key functionalities necessary for a fully autonomous waste management system — such as automated lid-locking when filled, and dual-alert (SMS and call) communication.

Furthermore, during a field inspection guided with our project supervisor, Prof. A. I. Obanor (personal communication, September 2025), it was observed that an existing smart waste bin system at the Department of Mechanical, suffered from design flaws, including improper ultrasonic sensor calibration that reduced distance detection accuracy and the absence of a compactor, which caused the bin to fill prematurely. These practical insights revealed the urgent need for an improved system design that enhances both efficiency and hygiene.

This project, therefore, aims to design and develop an improved smart dustbin system that integrates advanced sensing, communication, and control mechanisms. The system features automatic waste compaction**,** lid locking when the bin reaches full capacity, and dual-alert communication (SMS and automated phone calls) via a GSM module. These improvements collectively ensure more reliable waste monitoring, faster response time, and improved environmental sanitation.

Fig 1.1: Waste Management Issues in Nigeria

1.2 Statement of Problem

Despite the progress made in the design of smart waste management systems, several challenges remain unresolved in existing models. The previous project by Uzoekwe and project members (2025), although innovative, lacked mechanisms for compaction and secure lid locking, limiting its operational efficiency. Additionally, its reliance solely on SMS alerts introduced a potential delay in communication, particularly in areas with poor network connectivity or low attention to text notifications.

Field analysis carried out under the supervision of Prof. A. I. Obanor (personal communication, September 2025) further confirmed these limitations during the inspection of an existing bin prototype. The ultrasonic sensor's close placement to the lid distorted distance measurement, while the absence of a compactor led to rapid filling and frequent overflow. Such deficiencies not only undermine the purpose of smart waste management but also pose hygiene and maintenance issues.

The current project seeks to address these problems by introducing an improved system that automatically compresses waste, locks the lid once capacity is reached, and employs a dual-alert system using both SMS and automated phone calls to notify responsible authorities in real time. By resolving these design limitations, the system enhances operational reliability, reduces overflow, and ensures faster response in waste collection logistics.

1.3 Aim

The main aim of this project is to design and develop an improved smart dustbin system that enhances waste monitoring, collection efficiency, and hygiene through automation and IoT integration.

1.4 Objectives

1. Design a smart dustbin that automatically detects waste level using ultrasonic sensors.
2. Integrate a load sensor to monitor the bin's weight and confirm fullness accurately.
3. Implement a GSM communication module capable of sending SMS alerts and initiating automated phone calls to waste management authorities when the bin is full.
4. Develop an automatic compaction mechanism to compress waste and increase storage capacity.

5. Introduce a lid-locking system that prevents additional waste input once the bin is full until it has been emptied.
6. Test and evaluate the performance, reliability, and communication accuracy of the designed system under real-world conditions.

1.5 Methodology

This project adopted a design and development-based research methodology, combining both hardware and software approaches to design, implementing, and testing an improved smart waste bin system. The system integrates ultrasonic sensors for detecting the waste fill level and load sensors for monitoring bin weight, all interfaced with an Arduino microcontroller for real-time data processing and decision-making.

A SIM900 GSM module was employed to enable two-way communication, sending SMS alerts and automatic phone calls to notify waste management personnel when the bin is full. Additionally, a linear actuator mechanism was implemented to compact accumulated waste, thereby extending bin capacity and reducing collection frequency. To enhance hygiene and operational safety, the bin's lid is automatically locked when full and reopens only after the waste has been emptied.

The software design and simulation were carried out using the Arduino IDE, programmed in Embedded C/C++, while circuit design and sensor calibration were tested using Proteus simulation software. Hardware construction involves locally sourced, durable materials to ensure cost-effectiveness and environmental sustainability. A DC-DC converter and lithium battery system were used for power regulation and backup operation.

System performance was evaluated through a series of controlled tests, measuring parameters such as sensor accuracy, compaction efficiency, notification response time, and power consumption. The results from these evaluations provided the basis for analyzing the system's reliability, efficiency, and suitability for urban waste management applications.

1.6 Scope of Study

This study focuses on the design, development, and implementation of an improved smart dustbin system using IoT-based technology. The scope of work includes hardware design (sensors, microcontroller, actuator, GSM module, and power system) and software implementation (firmware programming and communication control).

The project's primary features include:

- Real-time waste level and weight detection
- Automatic compaction of waste using a linear actuator
- Automatic lid-locking when the bin is full
- Dual-alert notification system (SMS and call via GSM module)
- Rechargeable power system for sustainable operation

The project is limited to a prototype scale suitable for demonstration and testing. However, the design is scalable for use in residential, institutional, or municipal settings with minimal modification. The study does not cover large-scale waste transportation logistics or machine learning-based waste categorization, though it provides a foundation for such future enhancements.

1.7 Significance of Study

The significance of this study lies in its practical contribution to addressing the persistent challenges of inefficient and unhygienic waste management systems in urban areas. Conventional waste bins are often left unattended until they overflow, leading to environmental pollution, foul odours, and the spread of diseases. This project provides an innovative solution through an improved smart waste bin system that employs automated monitoring, compaction, and notification technologies to ensure timely and efficient waste disposal.

By integrating ultrasonic and load sensors for real-time level and weight detection, the system ensures accurate monitoring of waste accumulation. The inclusion of a GSM module capable of sending both SMS and automatic voice call alerts enhances communication reliability, especially in areas where SMS delivery may be delayed or unavailable. Moreover, the bin's automatic lid-locking feature, which activates once full, prevents further waste input until the bin is emptied, promoting hygiene and orderliness.

The incorporation of a linear actuator-driven compactor extends the bin's storage capacity and minimizes the frequency of waste collection, contributing to operational efficiency. The use of composite board materials ensures durability, moisture resistance, and ease of maintenance, addressing one of the major flaws identified in earlier designs that relied on wooden or metallic casings.

This project offers a scalable, and energy-efficient model that can be adopted by local governments, environmental agencies, and private waste management firms seeking to modernize their operations. It also benefits communities by promoting cleanliness, reducing human contact with waste, and lowering the risk of public health hazards associated with unmanaged refuse. Furthermore, the system lays a foundation for future improvements, such as the integration of GPS tracking and solar-powered energy systems, making it a vital contribution to the advancement of smart city infrastructure and sustainable urban living.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Solid waste management has become one of the most critical environmental challenges confronting modern society. The rapid rate of urbanization, industrialization, and population growth has led to an exponential increase in waste generation globally (Amasuomo & Baird, 2016). In developing nations such as Nigeria, poor waste handling, inadequate infrastructure, and inefficient collection systems continue to pose serious threats to human health and the environment. Traditional waste management practices often rely on manual collection and fixed schedules, which are inefficient in dealing with the dynamic nature of waste accumulation (Adewole, 2009).

The increasing complexity of urban waste management has therefore necessitated innovative approaches that leverage technology for sustainability and efficiency. Recent advancements in the Internet of Things (IoT), embedded systems, and automation have introduced new possibilities for smart and adaptive waste management systems. These systems employ sensors, microcontrollers, and wireless communication modules to monitor waste levels in real time, optimize collection routes, and reduce operational costs (Ali et al., 2020).

An improved smart dustbin system integrates sensor-based detection, GSM communication, and automated actuation mechanisms to enhance hygiene, efficiency, and responsiveness. Unlike conventional smart bins that rely solely on ultrasonic sensors and SMS alerts, the improved design also includes GSM-based call alerts and an automatic lock mechanism that prevents overfilling. This innovation bridges a major gap identified in earlier designs—where bins would still open even after reaching full capacity, leading to spillage and unsanitary conditions (Afolalu et al., 2021).

This chapter provides a detailed review of the theoretical foundations, conceptual background, related technologies, and prior research relevant to the development of an improved smart dustbin system. The review also highlights research gaps in existing studies and discusses how this work contributes to solving persistent challenges in waste collection and management.

2.2 Theoretical Framework

The theoretical framework of this study draws on three key foundations: environmental sustainability theory, Internet of Things (IoT) conceptualization, and automation theory. Together, these perspectives provide a scientific and technological basis for understanding how smart systems can improve urban waste management efficiency and promote cleaner environments.

2.2.1 Environmental Sustainability Theory

The environmental sustainability theory emphasizes the need for human activities to align with ecological limits to ensure the well-being of current and future generations (Lu et al., 2013). Waste management plays a central role in this theory, as improper disposal leads to soil contamination, air pollution, and the spread of diseases. Sustainable waste management therefore seeks to minimize waste generation, encourage recycling, and utilize eco-friendly technologies.

The smart dustbin concept embodies these principles by introducing a controlled, data-driven approach to waste handling. Through automation and digital monitoring, waste is collected only when bins reach optimal levels, preventing unnecessary energy use and reducing the number of collection trips (Abila & Kantola, 2013). Furthermore, integrating compaction mechanisms increases bin capacity, thereby extending collection intervals and reducing the carbon footprint associated with frequent transportation.

By promoting operational efficiency, the improved smart dustbin system contributes to the broader goal of sustainable urban infrastructure. It embodies the principles of the circular economy, where technology enhances environmental stewardship by reducing waste-related hazards.

2.2.2 Internet of Things (IoT) Conceptual Model

The Internet of Things represents a network of interconnected physical devices capable of sensing, collecting, and transmitting data over the internet without requiring human intervention (Hashem et al., 2016). In the context of waste management, IoT provides the infrastructure for smart bins to communicate real-time information to waste management authorities or cloud servers.

A typical IoT-based waste management framework consists of three layers:

1. **Perception Layer** – composed of sensors (e.g., ultrasonic and load sensors) that detect waste level and bin weight.
2. **Network Layer** – responsible for data transmission using communication protocols like GSM, Wi-Fi, or ZigBee.
3. **Application Layer** – where data is analyzed and visualized for decision-making and route optimization (Hannan et al., 2015).

In this study, the IoT concept is implemented through a GSM-based communication system that not only sends short message service (SMS) alerts but also initiates voice call notifications when the bin is full. This dual alert mechanism addresses one of the major limitations of existing smart bin systems — dependency on internet connectivity or SMS gateways that may fail in low-network environments.

Moreover, the inclusion of an auto-lock mechanism ensures that the bin remains sealed once full, promoting hygiene and preventing indiscriminate waste dumping. These design decisions are consistent with IoT's objective of intelligent interaction between devices and the environment, enabling real-time responsiveness and improved service delivery (Faccio et al., 2011).

2.2.3 Automation and Smart Systems Theory

Automation theory focuses on the design and application of systems capable of operating with minimal human intervention. Smart systems leverage sensors, actuators, and microcontrollers to perceive their environment and perform actions based on preprogrammed logic (Longhi et al., 2012). The improved smart dustbin system applies this concept through automatic lid control, compaction, and communication functions.

When waste reaches a predefined level, the system triggers a locking mechanism to prevent overloading and automatically sends an alert via GSM. This automation minimizes the need for constant human supervision, reduces operational delays, and enhances overall system reliability.

According to Karadimas et al. (2016), automation in waste management not only improves efficiency but also encourages behavioral change among users by ensuring cleaner and more organized waste disposal processes. The improved smart bin therefore aligns with modern trends in intelligent infrastructure systems designed for smart cities, where embedded automation ensures environmental sustainability and public convenience.

2.3 Concept of Solid Waste and Waste Management

2.3.1 Definition and Nature of Solid Waste

Solid waste refers to all discarded materials that arise from human and animal activities and that are usually solid in nature (Agunwamba, 1998). These materials include household refuse, industrial by-products, agricultural residues, packaging materials, and non-biodegradable substances such as plastics and metals. According to the United Nations Environment Programme (UNEP, 2022), solid waste encompasses anything that no longer has primary value to the possessor and must be disposed of responsibly to avoid environmental and health hazards.

The composition of solid waste varies depending on the socio-economic activities of a region. In developing countries such as Nigeria, the bulk of solid waste is composed of organic matter from food and agricultural products, while in industrialized nations, inorganic and packaging materials dominate (Abila & Kantola, 2013). The diversity in waste composition makes management complex because each category requires distinct handling, recycling, or treatment methods.

Solid waste is generally classified into municipal solid waste (MSW)**,** industrial waste**,** agricultural waste**,** hazardous waste, and electronic waste (e-waste) (Ezeudu & Ezeudu, 2019). Municipal solid waste—comprising household garbage, street sweepings, and market refuse—is the most common and visible in urban centers. The rapid generation of MSW is directly proportional to population growth, urbanization rate, and lifestyle changes, hence the increasing burden on city authorities to ensure timely and effective disposal (Adewole, 2009).

2.3.2 Importance of Solid Waste Management

Effective waste management is central to achieving environmental sustainability and public health protection. It involves a set of activities ranging from waste generation control, collection, transportation, processing, recycling, and final disposal (Amin et al., 2024). According to the World Bank (2022), globally more than 2 billion tonnes of solid waste are generated annually, with at least one-third of that amount improperly disposed of.

Proper waste management reduces the spread of vector-borne diseases, prevents flooding caused by blocked drainage systems, and curtails air pollution from indiscriminate burning. Additionally, resource recovery through recycling and energy conversion contributes to the circular-economy model, reducing the extraction of virgin materials and lowering carbon emissions (Ezeudu & Ismail, 2023).

In Nigeria, the Federal Ministry of Environment (FME, 2021) highlights that efficient waste management remains one of the least developed environmental services despite its strategic importance to health and sustainable urban living. Therefore, the implementation of intelligent, technology-driven waste management systems becomes essential to overcome existing human and logistical constraints.

2.3.3 Traditional Approaches to Waste Management

Historically, waste management in many developing nations has been manual and labor-intensive. Waste is collected through door-to-door visits or communal bins placed at designated points (Ojo & Bowen, 2014). This model is characterized by delayed pickups, inadequate coverage, and poor data on waste generation patterns. The absence of real-time monitoring means bins often overflow before collection teams arrive, leading to unhygienic conditions and unpleasant odors in residential areas (Omole et al., 2016).

In some cities, private contractors manage waste using fixed-route schedules. However, this approach does not account for the varying rates of waste generation across different neighborhoods (Adeyemo et al., 2019). As a result, some bins remain underutilized while others overflow. This inefficiency demonstrates the urgent need for adaptive and intelligent systems that can provide real-time feedback on bin status and collection requirements.

2.3.4 Challenges of Waste Management in Developing Nations

Waste management in developing nations such as Nigeria faces numerous interrelated challenges:

1. **Inadequate Infrastructure:** Most cities lack sufficient waste-collection vehicles, transfer stations, and disposal facilities.
2. **Poor Funding and Policy Implementation:** Government budgets for sanitation are often insufficient or mismanaged (Abba & Light, 2020).
3. **Public Awareness and Behavior:** Citizens sometimes dispose of waste indiscriminately due to inadequate sensitization on environmental hygiene (Etim, 2024).

4. **Weak Institutional Framework:** Overlapping responsibilities among federal, state, and local agencies hinder coordinated efforts (Edoho & Dibie, 2000).
5. **Technological Deficiency:** The absence of reliable data and monitoring tools impedes decision-making and efficient scheduling (Afolalu et al., 2021).
6. **Environmental and Health Impacts:** Uncollected waste blocks drain, contaminates groundwater, and fosters mosquito and rodent breeding, contributing to diseases such as cholera and malaria (Eneh, 2011).

These challenges have persisted because traditional systems rely heavily on manual supervision. The growing urban population amplifies waste generation, and without automation, collection agencies cannot respond promptly to dynamic accumulation patterns.

2.3.5 Transition Toward Intelligent Waste Management

Recent advances in microelectronics and wireless communication technologies have enabled a change in thinking from conventional to smart waste management systems. According to Hannan et al. (2015), IoT-based waste systems enable bins to sense fill levels, transmit data to control centers, and optimize collection schedules automatically. The integration of embedded sensors, GSM modules, and cloud-based analytics ensures that waste disposal decisions are informed by real-time data rather than static schedules.

Intelligent systems also reduce operational costs by minimizing fuel consumption through optimized routing (Ramson et al., 2021). For example, sensors trigger collection only when bins are near capacity, ensuring efficient resource allocation. Moreover, automated systems eliminate unnecessary human contact with waste, reducing occupational health risks for sanitation workers.

The improved smart dustbin system proposed in this study extends this innovation by adding a dual-communication GSM module that sends both SMS and voice call alerts when the bin is full. Furthermore, the system prevents the lid from opening once full, ensuring hygienic waste containment until collection occurs. These modifications directly address operational lapses identified in prior implementations (Ali et al., 2020; Wijaya et al., 2017).

2.3.6 Environmental and Health Implications of Poor Waste Disposal

Poor waste management is associated with severe ecological degradation and health problems. When waste is not promptly removed, decomposition releases methane—a potent greenhouse gas contributing to climate change (Hammed & Sridhar, 2021). Leachate from open dumps contaminates surface and groundwater sources, while burning waste releases toxic pollutants like dioxins into the atmosphere (Ogunrinola & Adepegba, 2012).

From a health perspective, unmanaged waste serves as a breeding ground for pathogens and disease-carrying vectors. The World Health Organization (WHO, 2021) estimates that nearly 22 diseases are directly linked to improper solid-waste handling, ranging from diarrhea and cholera to respiratory infections. Children and waste collectors in low-income neighborhoods are particularly vulnerable.

Smart and automated waste management systems contribute to public health improvement by eliminating overflow, reducing manual waste handling, and maintaining sanitary conditions. In this way, technology becomes an enabler of preventive health and environmental protection rather than merely a tool for convenience.

2.3.7 Summary of Conceptual Understanding

The concept of solid-waste management has evolved from simple collection and disposal toward intelligent systems emphasizing sustainability, hygiene, and efficiency. The deficiencies observed in traditional waste-handling practices—manual scheduling, lack of data, and delayed responses—underscore the relevance of automation and IoT integration. By embedding intelligence in waste bins, municipal agencies can monitor conditions continuously, prevent overflow, and plan logistics effectively.

The improved smart dustbin system exemplifies this evolution: it is not merely a container but an intelligent environmental management device that senses, communicates, and responds autonomously. Its operation supports the global Sustainable Development Goals (SDGs) on sustainable cities (Goal 11) and responsible consumption (Goal 12), highlighting how engineering innovation contributes to environmental governance.

2.4 Evolution of Smart Waste Management Systems

2.4.1 Overview

The concept of *smart waste management* has emerged from the broader vision of *smart cities*, where digital technologies are harnessed to optimize urban services and improve the quality of life. Waste management, once treated as a purely mechanical and logistical task, is now recognized as a data-driven process requiring continuous monitoring, timely response, and efficient resource utilization (Glouche & Couderc, 2014).

Smart waste management systems (SWMS) integrate sensors, microcontrollers, communication networks, and data analytics to automate waste monitoring and disposal. By using real-time data, these systems help decision-makers plan routes, predict fill levels, and deploy collection vehicles only when necessary. The introduction of such technology addresses the inefficiencies inherent in conventional waste collection methods, which rely on fixed schedules rather than actual bin status (Hannan et al., 2015).

The evolution of SWMS represents a paradigm shift from manual and reactive methods to proactive and intelligent operations. This transformation is driven by the convergence of *Internet of Things (IoT)*, *wireless communication*, and *embedded systems* technologies.

2.4.2 Traditional Waste Management vs. Smart Systems

Traditional waste management practices typically involve manual monitoring, static collection timetables, and the physical inspection of bins to determine when they require emptying (Ojo & Bowen, 2014). These practices, while effective in smaller communities, become inefficient in densely populated cities where waste generation rates vary across neighborhoods. Bins often overflow before collection or are emptied prematurely, resulting in wasted resources and increased operational costs.

Smart waste management systems eliminate these inefficiencies by introducing **real-time intelligence** into the process. Through sensors such as ultrasonic or infrared detectors, the system continuously measures waste levels and transmits the data to a central server or control unit (Islam et al., 2012). When the bin reaches a predetermined threshold, automated alerts are sent to waste management authorities via GSM or internet-based communication systems.

Moreover, unlike traditional systems, smart bins can lock themselves when full, preventing additional waste input and maintaining hygiene. Some advanced designs also feature compaction mechanisms that compress the waste, allowing for greater capacity before requiring collection (Afolalu et al., 2021). These enhancements make smart systems not only efficient but also eco-friendly, reducing emissions from unnecessary collection trips and minimizing manual handling.

The transition from traditional to smart systems thus reflects a technological and operational revolution—transforming waste management into a dynamic, self-regulating process guided by automation and communication technologies.

2.4.3 Integration of IoT in Waste Monitoring

The Internet of Things (IoT) plays a pivotal role in enabling smart waste management systems. IoT refers to the interconnection of physical devices through the internet to collect, exchange, and analyze data (Hashem et al., 2016). In the context of waste management, IoT allows waste bins to function as "smart nodes" that continuously monitor their environment and share data autonomously.

According to Faccio et al. (2011), an IoT-enabled waste management framework typically consists of three interconnected layers:

1. **Sensing Layer:** Incorporates ultrasonic sensors, infrared detectors, and weight sensors that capture real-time data on bin status.
2. **Network Layer:** Transmits collected data via communication protocols such as GSM, Wi-Fi, ZigBee, or LoRaWAN.
3. **Application Layer:** Analyzes and visualizes data for decision-making and collection-route optimization.

Through these layers, IoT systems enable municipal authorities to receive accurate information about waste distribution, predict bin fill levels, and allocate collection resources efficiently.

A notable advantage of IoT integration is its scalability—multiple bins across different locations can be networked and managed simultaneously through cloud-based platforms (Hannan et al., 2015). IoT-based analytics can also forecast waste trends, helping policymakers plan infrastructure expansion or recycling initiatives.

In the improved smart dustbin system proposed in this project, the IoT concept is realized through the use of a GSM module (SIM800L/SIM900) that transmits data and provides a voice call alert when the bin is full. This feature ensures reliable communication even in regions with unstable internet connectivity, making it more adaptable to Nigerian urban contexts where broadband infrastructure is limited.

2.4.4 Benefits of Smart Waste Management Systems

The adoption of smart waste management systems offers several strategic, environmental, and social advantages that justify their implementation. These include:

1. **Operational Efficiency:**
   Smart bins provide real-time data, allowing vehicle collection to operate only when necessary. This optimization reduces fuel consumption, labor costs, and traffic congestion caused by indiscriminate waste collection (Poddar et al., 2017).
2. **Environmental Protection:**
   Automated systems prevent waste overflow and the associated environmental hazards, such as water contamination and odor emission. By reducing the number of collection trips, carbon emissions from trucks are also significantly minimized (Karadimas et al., 2016).
3. **Public Health Improvement:**
   Overflowing bins attract pests and breed diseases. Smart systems prevent such conditions, ensuring a cleaner and healthier urban environment (Eneh, 2011).
4. **Data-Driven Decision-Making:**
   Continuous data collection provides valuable insights into waste generation patterns, helping local governments and private operators improve planning and allocate resources more effectively (Ramson et al., 2021).
5. **Automation and Hygiene:**
   With automatic lids, compaction mechanisms, and fill-level detection, smart bins reduce direct human interaction with waste, thus minimizing health risks among sanitation workers.
6. **Cost Reduction:**
   Studies indicate that IoT-enabled waste systems can reduce total operational costs by up to 30% through route optimization and predictive maintenance (Salehi-Amiri et al., 2022).
7. **Community Awareness:**
   When citizens interact with automated systems, it fosters awareness of environmental responsibility and cleanliness.

The improved smart dustbin system enhances these benefits by integrating *voice-call notification* and *auto-locking* functions, ensuring both reliability and sanitary efficiency.

2.4.5 Limitations of Existing Smart Waste Systems

Despite the significant progress in smart waste management technologies, several limitations persist in existing systems:

- **Dependency on Internet Connectivity:** Many IoT-based systems rely on stable internet connections, which are not always available in developing regions (Ali et al., 2020).
- **Power Consumption:** Continuous sensor monitoring and data transmission require energy, making system sustainability a challenge without efficient power management (Mamun et al., 2014).
- **High Implementation Costs:** The cost of deploying large-scale sensor networks and maintaining them remains a barrier for low-income municipalities (Ahmed et al., 2024).
- **Mechanical Reliability:** Some systems experience sensor degradation due to exposure to moisture, dust, or corrosive waste materials (Wijaya et al., 2017).
- **Limited Notification Systems:** Many prototypes depend solely on SMS alerts, which can be delayed or lost in areas with poor network coverage (Okubanjo et al., 2024).

The improved smart dustbin system developed in this research addresses these constraints by introducing:

- A dual GSM communication system (SMS and voice alert).
- A mechanical locking system that prevents overfilling and contamination.
- A compaction mechanism to extend capacity before collection.
- The use of composite board materials for durability and moisture resistance.

These innovations position the system as a more resilient and context-appropriate solution for developing urban centers.

2.4.6 Evolutionary Timeline of Smart Waste Technologies

The development of smart waste management technologies has followed a clear evolutionary pattern over the past two decades:

1. **Early 2000s – Manual Monitoring Systems:**
   Initial systems relied on mechanical level indicators or visual inspection. There was minimal automation, and waste collection was entirely human-dependent (Catania & Ventura, 2014).

2. **2010–2015 – Sensor Integration:**
   Ultrasonic and infrared sensors were introduced for fill-level detection. These systems improved data accuracy but still required human oversight for collection scheduling (Islam et al., 2012).

3. **2016–2019 – IoT-Based Systems:**
   The integration of microcontrollers with GSM and Wi-Fi modules enabled remote monitoring and alerting mechanisms (Ali et al., 2020). Projects during this phase began to experiment with real-time dashboards and mobile applications.

4. **2020–Present – Intelligent, Adaptive Systems:**
   Recent systems integrate machine learning and data analytics for predictive waste management. Additionally, renewable power sources and compaction mechanisms have been introduced to enhance sustainability (Olawade et al., 2024).

The improved smart dustbin system belongs to the fourth generation of this evolution—combining IoT communication, automation, sustainability, and mechanical intelligence into one cohesive design tailored for developing regions.

2.4.7 Future Directions of Smart Waste Management

The future of smart waste management lies in data integration, artificial intelligence, and sustainable design. Emerging systems will combine IoT with AI algorithms to predict waste trends and automate fleet management (Ahmed et al., 2024). Furthermore, blockchain technology may be adopted for transparent waste tracking, enabling accountability and recycling incentives.

In developing countries, the focus will likely be on low-cost, energy-efficient designs that leverage GSM-based communication instead of high-bandwidth networks. Solar-powered modules and edge-computing devices will help maintain continuous operation in areas with inconsistent electricity supply.

The improved smart dustbin system presented in this project anticipates these trends by incorporating power-efficient components, GSM communication suited for local infrastructure, and material durability suited for outdoor environments. This design approach bridges the gap between cutting-edge technology and practical deploy-ability in resource-constrained settings.

2.4.8 Summary

The evolution of smart waste management systems demonstrates a steady technological progression from manual methods to intelligent, networked solutions. Traditional systems focused on collection and disposal, while modern approaches emphasize real-time monitoring, automation, and sustainability. The integration of IoT has revolutionized waste management by enabling data-driven decision-making, enhancing hygiene, and optimizing operational costs.

However, limitations such as power dependence, cost, and network reliability continue to challenge implementation, particularly in developing nations. The improved smart dustbin system responds to these issues through dual GSM communication, auto-locking, compaction, and robust materials — marking a significant advancement in the ongoing evolution of smart urban infrastructure.

2.5 Review of Related Technologies and System Components

2.5.1 Overview

Smart waste management systems rely on a multidisciplinary integration of hardware and software technologies that collectively enable automation, communication, and environmental sensing. The success of such systems depends on the efficiency, reliability, and coordination of these individual components (Mamun et al., 2014). In designing an improved smart dustbin, each subsystem — from sensing to power regulation — plays a crucial role in achieving real-time monitoring, operational stability, and user responsiveness.

This section provides a comprehensive review of the key technological components utilized in smart waste management systems, including sensors, microcontrollers, communication modules, actuators and compaction units, power supply systems, and software integration platforms. The discussion emphasizes the conceptual functionality of each component, their interactions, and how they contribute to the innovation of the improved smart dustbin system.

2.5.2 Sensor Technologies

Sensors are fundamental to the functionality of smart waste systems. They serve as the *perception layer* of the Internet of Things (IoT) framework, enabling the system to detect and interpret environmental conditions. In the context of smart bins, sensors primarily measure parameters such as waste level, weight, moisture content, and lid position (Hannan et al., 2015).

The ultrasonic sensor is one of the most commonly used devices for fill-level detection. It operates by emitting high-frequency sound waves that reflect off the surface of the waste; the time delay between emission and reception determines the distance to the waste surface. This method offers high precision and non-contact measurement, which is ideal for maintaining hygiene (Wijaya et al., 2017). Ultrasonic sensors are particularly effective because they are unaffected by color, lighting, or dust, unlike optical sensors that may be influenced by environmental conditions (Islam et al., 2012).

The load cell sensor complements the ultrasonic sensor by providing information on the total weight of the waste within the bin. This dual-sensor arrangement allows the system to verify both volume and mass, ensuring more accurate bin status detection. For instance, lightweight materials such as paper may fill the bin without adding significant weight, while heavy materials such as metal cans may increase weight without filling the bin to capacity. Combining both data sets enhances system reliability (Faccio et al., 2011).

Some designs also incorporate infrared (IR) proximity sensors to detect the presence of a user near the bin. This enables the automatic opening of the lid without physical contact, thereby improving hygiene (Baby et al., 2017). Advanced systems may include moisture sensors to monitor humidity within the bin, preventing bacterial growth and detecting liquid waste contamination (Hannan et al., 2015).

In the improved smart dustbin system, the ultrasonic and load cell sensors form the primary sensing pair. The ultrasonic sensor continuously measures waste level, while the load cell provides confirmation of the actual waste mass. Once both parameters exceed their threshold limits, the system identifies the bin as full, triggers a GSM alert, and activates the auto-lock mechanism to prevent further disposal. This dual-validation approach reduces false triggers and enhances operational accuracy.

2.5.3 Microcontroller and Embedded Processing Unit

At the heart of every smart waste system lies a microcontroller, which serves as the central processing and decision-making unit. It interfaces with sensors, communication modules, and actuators, interpreting signals and executing control logic in real time (Longhi et al., 2012).

Commonly used microcontrollers include the Arduino Uno, ESP8266, and Raspberry Pi Pico due to their affordability, low power consumption, and compatibility with a variety of sensors and GSM modules. The Arduino platform, in particular, has gained popularity in academic and prototype development contexts because of its simplicity and open-source ecosystem (Afolalu et al., 2021).

The Arduino Uno, based on the ATmega328P microchip, provides sufficient memory, input/output pins, and clock speed to handle the computational requirements of waste monitoring. It processes distance readings from the ultrasonic sensor, interprets weight data from the load cell via an amplifier (such as HX711), and determines the bin's operational state — *empty*, *half-full*, or *full* (Michael et al., 2017).

Microcontrollers also manage communication between modules. For instance, in the improved smart dustbin system, the microcontroller transmits messages to the GSM module when threshold conditions are met. It also controls the linear actuator or motor driver responsible for lid operation or compaction.

The efficiency of a microcontroller-based system is determined by three factors: processing speed, energy management, and firmware optimization. Efficient code written in embedded C/C++ ensures that sensor data are processed with minimal delay and that only relevant notifications are sent, conserving both energy and communication costs (Hannan et al., 2015).

By acting as the brain of the smart dustbin, the microcontroller ensures coordinated functionality among all components, transforming raw sensor data into actionable decisions. In the improved system, this coordination enables a seamless sequence of events — sensing, alerting, locking, and resetting — without manual interference.

2.5.4 Communication Technologies (GSM, GPS, and IoT Protocols)

Communication technology defines how data from smart bins are transmitted to external systems or users. Without reliable communication, even the most advanced sensing and processing systems cannot function effectively.

In smart waste systems, the Global System for Mobile Communication (GSM) remains one of the most widely used communication methods due to its broad coverage, reliability, and simplicity. GSM modules such as SIM800L or SIM900 interface with the microcontroller to send alerts via Short Message Service (SMS) or voice calls (Ali et al., 2020). This form of communication is particularly advantageous in developing regions where internet access is limited or unstable.

More sophisticated implementations may utilize Wi-Fi (IEEE 802.11) or ZigBee (IEEE 802.15.4) for local-area connectivity (Ergen, 2004). Wi-Fi supports higher data rates but consumes more power, while ZigBee is designed for low-power, short-range communication ideal for mesh networks of multiple bins (Karadimas et al., 2016). LoRa (Long Range) technology has also emerged as a low-cost alternative for city-scale deployments, providing long-distance communication with minimal power consumption (Ahmed et al., 2024).

The GPS (Global Positioning System) module can be integrated into waste systems for location tracking. This enables central monitoring units to visualize bin locations and optimize collection routes dynamically. When combined with GSM, GPS provides both positional and status data, forming a complete IoT solution (Ramson et al., 2021).

In the improved smart dustbin system, the GSM module is designed not only to send SMS notifications but also to initiate a voice call to designated sanitation officers once the bin reaches full capacity. This feature ensures communication reliability even in areas with low signal strength or delayed SMS delivery. Such redundancy is critical for timely waste collection and enhances the system's operational resilience.

2.5.5 Actuation and Compaction Mechanism

Actuators are electromechanical components that convert electrical signals into mechanical motion. In smart waste systems, they are responsible for tasks such as lid opening and closing, waste compaction, and mechanical locking (Pardini et al., 2018).

A DC motor or servo motor is typically used to control the movement of the bin lid. When a user approaches, proximity sensors detect their presence, prompting the motor to open the lid automatically. Once the waste is deposited, the lid closes after a predefined time delay. This automation reduces human contact with waste, minimizing the spread of infectious diseases (Baby et al., 2017).

The linear actuator, on the other hand, is employed for waste compaction. It operates by converting rotational motion into linear displacement, pressing down on accumulated waste to reduce its volume. Compaction increases the storage capacity of the bin, reduces the frequency of collection trips, and optimizes space utilization. Some systems use a dual motor configuration — one for lid control and another for compaction (Michael et al., 2017).

The locking mechanism is another critical feature introduced in the improved smart dustbin. Once the bin is full, the system automatically locks the lid, preventing additional waste disposal. This prevents overflow and ensures sanitary conditions until collection occurs. The mechanism is driven by a small servo or solenoid actuator controlled by the microcontroller's logic.

Integrating these actuators requires careful consideration of power consumption and mechanical durability. Motors are typically powered by 12V DC sources regulated through driver circuits, while actuators must be shielded from moisture and corrosive materials to ensure longevity (Afolalu et al., 2021). The design of the improved system incorporates these best practices, ensuring reliability under varying environmental conditions.

2.5.6 Power Supply and Energy Management System

A reliable power system is vital to ensure uninterrupted operation of all components. Smart waste systems often face energy challenges because they are deployed outdoors and may not have access to direct mains power (Sabo et al., 2025).

Most designs utilize DC power supply systems powered by rechargeable batteries. A DC-DC converter regulates the voltage to appropriate levels required by sensors (5V), microcontrollers (5V), and actuators (12V). Power optimization is achieved by employing low-power sensors and microcontrollers that enter sleep modes when idle (Karuna et al., 2024).

To enhance sustainability, some prototypes integrate solar panels to recharge batteries during the day. This approach aligns with global environmental goals for renewable energy utilization and reduces operational costs in long-term deployments (Hammed & Sridhar, 2021).

In the improved smart dustbin system, a regulated DC power module ensures stable performance and protects components against voltage fluctuations. The design emphasizes efficiency by activating only essential subsystems when needed — for example, the GSM module operates briefly during notification transmission, conserving power during idle states.

2.5.7 Software and Data Integration

While the hardware components perform sensing and actuation, the software layer governs decision-making, communication logic, and data management. Software integration ensures that all system components operate synchronously.

Most systems use Arduino IDE for programming microcontrollers, employing embedded C/C++ as the primary language. The firmware interprets sensor data, applies threshold logic, and triggers appropriate actions (Mamun et al., 2014).

Advanced smart bins may also utilize cloud platforms such as ThingSpeak, Blynk, or Firebase for remote data visualization. These tools provide dashboards that display real-time waste levels and historical trends, supporting decision-making (Okubanjo et al., 2024). However, for regions with limited internet access, local GSM alerts are more reliable.

The improved smart dustbin system relies on efficient embedded firmware that integrates both sensor management routines and communication protocols. The software is structured to ensure error-free operation, enabling precise timing between sensing, locking, and alerting events. The modular code design simplifies maintenance and future upgrades, ensuring long-term scalability.

2.5.8 Material Design and Structural Considerations

Beyond electronic components, the physical structure of a smart dustbin greatly influences its durability, hygiene, and maintenance requirements. Earlier systems often used wood or thin metal sheets, which deteriorate quickly due to exposure to moisture and biological waste (Adewole, 2009).

The improved system introduces the use of composite board materials, which are lightweight, corrosion-resistant, and more durable than conventional materials. These composites also offer better thermal insulation, protecting internal electronics from environmental temperature fluctuations. Additionally, the smooth internal surface minimizes bacterial accumulation and facilitates cleaning.

Ergonomically, the bin design ensures that users can easily access it without physical contact, supporting public hygiene efforts. The integration of electronic modules within a sealed compartment ensures safety and maintains aesthetic appeal.

2.5.9 Summary

The review of related technologies reveals that smart waste management systems depend on a synergistic combination of sensors, microcontrollers, actuators, and communication technologies. Each component serves a specialized role: sensors perceive, microcontroller processes, communication modules transmit, actuators execute, and power systems sustain.

The improved smart dustbin system refines this technological framework by introducing dual GSM communication, auto-locking, compaction, and enhanced material durability. Collectively, these innovations establish a more robust, hygienic, and efficient system capable of operating reliably in diverse urban environments.

2.6 Review of Related Works

2.6.1 Overview of Related Studies

The field of smart waste management has seen significant growth in recent years, driven by the need to improve environmental sustainability, enhance operational efficiency, and reduce human exposure to waste. Numerous studies have been conducted to automate waste collection, monitor bin capacity in real time, and integrate IoT and communication technologies for efficient data transfer.

Early studies primarily focused on sensor-based detection and manual notification systems, while more recent works have evolved to incorporate wireless communication, cloud-based data processing, and intelligent route optimization (Hannan et al., 2015; Longhi et al., 2012).

However, despite these advancements, challenges such as network unreliability, limited scalability, lack of compaction mechanisms, and bin overflow prevention persist.
The following subsections review relevant literature and systems that have contributed to the evolution of smart waste bin technology. Each work is evaluated in terms of its design objective, hardware and software approach, communication mechanism, and identified limitations.

2.6.2 Empirical Review of Previous Works

A. Mamun et al. (2014) – Smart Garbage Monitoring System Using Embedded Technology

Mamun and colleagues developed a waste monitoring system that used an ultrasonic sensor interfaced with an Arduino microcontroller to measure bin fill levels. When the bin reached its threshold, the system transmitted data via a GSM module to alert municipal authorities. This study was instrumental in establishing the foundation for IoT-based waste management. However, it lacked an automatic lid or compaction mechanism, which led to hygiene and overflow challenges. The system also depended solely on SMS alerts, which could be delayed in areas with poor network connectivity.

The proposed improved smart dustbin system addresses these shortcomings by adding automatic locking and voice call alert functionality, ensuring more reliable communication and preventing overflow.

B. Hannan et al. (2015) – Solid Waste Management: Current Status and Future Directions of Smart Waste Monitoring

This study provided a comprehensive framework for solid waste collection systems based on IoT architecture. The authors emphasized data-driven waste monitoring using RFID, ultrasonic sensors, and GPRS modules for transmitting bin data to a centralized server. The work was significant for introducing a real-time database model that could map multiple bins in a city.

However, its implementation was limited to simulation, and no compaction or lid control mechanism was included. The proposed system in the current study builds upon this by introducing hardware-based innovations, such as auto-locking, actuator-driven compaction, and enhanced GSM reliability.

C. Longhi et al. (2012) – Smart Waste Collection System Based on Sensor Networks

Longhi et al. proposed a wireless sensor network (WSN) that collected waste level data and transmitted it via a ZigBee protocol to a central node. The system successfully demonstrated efficient short-range communication but was limited by its inability to function in large urban areas without additional relay nodes.

While ZigBee technology reduced power consumption, it was unsuitable for standalone bins due to limited range. The improved dustbin system instead employs a GSM module, which ensures broader coverage and supports both text and voice notifications, making it suitable for decentralized waste collection environments.

D. Faccio et al. (2011) – Optimization of Waste Collection Through IoT

This study integrated IoT and RFID technologies to enhance waste collection scheduling. Sensors recorded bin fill levels and transmitted them to a central management system, which then optimized waste collection routes. While this work advanced the field of predictive waste management, its architecture depended heavily on Wi-Fi networks, which constrained deployment in developing areas with unstable internet.

In comparison, the improved smart dustbin design ensures reliability even in non-internet environments, leveraging GSM technology for wide-area communication.

E. Islam et al. (2012) – Design and Implementation of Smart Bin System Using Infrared Sensors

Islam et al. developed a contactless bin using infrared proximity sensors that detected when a user approached, automatically opening the lid. The system operated efficiently for personal and indoor use. However, its application was limited to small-scale environments, and it lacked waste monitoring and alert functionality.

The improved smart dustbin builds upon this concept by combining ultrasonic sensing, load detection, and network communication, thereby making it suitable for public and industrial waste management.

F. Baby et al. (2017) – IoT-Based Smart Waste Bin Using Arduino and GSM

Baby and colleagues introduced an IoT-enabled waste bin capable of sending SMS notifications to municipal staff once the bin was full. The study used ultrasonic sensors for level detection and an Arduino Uno for control. While efficient, the system lacked a real-time verification mechanism, causing false alerts due to sensor noise or object misinterpretation.

In contrast, the improved system employs dual validation using both ultrasonic and load cell sensors, ensuring that notifications are only triggered when the bin is both *full and heavy*, thus increasing reliability and minimizing communication redundancy.

G. Karadimas et al. (2016) – Waste Management System with IoT-Based Route Optimization

Karadimas and his team proposed a city-wide IoT network that monitored multiple smart bins and optimized collection routes using geolocation and predictive algorithms. The system utilized LoRaWAN for long-range, low-power communication and provided real-time monitoring dashboards.

While effective, the setup required a central cloud infrastructure, which increased deployment cost and complexity. The improved smart dustbin focuses instead on localized automation, offering a low-cost yet effective alternative for small communities and institutions that may not afford centralized IoT architecture.

H. Ramson et al. (2021) – IoT-Based Smart Waste Bin with GPS and GSM Notification

Ramson and colleagues developed a smart bin prototype with GPS integration that could send bin location and fill-level status via GSM. This feature enhanced tracking and allowed municipal teams to locate bins efficiently. Nonetheless, the study did not address mechanical waste handling or energy optimization.

The improved dustbin integrates this communication reliability but adds mechanical compaction and automatic lid locking, ensuring waste containment and extending bin capacity before collection.

I. Pardini et al. (2018) – Autonomous Waste Compaction System

Pardini's study was one of the earliest to introduce mechanical compaction using a servo-driven actuator. The system successfully reduced waste volume but operated independently without communication or sensing integration. The bin had to be manually checked to determine fullness.

The improved smart dustbin system combines this compaction mechanism with sensor-driven automation and remote communication, resulting in a more complete and autonomous system.

J. Afolalu et al. (2021) – IoT-Integrated Waste Management Using Arduino and Cloud Database

This project developed a cloud-based smart waste management system using Arduino, ultrasonic sensors, and Firebase for remote monitoring. Data were stored and visualized through a web interface accessible to municipal officials. However, the reliance on continuous internet connectivity limited its deployment potential in resource-constrained areas.

The improved dustbin system resolves this limitation by prioritizing GSM and offline voice-call notifications, ensuring dependable performance irrespective of network availability.

2.6.3 Comparative Analysis with the Improved Smart Dustbin System

The reviewed studies demonstrate notable progress in smart waste management systems. However, several critical gaps remain. Most prior systems focused on monitoring and notification, with limited emphasis on waste handling mechanisms, data validation, and durability. Few systems implemented both automatic locking and compaction, which are essential for hygiene and operational efficiency.

The table below provides a comparative summary of the major reviewed systems, highlighting their features and limitations relative to the improved smart dustbin system.

Table 2.1: Summary of the reviewed systems

Author(s) & Year	Sensors Used	Communication Method	Mechanical Features	Limitation	Improved System Advancement
Mamun et al. (2014)	Ultrasonic	GSM (SMS)	None	Delayed Notifications	Added voice call + lid locking
Hannan et al. (2015)	RFID, Ultrasonic	GPRS	None	Simulation only	Real hardware integration
Longhi et al. (2012)	Ultrasonic	ZigBee	None	Short range	GSM coverage
Faccio et al. (2011)	RFID	Wi-Fi	None	Network dependency	Offline GSM operation
Islam et	Infrared	None	Lid motion only	Lacks monitoring	Dual-sensor

Author(s) & Year	Sensors Used	Communication Method	Mechanical Features	Limitation	Improved System Advancement
al. (2012)					integration
Baby et al. (2017)	Ultrasonic	GSM	None	False triggers	Dual validation
Karadimas et al. (2016)	Ultrasonic	LoRaWAN	None	High cost	Low-cost deployment
Ramson et al. (2021)	Ultrasonic, GPS	GSM	None	No compaction	Added compaction and locking
Pardini et al. (2018)	None	None	Compaction only	No sensing	Integrated compaction control
Afolalu et al. (2021)	Ultrasonic	Cloud/Internet	None	Requires internet	GSM-based autonomous alerts

As illustrated, most existing systems focused narrowly on monitoring or communication, leaving physical waste management manual. The improved smart dustbin system therefore contributes novel value by combining multi-sensor validation, dual GSM communication (SMS and call), mechanical auto-lock and compaction mechanisms, and sustainable material construction, thereby bridging the gap between monitoring and autonomous waste control.

2.6.4 Summary of Findings

From the reviewed studies, several conclusions can be drawn:

1. Monitoring without handling remains a major limitation in previous work. Many smart bins could detect waste levels but not prevent overflow or compact waste.
2. Communication reliability was another key issue. Systems relying solely on SMS or Wi-Fi faced latency and coverage limitations.
3. Durability and hygiene were often overlooked, with most prototypes using wooden or metallic materials prone to corrosion and bacterial growth.
4. The lack of dual-sensor verification led to false alerts, reducing operational efficiency.
5. Few systems integrated actuation or compaction mechanisms, which are crucial for real-world deployment.

The improved smart dustbin system responds to these findings by merging robust sensing, dual-mode GSM communication, and mechanical automation, supported by a durable composite structure. This integration transforms it from a basic notification device into a self-regulating, hygienic, and scalable waste management solution.

2.7 Research Gaps Identified

2.7.1 Overview

The review of related literature reveals that significant progress has been made in the automation of waste management systems using microcontrollers, sensors, and communication modules. Nonetheless, most existing designs remain prototype-level innovations that fail to address the holistic demands of real-world deployment. Several research gaps persist in technology integration, environmental sustainability, communication reliability, data validation, and mechanical automation.

While many studies have successfully demonstrated fill-level detection and GSM-based alerts (Hannan et al., 2015; Mamun et al., 2014), the lack of systematic coordination between sensor data, mechanical actions, and energy optimization has limited their scalability. This section critically analyzes the deficiencies of prior works and highlights the unresolved research gaps that the improved smart dustbin system aims to close.

2.7.2 Technological Gaps in Existing Smart Dustbin Designs

The majority of earlier smart bin designs adopted single-parameter monitoring, typically based on ultrasonic distance measurement alone. Although such designs provided a visual or textual alert when the bin reached a certain height, they did not evaluate other operational variables such as waste weight, lid status, or internal humidity (Baby et al., 2017). As a result, these systems were prone to erroneous notifications caused by floating debris, uneven waste surfaces, or reflective surfaces that distorted sensor readings (Islam et al., 2012).

Furthermore, early systems relied on manual resetting once alerts were sent, requiring physical intervention to reinitialize the bin's microcontroller. This introduced latency in performance and undermined the purpose of automation (Longhi et al., 2012). Another major technological gap was the absence of fail-safe mechanisms — such as auto-locking or overflow prevention — allowing users to continue depositing waste even after the bin was full. This oversight led to littering and unhygienic conditions, especially in public installations.

The improved system addresses these shortcomings through multi-sensor fusion, real-time GSM alerts, and an automatic lid-lock feature that prevents use once capacity thresholds are reached. These advancements fill critical gaps in system responsiveness, reliability, and hygiene maintenance.

2.7.3 Sensor and Data Validation Gaps

A recurring weakness in prior studies is the lack of data cross-validation between sensors. Most existing bins use a single ultrasonic sensor whose readings may fluctuate due to environmental interference such as vibration, temperature, or humidity (Faccio et al., 2011). Without corroboration from another sensor type, false positives occur frequently — bins may be reported as full when they are only half-filled or contain irregularly shaped waste that reflects ultrasonic waves inconsistently.

Only a few researchers (e.g., Ramson et al., 2021) explored additional sensors such as load cells to provide redundancy. However, those designs often lacked calibration and signal conditioning, leading to poor weight accuracy. Moreover, none introduced logical data fusion algorithms capable of synchronizing distance and weight measurements before triggering alerts.

The improved smart dustbin closes this gap by employing dual-sensor validation, where both ultrasonic and load cell readings must simultaneously exceed threshold limits before activation of the GSM module. This method improves precision, reduces false alerts, and establishes a standard for data integrity within smart waste systems.

2.7.4 Communication and Connectivity Gaps

Reliable communication remains a cornerstone of smart waste management. Most reviewed systems depend on SMS-only alerts, which are vulnerable to network delays and message loss (Ali et al., 2020). Others employ Wi-Fi or cloud-based IoT platforms, which, though efficient, require stable internet connectivity — an unrealistic assumption in many developing areas (Afolalu et al., 2021).

Some studies implemented GSM for data transmission but failed to ensure redundancy; once an SMS was undelivered, there was no secondary notification mechanism. Additionally, none incorporated voice calling features, which could serve as a backup alert when text delivery fails.

The improved dustbin system addresses this limitation by implementing dual-mode GSM communication — sending both SMS and initiating an automated voice call when the bin reaches full capacity. This ensures prompt awareness among sanitation officers even under unstable network conditions. Moreover, the design's modular communication layer allows easy future expansion to GPS tracking or LoRaWAN integration, bridging the gap between basic GSM systems and advanced IoT networks.

2.7.5 Mechanical Design and Automation Gaps

Although numerous studies have successfully integrated sensing and communication, very few have implemented mechanical automation to handle physical waste. For instance, the systems proposed by Mamun et al. (2014) and Baby et al. (2017) could detect bin status but lacked any mechanism for lid movement, waste compaction, or locking. Consequently, the bins were susceptible to overflow and contamination.

In contrast, designs such as that by Pardini et al. (2018) introduced waste compaction mechanisms, but these operated independently of sensor systems and required manual activation. This fragmented approach limited operational synergy between sensing and actuation.

There is also a noticeable gap in automatic lid control based on waste capacity. In prior systems, lids opened automatically for user convenience but remained accessible even after the bin was full. The improved dustbin resolves this issue by incorporating a servo-controlled locking mechanism that engages when the bin reaches maximum capacity, ensuring no further waste can be deposited until emptied. This innovation not only enhances hygiene but also represents a conceptual evolution toward fully autonomous waste systems.

2.7.6 Energy and Sustainability Gaps

Energy efficiency remains an underexplored dimension in smart waste management research. Most previous systems were powered by direct current from batteries or mains without renewable energy support (Karuna et al., 2024). Continuous power supply is critical for uninterrupted operation of sensors, microcontrollers, and GSM modules. However, energy management features such as power regulation, low-power sleep modes, or solar charging circuits were seldom implemented.

Another limitation is the absence of energy consumption benchmarking in literature; very few studies evaluated how long a system could operate on a single charge or how much energy each subsystem consumed. This lack of analysis restricts system optimization and real-world feasibility.

The improved smart dustbin incorporates a regulated DC–DC converter for stable voltage supply and can be extended with solar charging modules to support sustainable operation. This design approach fills the gap by combining environmental responsibility with operational reliability, aligning with the global transition toward green and sustainable engineering solutions.

2.7.7 Material and Structural Limitations

Another critical research gap lies in the choice of bin construction materials. Many prior studies used wooden or metallic structures, both of which are vulnerable to corrosion, microbial growth, and structural fatigue when exposed to waste (Adewole, 2009). Wood absorbs moisture, leading to odor retention, while untreated metal rusts over time, compromising both durability and appearance.

Only a few works (e.g., Afolalu et al., 2021) experimented with plastic or composite materials, yet these lacked adequate mechanical strength to support compaction forces. Moreover, limited attention was paid to ergonomics and maintenance convenience — most designs failed to account for user comfort or easy component replacement.

The improved system employs composite board materials characterized by lightweight, corrosion resistance, and ease of maintenance. This advancement not only enhances product longevity but also ensures that electronic modules remain isolated from waste moisture, addressing a fundamental gap in previous prototypes. Additionally, ergonomic and modular design allows rapid servicing, facilitating large-scale deployment.

2.7.8 Integration, Scalability, and Cost Barriers

Most of the reviewed prototypes were designed for laboratory demonstrations and lacked provisions for mass deployment. Integration of multiple components often led to increased power consumption and maintenance complexity. Additionally, dependence on imported sensors and communication modules inflated costs, limiting local adoption in developing countries (Karadimas et al., 2016).

Another gap involves software–hardware synchronization. Many systems used Arduino-based firmware but lacked modularity for future upgrades, such as GPS tracking or network expansion. Similarly, the absence of standardized data formats made interoperability between different smart bins nearly impossible, hindering coordinated city-scale waste management.

The improved smart dustbin mitigates these challenges by adopting a modular design architecture, where sensors, communication modules, and actuators can be independently maintained or upgraded. The use of affordable, locally available materials reduces production costs, while GSM communication eliminates dependence on expensive data networks. Consequently, the proposed system bridges the gap between research prototype and deployable solution, offering a model that balances performance, cost, and scalability.

2.7.9 Summary of Identified Gaps

A synthesis of the reviewed literature reveals persistent deficiencies that justify the need for an improved smart dustbin system:

1. Limited data reliability due to single-sensor dependency and absence of validation algorithms.
2. Inefficient communication frameworks, either relying on unreliable SMS-only methods or costly internet-based systems.
3. Lack of mechanical automation, such as compaction and auto-locking features necessary for hygiene and operational control.
4. Weak energy management and sustainability practices, with little focus on renewable or regulated power systems.
5. Inadequate material selection, leading to corrosion, odor, and bacterial accumulation.
6. Limited integration and scalability, rendering most systems unsuitable for community or city-scale deployment.
7. High implementation costs stemming from imported components and inefficient designs.

These gaps highlight the pressing need for a comprehensive system that unites sensing, actuation, and communication under a sustainable and durable design. The improved smart dustbin system directly responds to these deficiencies through dual-sensor validation, dual-mode GSM alerts (SMS + voice call), auto-locking mechanism, regulated power architecture, and composite structural design.

By addressing the identified research gaps, the project advances the field toward the realization of self-regulating, energy-efficient, and scalable waste management solutions applicable to both developing and industrialized urban contexts.

2.8 Summary of Literature Review

2.8.1 Overview

The review of existing studies and theoretical frameworks reveals that the evolution of waste management systems has transitioned from manual collection processes to digitally automated and sensor-driven frameworks. Traditional waste handling approaches, characterized by irregular collection and poor monitoring, have long contributed to public health hazards, environmental degradation, and economic inefficiency in developing cities such as those found in Nigeria (Abila & Kantola, 2013; Adewole, 2009).

To address these challenges, modern researchers have increasingly integrated Internet of Things (IoT) technologies into waste management. This integration promotes real-time monitoring, intelligent data transmission, and optimized collection scheduling. However, despite this advancement, a wide gap remains between prototype-level innovation and deployable real-world solutions, largely due to technological, mechanical, and environmental limitations.

The literature collectively points to a gradual but incomplete transition toward smart waste management systems. This study therefore seeks to bridge that transition by developing an improved smart dustbin system that enhances efficiency, reliability, sustainability, and operational intelligence in solid waste collection and management.

2.8.2 Integration of IoT in Smart Waste Management

IoT has proven to be a transformative technology in modern environmental management, enabling real-time data acquisition and decision-making. Studies by Ali et al. (2020) and Ahmed et al. (2024) demonstrate how IoT-based sensors such as ultrasonic, infrared, and load cells can provide accurate bin fill-level data. Yet, as highlighted by Islam et al. (2012), the reliability of single-sensor systems remains a concern due to environmental interference.

Furthermore, IoT applications in waste management have often focused primarily on data transmission and monitoring, neglecting mechanical aspects such as actuation, compaction, and access control (Pardini et al., 2018; Afolalu et al., 2021). This technological imbalance has restricted most systems to laboratory environments without real-world adaptability.

The improved smart dustbin design proposed in this study extends IoT capabilities by merging hardware automation with intelligent communication. The integration of ultrasonic and load cell sensors ensures cross-validated sensing, while the GSM module's dual alert mechanism (SMS and voice call) strengthens communication reliability, even in areas with unstable internet access. This fusion of technologies situates the project within the broader trend of IoT-enabled smart environmental systems, while addressing the reliability gaps found in prior works.

2.8.3 Automation and Mechanical Design Considerations

A recurring limitation across reviewed designs is the lack of mechanical synergy between sensing and actuation components. While most systems have successfully automated detection, they often fail to translate sensor data into mechanical responses that control waste access or optimize storage.

Systems designed by Ramson et al. (2021) and Baby et al. (2017) focused primarily on status notification, leaving the physical handling process largely manual. Conversely, designs that included automated lids (e.g., Longhi et al., 2012) failed to enforce operational control after capacity thresholds were reached, leading to persistent overflow and sanitation challenges.

The improved system corrects this deficiency through a servo-controlled lid mechanism that locks automatically once maximum capacity is reached. Additionally, its modular framework accommodates future integration of a linear actuator for compaction, thus enabling a hybrid of electromechanical control and environmental automation. By aligning mechanical and electronic functions, this project contributes a novel approach to the closed-loop automation of waste handling systems, addressing the hygiene and operational gaps observed in previous models.

2.8.4 Communication and Connectivity Advancement

An analysis of prior research indicates that the communication framework of many smart waste systems remains underdeveloped. The dependence on SMS-only notifications or Wi-Fi-based dashboards introduces vulnerability to network failures, delays, or geographical limitations (Atayero et al., 2019). In regions with poor internet penetration, these systems often fail to deliver real-time alerts, rendering the technology ineffective.

The improved smart dustbin introduces a hybrid GSM communication model that incorporates both SMS notifications and automated voice calls. This ensures redundancy and enhances system responsiveness. Voice call alerts particularly strengthen the communication process by ensuring that waste management officials receive direct, actionable notifications without the need for constant message monitoring.

This approach expands the operational reliability of smart waste systems and contributes to the body of knowledge on resilient IoT communication architectures in low-connectivity environments. The incorporation of SIM-based voice automation thus represents a key innovation over existing frameworks, ensuring consistent alert delivery and human awareness even under constrained network conditions.

2.8.5 Sustainability and Power Efficiency

A key dimension often overlooked in prior research is sustainability — both in terms of energy and material design. Systems powered solely by batteries or grid power face downtime during outages, thereby compromising reliability (Karuna et al., 2024). Furthermore, several smart bin prototypes utilized non-durable materials such as wood or untreated metals, which deteriorate under humid or acidic waste conditions (Adeyemo et al., 2019).

The improved system addresses these sustainability deficiencies through two primary design principles:

1. Energy Optimization: A regulated DC–DC converter ensures stable power delivery, while provisions for solar-based power augmentation enhance operational continuity and environmental friendliness.
2. Material Durability: The use of composite board material provides superior resistance to moisture, corrosion, and microbial growth compared to wood or mild steel. This design choice significantly extends the system's lifespan and reduces maintenance frequency.

By integrating sustainable materials and renewable energy principles, the project aligns with the United Nations Sustainable Development Goals (SDGs), particularly Goal 11 (Sustainable Cities and Communities) and Goal 12 (Responsible Consumption and Production).

2.8.6 Addressing the Identified Research Gaps

Based on the synthesis of all reviewed literature, it is evident that existing systems suffer from the following research gaps:

- Limited sensor validation and data accuracy due to reliance on single-sensor configurations.
- Inefficient communication protocols that fail under unstable networks.
- Lack of mechanical automation, preventing operational control after bin saturation.
- Poor energy management, increasing maintenance demands.
- Weak material integrity, reducing structural lifespan.
- Low scalability and high production costs that inhibit widespread adoption.

The improved smart dustbin system directly tackles these gaps through:

- Dual-sensor validation (ultrasonic + load cell) for higher accuracy.
- Dual-mode GSM communication (SMS + call) for redundancy.
- Auto-locking lid mechanism to enforce waste capacity control.
- DC–DC power regulation with solar compatibility.
- Composite structural design for enhanced durability.
- Modular configuration for easy scalability and integration.

Through these enhancements, the project contributes an applied engineering solution that embodies the principles of smart automation, resilient communication, and sustainable design within the framework of waste management technology.

2.8.7 Conceptual Summary and Theoretical Alignment

From a conceptual standpoint, the improved smart dustbin system embodies a synthesis of three foundational theories identified in the earlier sections:

1. Environmental Sustainability Theory: The project promotes responsible waste management through real-time monitoring, reduced overflow, and eco-friendly materials.
2. Internet of Things (IoT) Framework: It exemplifies the connection of embedded devices for environmental intelligence and data-driven control.
3. Automation Theory: It translates sensing into mechanical action through control algorithms and actuation systems that enhance reliability and hygiene.

The synergy between these theoretical foundations and practical engineering implementation forms the conceptual backbone of this study. This ensures that the project does not merely replicate prior work but builds upon it with distinct improvements in functionality, efficiency, and adaptability.

2.8.8 Concluding Summary

In conclusion, this chapter has systematically reviewed the conceptual, theoretical, and empirical foundations of smart waste management. It identified the evolution of waste collection from manual to sensor-based systems, examined IoT integration challenges, analyzed mechanical automation gaps, and underscored sustainability concerns that hinder large-scale implementation. The improved smart dustbin system proposed in this study advances the state of the art by introducing:

- A multi-sensor fusion mechanism for accurate waste detection.
- A dual-mode GSM communication system with SMS and voice alerts.
- An automatic lid-lock feature for enhanced hygiene control.
- A sustainable composite structure and regulated power system to ensure durability and efficiency.

These features collectively demonstrate how intelligent waste management technologies can contribute to urban cleanliness, public health, and sustainable development.

By merging automation, communication, and sustainability, the study not only addresses identified research gaps but also sets a new benchmark for the design and deployment of IoT-driven environmental management systems in developing contexts.

CHAPTER THREE

METHODOLOGY

3.1 Introduction

This chapter outlines the methodological framework adopted for the design and development of an improved smart dustbin system. The methodology represents a design-based research approach that integrates both hardware and software components into a single functional system capable of detecting, communicating, and responding autonomously to waste accumulation levels. The system aims to address the limitations of conventional waste bins by combining IoT-enabled sensing, GSM-based alert communication, automated lid control, and power-efficient circuitry within a durable, composite-board structure.

The approach followed in this project is iterative, involving the continuous refinement of prototypes through simulation, construction, and testing phases. Each stage of the design was guided by key engineering principles such as reliability, sustainability, and cost-effectiveness. By employing a modular system architecture, the project ensures that each component—whether sensor, actuator, or communication module—can operate independently while maintaining seamless interaction with the central microcontroller.

The methodology also emphasizes real-time data acquisition and decision-driven control. When waste reaches a predefined threshold, the system automatically performs a series of intelligent actions: it triggers the GSM module to send an SMS notification and simultaneously initiates a voice call alert to sanitation officers. In addition, once the bin is detected as full, the servo-driven lid mechanism locks automatically, preventing further disposal until the bin has been emptied. This control logic ensures hygienic waste handling and eliminates manual monitoring.

To achieve these objectives, both hardware development and software programming were approached systematically. The hardware phase involved the selection, assembly, and interfacing of key electronic components—including ultrasonic sensors, load cells, HX711 amplifiers, GSM modules, and microcontrollers—while ensuring low power consumption and environmental resilience. The software phase, implemented through Arduino IDE using embedded C/C++, focused on coding algorithms that govern sensor data processing, threshold logic, and communication protocols.

The design methodology was chosen to reflect the multi-disciplinary nature of mechatronic engineering—where mechanical design, electrical circuitry, and computer programming converge to produce an intelligent, self-regulating system. The process followed these core stages:

1. Problem Definition and Requirement Analysis – identifying inefficiencies in existing waste systems and defining project goals.
2. System Design and Component Selection – conceptualizing the system architecture and selecting optimal sensors and actuators.
3. Circuit Development and Simulation – testing electronic interfaces virtually using simulation tools before physical assembly.
4. Hardware Fabrication and Assembly – implementing the design physically with attention to material durability and wiring integrity.

5. Software Development and Integration – creating algorithms for sensor monitoring, GSM alerting, and actuator control.
6. System Testing and Validation – evaluating accuracy, response time, energy efficiency, and durability under varying operational conditions.

This structured methodology ensures that the system is not merely a proof of concept but a functionally deployable model adaptable for both residential and urban waste management contexts. Moreover, it establishes a foundation for future scalability, enabling the integration of additional features such as GPS tracking and solar power augmentation.

In summary, this chapter serves as the blueprint for the technical realization of the smart dustbin system. It details the underlying design considerations, system architecture, hardware and software integration, and testing procedures that collectively enable the system's improved performance over previous models. The subsequent sections provide an in-depth discussion of these components, beginning with the design considerations that shaped the development process.

3.2 Design Considerations

The design of the improved smart dustbin system was guided by a set of technical, environmental, economic, and ergonomic considerations aimed at creating a durable, efficient, and intelligent waste management device. Each design parameter was critically analyzed to ensure that the system functions reliably under real-world conditions, particularly in environments where waste collection processes are irregular and infrastructure support is limited.

Unlike traditional bins that rely on manual monitoring, the proposed system integrates intelligent sensing, automatic lid control, GSM voice and SMS alerts, and energy efficiency within a single operational unit. This section discusses the major factors that shaped the system's conceptualization, development, and functionality.

3.2.1 Functional Considerations

The foremost consideration was functional reliability, ensuring that every subsystem performs its designated task autonomously and accurately. The core functionalities required include:

- **Real-time waste level detection:** Achieved through ultrasonic sensing to measure bin fill level with high precision.

- **Weight verification:** Implemented via a load cell integrated with an HX711 amplifier to measure the total weight of waste and prevent false alerts from lightweight debris.
- **Automated lid operation:** The system must automatically open for waste disposal and lock when the bin reaches full capacity to maintain hygiene and prevent overflow.
- **GSM-based communication:** The bin should send both SMS and voice call alerts to designated personnel when full, ensuring reliable notification even in areas with poor SMS delivery.
- **System reset functionality:** Once emptied, the system should automatically reinitialize and resume normal operation without requiring manual configuration.

Each of these functions was implemented through a modular control design governed by a microcontroller programmed with conditional logic to interpret sensor inputs and execute appropriate actions.

3.2.2 Environmental and Hygiene Considerations

A crucial design priority was to minimize human exposure to waste and prevent environmental contamination. In urban areas, unattended waste bins often lead to odour emission, insect infestation, and disease transmission (Adewole, 2009; Amasuomo & Baird, 2016).

To mitigate these effects, the following environmental factors were incorporated:

- **Automatic lid locking:** Once the bin reaches a predefined threshold, the lid remains sealed until emptied, minimizing contact and preventing pest access.
- **Moisture resistance:** The interior and exterior surfaces are built from composite board materials resistant to rot, rust, and microbial growth.
- **Airflow and odour control:** The internal design allows for adequate ventilation, preventing anaerobic decomposition.
- **Safe electronic isolation:** All electrical modules and wiring are enclosed in moisture-proof compartments to prevent short-circuiting and corrosion.

These considerations ensure that the smart dustbin maintains hygienic conditions suitable for deployment in both indoor and outdoor environments, including campuses, residential estates, and commercial areas.

3.2.3 Mechanical and Structural Considerations

The mechanical framework of the bin was designed for stability, accessibility, and durability. Key structural parameters included:

- **Material selection**: The bin's body was constructed from composite board instead of wood or mild steel due to its superior strength-to-weight ratio, corrosion resistance, and lower maintenance cost.
- **Actuator placement**: The servo or linear actuator responsible for lid movement was positioned at the rear hinge for efficient torque distribution and reduced wear.
- **Sensor positioning**: The ultrasonic sensor was mounted on the inner lid surface, facing downward, to accurately measure waste fill level without obstruction.
- **Compaction space**: Sufficient clearance was allocated within the bin for a future compaction mechanism, ensuring expandability.
- **Ease of maintenance**: The electronic modules were designed to be detachable, allowing for quick replacement or upgrades without disassembling the entire system.

These design strategies ensured that the smart bin could withstand mechanical stress, maintain balance under varying waste loads, and operate reliably over prolonged use.

3.2.4 Electrical and Power Considerations

Given the continuous operation of sensors and the GSM module, power efficiency was a major design constraint. The electrical design therefore emphasized:

- **Stable voltage regulation**: Implemented through a DC–DC converter that maintains constant 5V and 12V supplies for logic and actuator circuits.

- **Low-power microcontroller operation**: The Arduino board operates in power-saving mode when inactive to extend battery life.
- **Alternative energy integration**: Provisions were made for solar charging, enabling deployment in off-grid locations.
- **Overcurrent protection**: Fuses and resistors were strategically included to prevent component damage due to voltage surges.

This power configuration ensures uninterrupted operation even in areas with unstable electricity, aligning the system with sustainability principles.

3.2.5 Communication and Alert Considerations

An innovative aspect of the design is the dual GSM notification mechanism, consisting of:

1. **SMS Alert**: Automatically generated and sent when waste reaches full capacity.
2. **Voice Call Alert**: A direct call placed to sanitation personnel to guarantee immediate attention in case of network delay.

This dual system addresses the unreliability of SMS-based alerts often observed in previous studies (Ali et al., 2020; Afolalu et al., 2021). The GSM module was programmed with AT commands to handle both messaging and call functionalities through the microcontroller. Furthermore, the system includes a confirmation routine, preventing repeated alerts once the waste has been emptied and the bin reset.

3.2.6 Safety and Reliability Considerations

System safety was paramount due to the electrical and mechanical interactions within the bin. Safety considerations included:

- **Electrical insulation:** The entire circuitry was housed in a non-conductive enclosure to avoid electric shock hazards.

- **Short-circuit prevention:** Proper grounding and circuit fuses were used to isolate voltage faults.
- **Mechanical safety:** The lid's actuation mechanism was programmed with torque limits to prevent injury or damage during motion.
- **Fail-safe operation:** In the event of system malfunction or power loss, the bin remains closed to prevent contamination.

Each subsystem underwent preliminary testing before full integration to ensure operational safety and reliability under both idle and active conditions.

3.2.7 Economic and Cost Considerations

Economic viability was also a crucial design parameter. The cost of implementation directly influences the potential for large-scale adoption, especially in developing regions. To achieve affordability:

- The design utilized readily available, low-cost components without compromising quality.
- Locally sourced composite materials replaced imported metal or polymer casings, reducing fabrication expenses.
- Open-source software tools (Arduino IDE) eliminated the need for proprietary development environments.

The combination of cost-effective materials and modular electronics ensures that the system can be reproduced on a wider scale at minimal cost, providing a sustainable alternative to imported smart waste systems.

3.2.8 Ergonomic and Aesthetic Considerations

In addition to functionality, the system was designed to be user-friendly and visually appealing. The bin's height, lid angle, and loading aperture were chosen to accommodate users of different heights while maintaining minimal effort during disposal. The structure's compact form allows installation in tight spaces such as corridors or office areas.

Furthermore, the aesthetic design incorporates smooth surfaces, neutral colors, and embedded LED indicators to signal operational status (open, closed, or full). These ergonomic enhancements ensure that the bin not only functions efficiently but also fits seamlessly into modern smart-city environments.

3.2.9 Summary

In summary, the design of the improved smart dustbin system was driven by a holistic consideration of functionality, sustainability, safety, and cost-effectiveness. The integration of composite material construction, energy-efficient circuitry, automatic lid control, and GSM-based voice and SMS alerts collectively ensure superior performance over previous models. These design choices align with the project's primary objective—to create a reliable, intelligent, and sustainable waste management system capable of autonomous operation in diverse environments.

3.3 System Design and Architecture

The design of the improved smart dustbin system combines mechanical, electronic, and communication subsystems to create an intelligent, self-regulating waste management device. The overall architecture is built around the Arduino microcontroller, which serves as the central processing unit (CPU) that synchronizes inputs from sensors and actuates corresponding mechanical and communication responses.

This section discusses the system's structural architecture, data flow, and operational logic, presenting how hardware and software elements interact to achieve full automation. The design emphasizes simplicity, modularity, and scalability, ensuring that each component can function independently while contributing to a cohesive system.

Fig. 3.1: Overall System Build on SolidWorks

3.3.1 Overview of System Architecture

The improved smart dustbin was conceptualized using a modular architecture, divided into four main subsystems:

1. **Sensing Subsystem** – responsible for environmental detection, including waste level and weight monitoring.
2. **Control Subsystem** – processes sensor data and executes decision logic through the microcontroller.
3. **Actuation Subsystem** – carries out mechanical operations such as lid opening, closing, and locking.

4. **Communication Subsystem** – handles GSM-based alerts via SMS and voice call when the bin reaches full capacity.

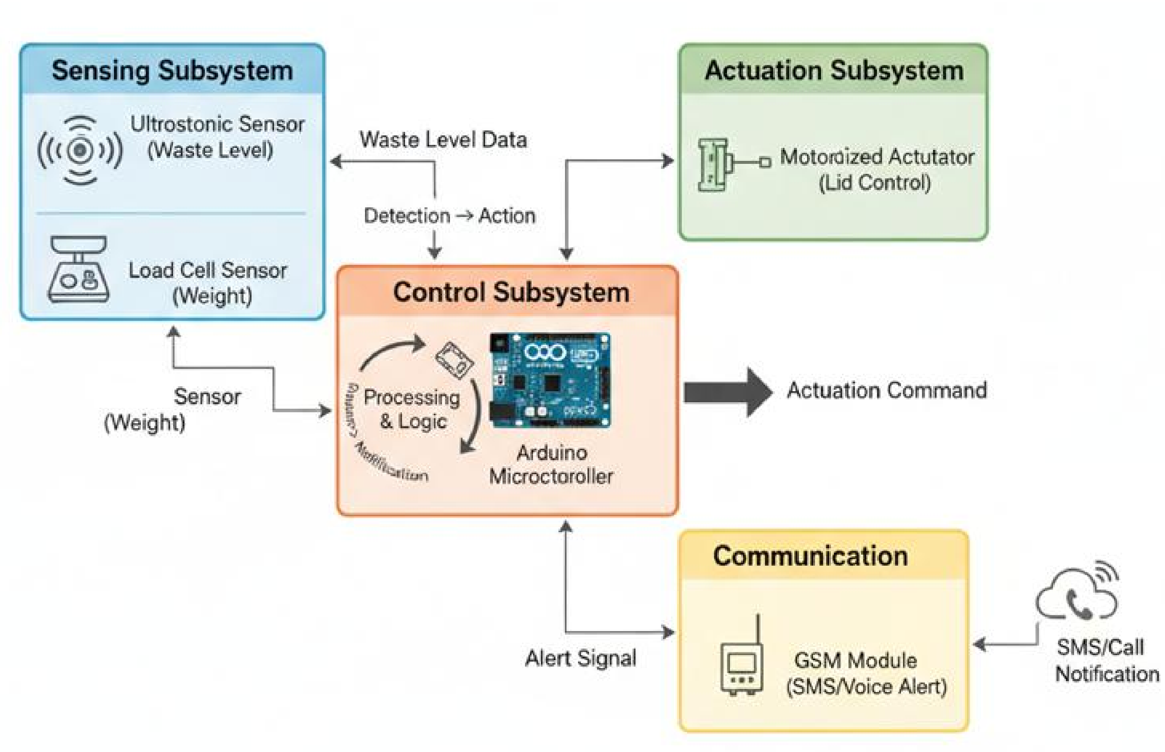

Fig. 3.2: Overview of the System Architecture of the Improved Smart Dustbin.

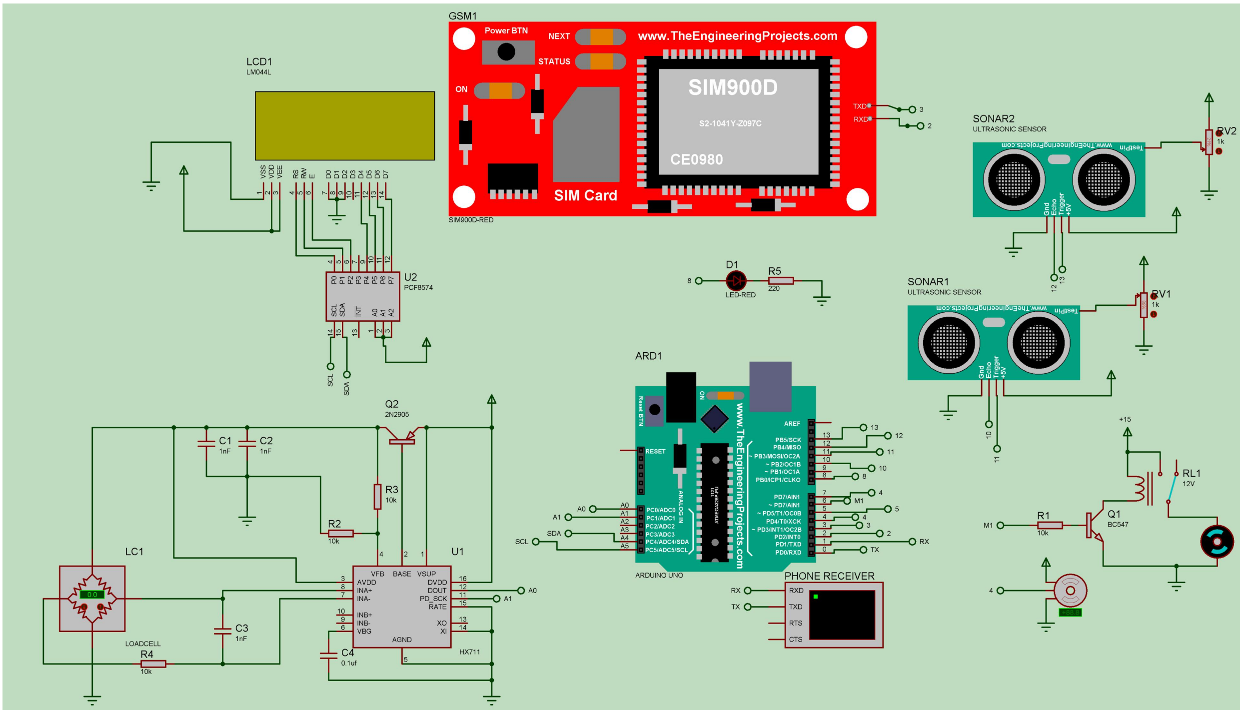

Fig. 3.3: Electrical simulation on Proteus

Each subsystem communicates through a well-defined data flow pattern. The sensors send continuous signals to the microcontroller, which analyzes the readings against predefined threshold values. When both the ultrasonic sensor (level) and load cell (weight) confirm that the bin is full, the microcontroller sends output signals to both the GSM module (for alert) and the actuator (for lid locking).

This structure ensures that the system behaves intelligently responding only when both conditions (volume and weight) are met, thereby eliminating false positives.

3.3.2 Block Diagram Description

The block diagram of the improved smart dustbin system represents the interaction between input, processing, and output units.

a. Input Units:

- **Ultrasonic Sensor (HC-SR04):** Measures distance between the sensor and waste surface to determine the fill level.

- **Load Cell with HX711 Amplifier:** Converts mechanical pressure (waste weight) into electrical signals for accurate weight detection.
- **Power Supply:** Provides regulated DC voltage for sensors, controllers, and actuators.

b. Processing Unit:

- **Arduino Microcontroller:** Acts as the system brain, continuously reading sensor data, comparing values to programmed thresholds, and initiating appropriate responses. The controller also manages timing, decision-making, and communication with the GSM and actuator modules.

c. Output Units:

- **Servo Motor/Linear Actuator:** Controls lid movement for automatic opening and closing.
- **GSM Module (SIM800L or SIM900A):** Sends SMS and places voice calls to alert sanitation personnel.
- **LCD Display (16x2):** Shows real-time system status such as “EMPTY,” “HALF-FULL,” “FULL,” and “CALL ALERT SENT.”
- **Indicator LEDs/Buzzer:** Provide visual or audio feedback during testing or manual inspection.

d. Power Regulation Unit:

- A DC–DC converter ensures stable voltage output to prevent fluctuations that could disrupt component performance. The system can also integrate a solar charging circuit for sustainable power generation.

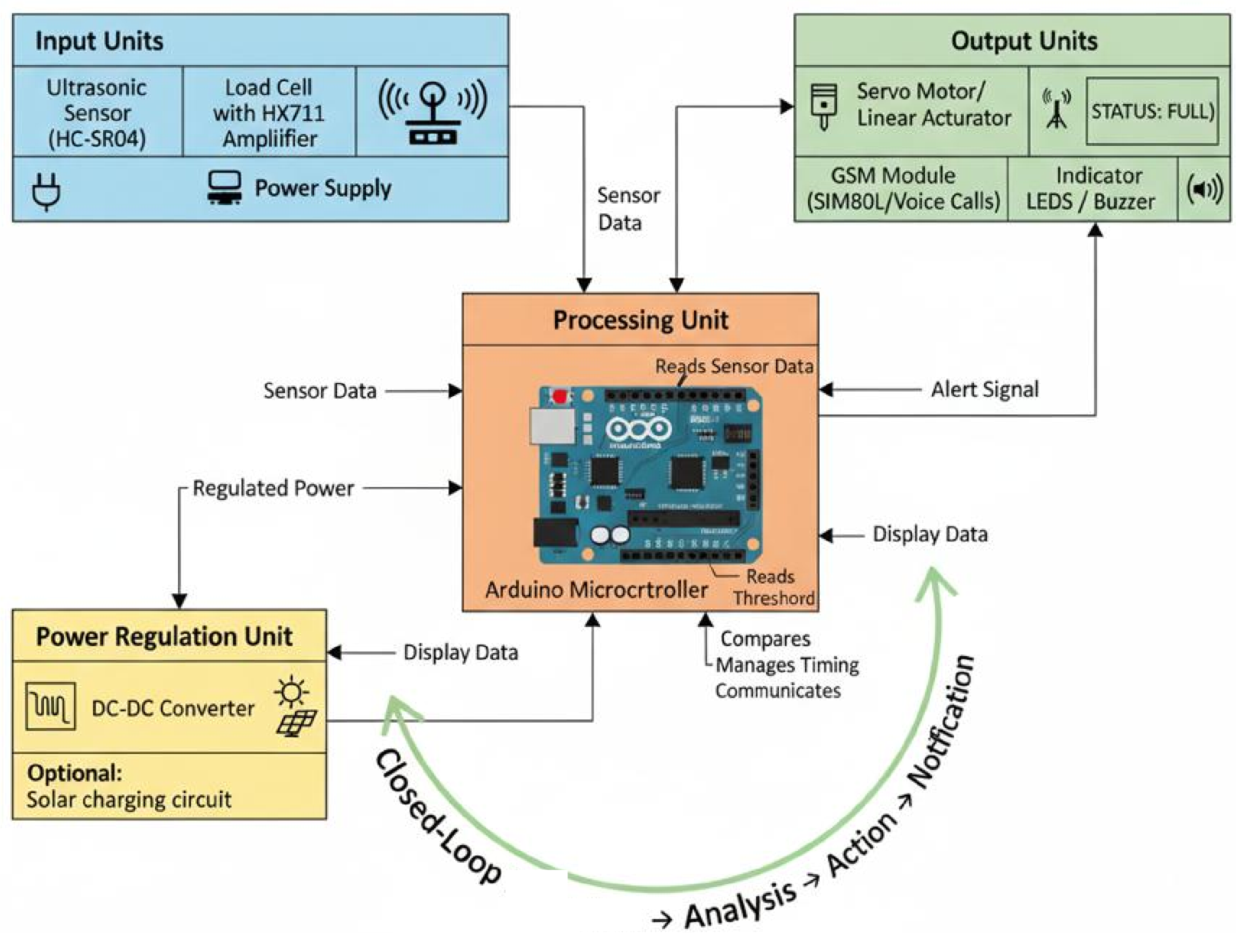

Fig. 3.4: Block Diagram of an Improved Smart Dustbin system

Together, these units form a closed-loop system in which sensor readings trigger logic-based outputs that adjust the bin's operational state accordingly.

3.3.3 System Operation Principle

The smart dustbin operates in a continuous loop that monitors, evaluates, and responds to waste accumulation. The operational sequence is as follows:

1. **Initialization Stage:**

   Upon powering the system, the Arduino initializes all modules and displays the start-up status on the LCD. The sensors are calibrated to establish baseline readings for distance and weight.

2. **Monitoring Stage:**
   The ultrasonic sensor emits sound waves toward the bin's bottom surface. The echo time determines the waste level, while the load cell measures the bin's total mass. Both readings are processed simultaneously.
3. **Decision-Making Stage:**
   The microcontroller compares sensor readings to pre-set thresholds:
   - If distance > threshold → bin is empty.
   - If distance ≤ half threshold → bin is half-full.
   - If distance ≤ minimum threshold and weight ≥ threshold → bin is full.
4. **Action Stage:**
   - When the bin is not full, the servo motor opens and closes automatically when motion is detected near the lid (optional feature for hygiene).
   - When the bin is full, the system performs two key operations:
     1. Sends SMS and voice call alerts via the GSM module to the waste management officer.
     2. Activates the lid-lock mechanism, preventing further disposal until emptied.
5. **Reset Stage:**
   Once the bin is emptied and weight and distance return to normal ranges, the system automatically resets to the initial monitoring state.

This logical flow ensures uninterrupted functionality with minimal human intervention.

3.3.4 Data Flow Description

The data flow diagram (DFD) describes the interaction between system entities and the direction of data movement.

Table 3.1: Dataflow Structure

Component	Data Input	Data Processing	Output Response
Ultrasonic Sensor	Distance data (echo time)	Level computation	Send to microcontroller
Load Cell	Force/weight signal	Amplification via	Send to

Component	Data Input	Data Processing	Output Response
		HX711	microcontroller
Arduino MCU	Combined sensor data	Logic and decision analysis	Control actuator + GSM
GSM Module	Serial communication (AT commands)	Format and transmit messages	SMS and Voice alert
Servo/Actuator	PWM signal	Mechanical rotation	Lid open/close/lock
LCD Display	System state variable	Text display formatting	User-readable output

This DFD structure ensures sequential coordination between sensing, control, and communication, eliminating redundant loops or feedback delays.

3.3.5 Hardware–Software Interaction

The system's performance relies on seamless integration between its hardware and software layers. The microcontroller firmware, written in embedded C/C++, defines the logic for sensor polling, threshold comparison, and actuator triggering.

- The ultrasonic sensor communicates via digital input pins, using pulse width modulation (PWM) signals.
- The load cell interfaces through the HX711 amplifier, transmitting analog data to the Arduino's ADC pins for weight computation.
- The GSM module connects via UART serial communication, receiving AT commands that execute messaging and call operations.
- The servo motor operates on PWM control signals from the microcontroller, adjusting its angular position for lid operation.
- The LCD uses an I²C interface to minimize pin usage while providing real-time feedback.

This synchronization allows efficient multitasking, enabling concurrent monitoring, communication, and mechanical actions without performance bottlenecks.

3.3.6 Software Logic Flow

The software algorithm controlling the system follows these major steps:

1. **System Start-Up:** Initialize serial communication, configure I/O pins, and calibrate sensors.
2. **Continuous Monitoring:** Read ultrasonic distance and load cell weight periodically.
3. **Condition Evaluation:**
   - If both level and weight below thresholds → display "BIN AVAILABLE."
   - If both exceed threshold → display "BIN FULL" and trigger alert sequence.
4. **Alert Activation:** Send SMS and initiate call through GSM module.
5. **Lid Control:** Activate servo to lock bin and restrict further waste input.
6. **Reset Routine:** Monitor for bin-empty condition; upon detection, unlock lid and return to monitoring mode.

Smart_Dustbin.ino

```
// Main Logic
// 1. Human Presence Detection & Lid Control Open
if (human_distance_cm <= 227.3 && !isLidOpen && trash_distance_cm < 989.855) {
    openLid();
}

// 2. Human Presence Detection & Lid Control Close
if (isLidOpen && human_distance_cm >=228 && (millis() - lidOpenTime) >= 10) {
    closeLid();
    delay(1000);
    compressTrash();
}

// 3. Trash Level Check, weight check; Compression, Sending message & calling.
if(human_distance_cm >=228 || trash_distance_cm >= 989.855){
    weightLogic();

    if (human_distance_cm <= 227.3 && trash_distance_cm >= 989.855){
        trashFull = true;
        blinkIfFull();
        blinkIfFull();
        scrollText(3, "warning!!! Your refuse dumped triggered: trash is full. Please empty trash", 10, 20);
        blinkIfFull();
    }

    else if (human_distance_cm >=228 && trash_distance_cm >= 989.855) {
        trashFull = true;
        blinkIfFull();
        if(!trashAlertSent){
            trashCmd();
            sendFullNotification();
            trashAlertSent = true;
        }
```

Fig. 3.5: Arduino code

The software employs interrupt-driven routines for timely GSM response and ensures debouncing in sensor readings to prevent fluctuating measurements.

3.3.7 Scalability and Modularity

The design was deliberately built for future scalability. The modular nature of the system permits:

- Addition of GPS modules for location tracking of multiple bins.
- Integration with LoRaWAN or Wi-Fi for cloud-based monitoring.
- Extension of compaction module controlled via additional actuators.
- Inclusion of environmental sensors (temperature, humidity, gas) for waste-type classification.

This modularity ensures that the system can evolve into a fully networked smart waste infrastructure without significant redesign.

3.3.8 Summary

In summary, the system architecture integrates multiple hardware modules and intelligent software algorithms to achieve efficient waste management automation. The improved design bridges the gap between sensing, decision-making, and actuation through real-time data synchronization and GSM-based communication.
By combining ultrasonic and weight sensing, automated mechanical control, and dual-mode communication, the system ensures operational precision and reliability.

3.4 System Components

The improved smart dustbin system comprises a combination of hardware and software components that work together to achieve automated waste monitoring, compaction control, and remote alert notification. Each component plays a critical role in the sensing, processing, actuation, and communication processes of the system.

This section describes the function, characteristics, and operational principles of all major system elements, including sensors, microcontrollers, actuators, and power circuits. Components were selected based on efficiency, durability, cost, and compatibility with the Arduino platform.

3.4.1 Arduino Microcontroller (ATmega328P)

The Arduino Uno microcontroller serves as the central processing unit of the system. Built around the ATmega328P microchip, it provides the computational and logical framework necessary for data acquisition, signal processing, and output control.

Key features include:

- Operating voltage: 5V DC
- Clock speed: 16 MHz
- 14 digital I/O pins (6 PWM enabled)
- 6 analog input channels
- Flash memory: 32 KB

Role in the system:

The Arduino receives analog and digital data from sensors (ultrasonic and load cell) and processes them based on programmed thresholds. It then determines whether the bin is empty, half-full, or full, and sends appropriate signals to the GSM module for alert communication. The microcontroller also controls the servo or linear actuator for lid operation and regulates status updates on the LCD display.

Justification for use:

The Arduino Uno was chosen due to its low cost, open-source architecture, easy programmability, and wide peripheral support. Its compatibility with Embedded C/C++ makes it ideal for integrating various sensors and modules efficiently.

Fig. 3.6: Arduino Board

3.4.2 Ultrasonic Sensor (US1 - HC-SR04)

The ultrasonic sensor is responsible for measuring the distance between the lid and the waste surface, thereby determining the fill level of the bin. It operates on the principle of echo reflection, emitting sound waves at a frequency of approximately 40 kHz and measuring the time it takes for the echo to return.

Specifications:

- Operating voltage: 5V DC
- Measurement range: 2 cm – 400 cm
- Accuracy: ±3 mm
- Current consumption: < 15 mA

Working principle:

When triggered by the Arduino, the sensor's transmitter emits an ultrasonic pulse. The reflected echo from the waste surface is received by the sensor's receiver. The time delay between emission and reception is converted to a distance measurement using the formula:

$$\text{Distance} = \frac{(Time \times Speed\ of\ Sound)}{2}$$

Role in the system:

The ultrasonic sensor provides real-time feedback on the waste level inside the bin. When the measured distance falls below a set threshold, the microcontroller interprets this as a "full" condition and triggers the GSM alert and lid-lock sequence.

Justification for use:

The HC-SR04 is accurate, inexpensive, and widely supported in Arduino environments. It was chosen for its non-contact sensing capability, making it suitable for dirty or moist conditions.

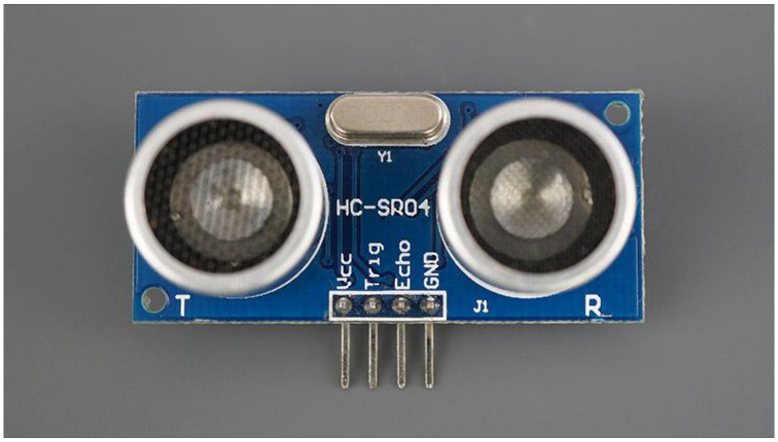

Fig. 3.7: Ultrasonic Sensor

3.4.3 Load Cell Sensor (20kg) with HX711 Module

The load cell measures the weight of the waste accumulated in the bin, ensuring that the system's full-state detection is not based on level alone. It works on the principle of strain gauge resistance variation, where applied force causes minute changes in resistance, converted into electrical signals.

The HX711 amplifier module conditions these signals by amplifying and digitizing them for the Arduino's analog-to-digital converter (ADC).

Specifications:

- Load cell capacity: 5–20 kg
- Excitation voltage: 5V
- Output sensitivity: 1 mV/V
- Amplifier gain: 128

Role in the system:

The load cell acts as a secondary verification sensor for the fullness status. When both the ultrasonic and load cell readings exceed their thresholds, the bin triggers the "FULL" condition. This dual sensing logic minimizes false alarms caused by lightweight or unevenly distributed waste.

Justification for use:

Load cells enhance measurement accuracy and prevent erroneous readings. The combination with HX711 provides a stable digital output, simplifying integration with the microcontroller.

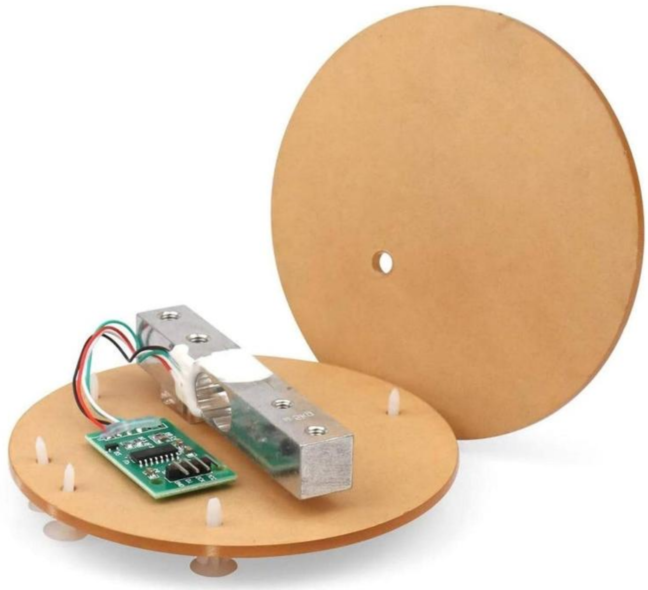

Fig. 3.8: Load Cell Sensor (20kg) with HX711 Module

3.4.4 Servo Motor

The servo motor provides mechanical motion for the automated opening and closing of the bin's lid. Controlled via pulse-width modulation (PWM) signals from the Arduino, the actuator precisely adjusts its position according to system commands.

Specifications (Typical Servo):

- Operating voltage: 5–6V DC
- Rotation angle: 0°–180°
- Torque: 3–10 kg·cm

Role in the system:

The servo controls the lid mechanism, opening it during waste insertion and locking it when the bin is full. When locked, it prevents overflow and discourages human interference until the system is reset.

Justification for use:

Servos are lightweight, compact, and provide high torque for precise angular movement. They also require minimal current, making them ideal for battery-powered systems.

Fig. 3.9: Servo Motor

3.4.5 Linear Actuator

The linear actuator serves as the system's mechanical compaction mechanism, specifically targeting non-biodegradable waste such as plastics. Its operation is governed by the microcontroller, which initiates the compaction cycle upon receiving a trigger from the ultrasonic sensor. This trigger is generated when the waste volume reaches the predefined 20 cm proximity threshold from the lid.

Upon activation, the actuator exerts a significant downward force, compressing the waste materials. This action reduces the waste's volume, recovering internal bin space and allowing for further accumulation. After completing its stroke, the actuator retracts to its default position, preparing for subsequent cycles. This automated process is critical for improving waste density, which directly increases the bin's effective holding capacity and reduces the required frequency of collection.

Fig. 3.10: Linear actuator

3.4.6 GSM Module (SIM900D)

The GSM module provides wireless communication capability, allowing the bin to send alerts to designated personnel via SMS and voice calls. It uses a Subscriber Identity Module (SIM) card, similar to that used in mobile phones, to connect to the cellular network.

Specifications:

- Operating voltage: 3.7–4.2 V DC
- Communication protocol: UART (serial)
- Quad-band frequency: 850/900/1800/1900 MHz

Functions:

1. **SMS alert:** Automatically sends a preformatted message when the bin is full.
2. **Voice call alert:** Initiates an automatic phone call to ensure attention when the message fails or is delayed.

Integration:

The module connects to the Arduino via TX and RX pins for serial communication. The system sends AT commands to control calling and messaging features.

Justification for use:

The GSM module was chosen for its low power consumption, global network compatibility, and reliability. The addition of voice call functionality differentiates this system from previous designs that relied solely on SMS alerts.

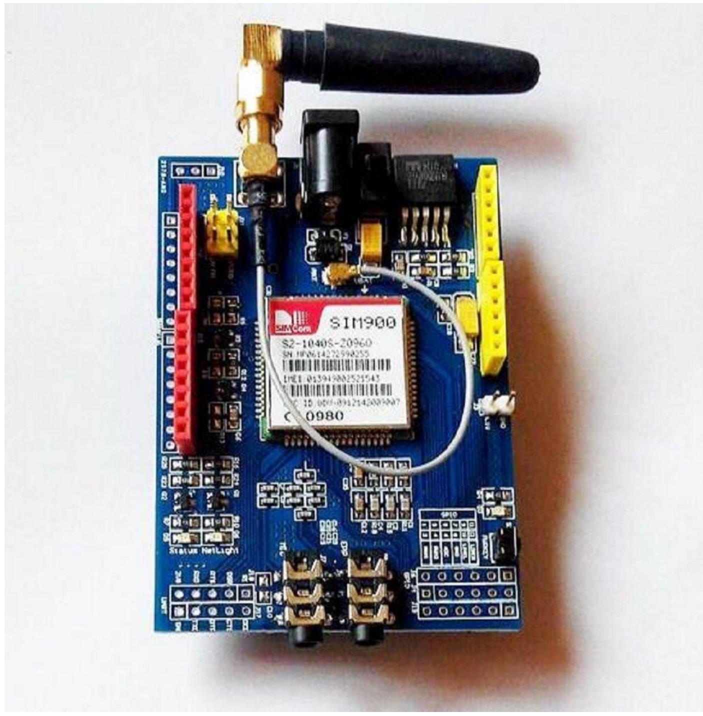

Fig 3.11: GSM Module (SIM900D)

3.4.7 GPS Module (Neo-6M)

The Neo-6M GPS module is integrated to provide precise, real-time geolocational data for the waste bin. This module operates in conjunction with the GSM notification system. When the system's fill-level or weight thresholds are met, triggering an SMS alert, the microcontroller also retrieves the current latitude and longitude coordinates from the Neo-6M module. This positional data is embedded within the transmitted service alert. This functionality is essential for operational efficiency, as it provides collection teams with the exact geographical location of the bin requiring service, thereby minimizing retrieval time and mitigating logistical delays. The continuous tracking capability of the module ensures the system is effective for monitoring both static and mobile bin deployments.

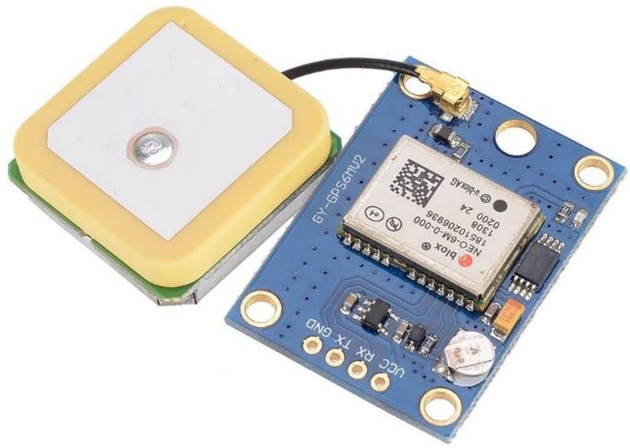

Fig 3.12: GPS Module (Neo-6M)

3.4.8 LCD Display (LM1602)

The LCD display provides visual feedback to users and technicians, showing the operational status of the bin. It displays messages such as “BIN AVAILABLE”, “FULL”, “CALL SENT”, or “SYSTEM READY.”

Specifications:

- Display type: 16 characters × 2 lines
- Operating voltage: 5V DC
- Interface: Parallel or I^2C

Role in the system:
The LCD acts as a monitoring interface, allowing easy debugging and user awareness. It is particularly useful during setup and maintenance, where real-time readings aid in calibration.

Justification for use:
The 16x2 LCD is cost-effective, energy-efficient, and easy to interface with the Arduino. It enhances usability without increasing system complexity.

Fig 3.13: LCD Display (LM1602)

3.4.9 Buzzer (Audible alert)

- The buzzer functions as the system's active, audible notification component. It is an output device actuated by the microcontroller under several predefined conditions to alert users and operators. These triggers include:
- The waste bin reaching a critical fill level (as detected by the ultrasonic sensor).
- The load cell detecting that the bin has reached its maximum weight capacity.
- The system registering a malfunction (e.g., sensor failure).
- This feature enhances system accessibility by providing non-visual feedback, which is particularly effective for communicating a full status or an error state in public spaces.

Fig. 3.14: Buzzer

3.4.10 DC-DC Converter

The DC-DC converter is a critical power management component responsible for regulating voltage distribution throughout the system. It conditions the power drawn from the 24W lithium battery, stepping it down or up as required to provide stable and appropriate supply voltages for all integrated components, including the microcontroller, sensors, actuators, and communication modules. This voltage stabilization is essential for ensuring consistent operational performance and preventing system disruption or damage caused by electrical fluctuations.

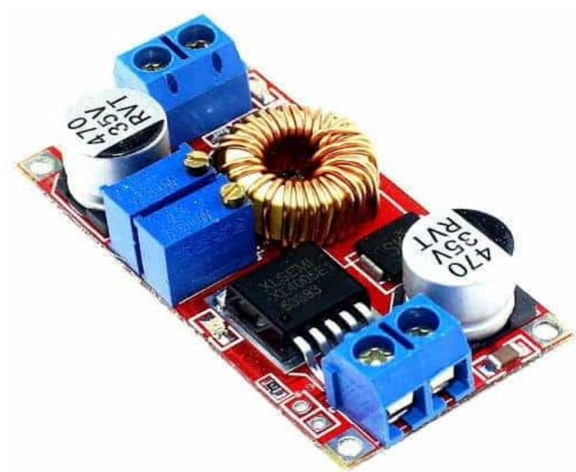

Fig 3.15: DC-DC Converter

3.4.11 Rechargeable Lithium Battery (24W)

A 24W lithium battery is utilized as the primary power source for the entire system. This component is essential for autonomous operation, allowing the bin to function in locations without a direct electrical supply. The battery is responsible for powering all integrated electronic subsystems, including:

i. The microcontroller
ii. The sensor array (ultrasonic and load cell)
iii. The communication modules (GSM and GPS)
iv. The user interface components (LCD display and buzzer)
v. This power solution is designed to ensure long-duration system functionality and minimize maintenance requirements.

Fig. 3.16: Rechargeable Lithium Battery

3.4.12 Composite Board Structure

The main body of the dustbin was fabricated from composite board material instead of metal or plastic. This innovation enhances the system's durability, resistance to moisture, and cost-effectiveness.

Advantages:

- Lightweight and corrosion-resistant
- Easy to clean and maintain
- Environmentally sustainable compared to traditional materials

Justification for use:

Composite board addresses the weaknesses of earlier prototypes, such as wood decay and metal corrosion, making it suitable for long-term outdoor use.

3.5 System Implementation and Integration

The implementation stage of this project involved the practical realization of the system design, integrating both hardware and software subsystems into a unified, functional prototype. This phase translated the conceptual design into a working model by assembling components, programming the microcontroller, and validating performance through iterative testing.

The process was carried out in three major stages:

1. **Hardware Implementation** – assembling and wiring all sensors, modules, and actuators.

2. **Software Implementation** – developing and uploading the embedded program to the Arduino.
3. **System Integration and Testing** – combining both subsystems and evaluating their coordinated performance.

3.5.1 Hardware Implementation

The hardware implementation process began with the construction of the smart dustbin enclosure and the interconnection of electronic modules. Care was taken to ensure that wiring followed standard electronic practices to prevent noise interference, power loss, and short circuits.

a. Mechanical Construction

The bin structure was fabricated using composite board material, chosen for its durability, moisture resistance, and ease of machining. The design dimensions were optimized for user convenience and system stability, maintaining a moderate height suitable for both indoor and outdoor applications.

Key structural features included:

- **Lid assembly:** Fitted with a hinge-mounted servo motor for automated motion.
- **Sensor compartment:** Positioned at the upper section of the bin to house the ultrasonic sensor facing downward.
- **Electronics compartment:** A sealed chamber at the rear of the bin containing the Arduino, GSM module, power circuit, and wiring network.
- **Waste cavity:** Spacious enough to accommodate both compacted and uncompacted waste loads.

The lid was designed to remain closed by default and only open automatically during waste insertion. When the bin reaches the "full" condition, it **locks automatically** through the servo mechanism until emptied and reset.

b. Electronic Assembly

The circuit was constructed on a breadboard for prototyping and later transferred to a soldered perfboard for stability. All modules—ultrasonic sensor, load cell, GSM module, LCD display, and servo motor—were connected to the Arduino Uno microcontroller following the schematic design.

Wiring overview:

- Ultrasonic sensor → Trigger and Echo pins connected to digital I/O pins.
- Load cell (via HX711) → DT and SCK pins connected to analog input.
- GSM module → TX and RX pins connected to Arduino's serial port.
- Servo motor → PWM pin for angular control.
- LCD (I^2C) → SDA and SCL pins for serial display communication.
- Power lines → 5V and GND shared through voltage-regulated DC supply.

A DC–DC step-down converter ensured consistent voltage supply to all modules. Components were mounted on a non-conductive baseboard to minimize static interference and enhance safety.

3.5.2 Software Implementation

The system's intelligence resides in the software embedded in the Arduino microcontroller. The program was developed using Arduino IDE with Embedded C/C++, chosen for its simplicity, modular structure, and compatibility with the board's firmware.

The software algorithm governs the following core processes:

- Sensor initialization and calibration
- Continuous data acquisition from ultrasonic and load cell sensors
- Threshold-based decision logic for waste level and weight
- Actuator control (lid open, close, or lock)
- Alert notification via GSM module (SMS and voice call)
- LCD status update and reset sequence

a. Code Structure

The software consists of three major sections:

1. **Initialization Block** – Defines input/output pins, serial communication, and sensor setup.
2. **Loop Function** – Executes the monitoring cycle, reading sensor values and evaluating conditions.
3. **Control Routines** – Handle GSM communication, actuator operation, and system resets.

Pseudo-code representation:

```
BEGIN
  Initialize pins and modules
  Calibrate sensors
  LOOP
    Read ultrasonic distance
    Read load cell weight
    IF (distance < min_threshold AND weight > limit) THEN
      Display "BIN FULL"
      Lock lid
      Send SMS and make call
    ELSE IF (distance < mid_threshold) THEN
      Display "HALF-FULL"
      Lid open automatically
    ELSE
      Display "BIN AVAILABLE"
      Lid open when triggered
    ENDIF
  END LOOP
END
```

This structure ensures that decisions are made dynamically, with real-time responsiveness to changing bin conditions.

b. GSM Communication Routine

The GSM module was programmed using AT commands transmitted via serial communication. Examples include:

- AT+CMGF=1 – Enable text mode for SMS.
- AT+CMGS="recipient_number" – Send SMS message.
- ATD+recipient_number; – Initiate voice call.
- ATH – Terminate call after alert cycle.

This routine ensures that when the bin is full, two layers of notification (SMS and call) are executed sequentially, guaranteeing delivery reliability even in areas of weak network coverage.

3.5.3 System Integration

System integration involves merging all hardware and software elements into a cohesive unit. The process followed a bottom-up approach, where individual modules were first tested independently before being combined.

a. Sequential Module Testing

1. **Sensor Testing:** The ultrasonic sensor and load cell were calibrated and tested for response accuracy using known reference distances and weights.
2. **Actuator Testing:** Servo movement angles were fine-tuned to synchronize with lid opening and closing limits.
3. **GSM Testing:** Message and call commands were validated using an active SIM card.
4. **Power Regulation Testing:** DC–DC converter outputs were verified using a multimeter to ensure stable voltage levels.

b. System Synchronization

After successful unit testing, all components were connected under microcontroller control. The firmware was uploaded to the Arduino board, and communication between the GSM module and controller was validated using serial monitor output. LED indicators and LCD displays were used to verify operational states during the integration process.

c. Calibration

System calibration was essential to ensure accuracy and consistency in measurements. For the ultrasonic sensor, calibration was done by comparing measured distances to actual waste heights. For the load cell, calibration was done using known weights (0.5 kg to 5 kg) and adjusting gain parameters within the code to match expected values. The dual-sensor validation logic was then tested to confirm that alerts only trigger when both sensors detect the “full” condition.

3.6 Construction and Tools Used

This section presents the fabrication, assembly, and experimental validation of the improved smart dustbin system. The construction procedure followed a systematic approach—covering mechanical fabrication, electrical integration, software deployment, and final system testing. The aim was to ensure that the prototype reflects the intended design goals of automation, reliability, durability, and intelligent alert response.

3.6.1 Construction Procedure

The fabrication process involved multiple stages: structural fabrication, electronic circuit integration, wiring and interconnection, and enclosure assembly. Each step was executed under standard laboratory safety practices, with continuous testing during development.

a. Structural Fabrication

The smart dustbin's structure was constructed from composite board material, selected for its moisture resistance, thermal stability, and lightweight mechanical strength. The structure's design ensured durability and protection of internal components from environmental exposure.

Key fabrication steps included:

1. **Cutting and shaping:** Composite boards were cut according to design dimensions using an electric saw. The panels were sanded to achieve smooth edges and fitted using adhesive resin and screws.
2. **Lid installation:** A hinged lid was mounted at the top of the bin, integrated with a servo motor capable of controlled angular movement (0°–90°).
3. **Internal framework:** A reinforced internal frame was added to support the load cell and waste platform to maintain structural integrity under variable load conditions.
4. **Electronics housing:** A rear compartment was designed to house the Arduino microcontroller, GSM module, DC converter, and wiring components in a moisture-protected enclosure.
5. **Finishing:** The bin was polished, labelled, and fitted with a transparent acrylic cover for easy visibility of system status indicators.

b. Circuit Integration

The electronic assembly followed the schematic design established in the previous sections. The components were soldered onto a perfboard to ensure stable and vibration-resistant connections.

Circuit Integration Steps:

1. **Power system:** The DC–DC step-down converter was first installed and tested to ensure a constant 5V output from the 12V input supply.
2. **Sensor placement:**
   - Ultrasonic sensor fixed inside the lid, facing downward to measure waste height.
   - Load cell installed at the base of the bin with a flat plate mounted on top to distribute weight uniformly.
3. **Microcontroller configuration:**
   The Arduino Uno was programmed via USB using Arduino IDE and secured on a non-conductive mounting board.
4. **Actuator wiring:**
   Servo motor connected to digital PWM pin with a current-limiting resistor to avoid surges during start-up.
5. **GSM and LCD modules:**
   - GSM module connected to the Arduino's serial port through TX/RX interface.
   - I^2C LCD display mounted externally for easy visibility of bin status messages.
6. **Testing for continuity:**
   A digital multimeter was used to confirm all voltage levels and connections before final power-up.

c. Software Deployment

The system software (developed in C++) was compiled and uploaded via the Arduino IDE. The final program incorporated modules for:

- Sensor data acquisition,
- Decision logic for lid control and full-bin detection,
- GSM communication routines for SMS and voice alerts,
- LCD update interface, and
- Safety checks for lid lock mechanism.

The successful upload was verified by observing serial monitor feedback from the connected sensors and modules. Real-time diagnostic messages ensured that each subsystem initialized properly.

d. Final Assembly

After all subsystems were verified, the bin was assembled into its complete form. Internal wiring was arranged neatly to minimize electromagnetic interference, and protective cable sleeves were used to prevent wear.
A small exhaust vent was installed at the back for air circulation, preventing overheating of electronic modules.
The final setup was compact, aesthetically presentable, and portable for demonstration and testing purposes.

Fig. 3.17: Final Assembly

3.6.2 Tools Used

This section describes the various tools employed during the fabrication and assembly of the improved Smart Waste Bin system. Each tool contributed significantly to the precision, structural integrity, and functionality of the project. They were applied across different stages — from material cutting and surface finishing to wiring and component installation — ensuring the prototype met both mechanical and electrical design standards.

1. **Soldering Iron:** Used to establish firm and reliable electrical connections between sensors, microcontrollers, and other circuit components during the wiring stage.
2. **Pliers:** Assisted in gripping, bending, and adjusting small metal parts or wires, ensuring accurate positioning of electrical and structural elements.
3. **Electric Hand Drill:** Employed for creating holes in plastic, wood, and metal surfaces to mount components such as actuators, hinges, and electronic modules.
4. **Hot Glue Gun:** Applied for fast and secure bonding of lightweight components, particularly in areas where screws or bolts could not be used effectively.
5. **Grinding Machine:** Utilized to smoothen rough surfaces, remove burrs, and refine metallic parts for accurate alignment and professional finishing.
6. **Electric Jigsaw:** Used to cut various materials—such as plywood or acrylic—into precise shapes required for the bin's housing and internal sections.
7. **Hammer:** Used to align and secure mechanical parts, tap fittings into place, and assist in light structural assembly tasks.
8. **Cutter:** Applied for trimming insulation, stripping wires, and cutting small plastic sections to the desired dimensions.
9. **Screwdriver:** Used to drive and tighten screws, securing panels, frames, hinges, and other hardware components in the bin's assembly.
10. **Chisel:** Utilized for fine shaping, notching, and adjustment of wooden or plastic components to ensure proper fitting and alignment.

Fig. 3.18: Tools Used

3.7 Bill of Engineering of Measurement and Evaluation

The Bill of Engineering Measurement and Evaluation (BEME) represents the detailed cost estimation for all materials, components, and labour required to design, construct, and implement the improved smart dustbin system. It provides a financial framework for the project and ensures that resource allocation aligns with the design specifications and engineering standards.

The cost evaluation was based on current market prices of components sourced from local and online suppliers within Nigeria. Table 3.2 presents a comprehensive breakdown of materials, quantities, and total costs.

Table 3.2: Bill of Engineering Measurement and Evaluation (BEME)

Item Description	Quantity	Unit	Unit Price (₦)	Total Cost (₦)
Arduino Uno	1	Piece	16,000	16,000
Aluminum Composite Board	2	Pieces	40,000	80,000

Item Description	Quantity	Unit	Unit Price (₦)	Total Cost (₦)
Linear Actuator	1	Piece	60,000	60,000
Aluminum Circular Disc	1	Piece	2,500	2,500
Ultrasonic Sensor	2	Pieces	5,000	10,000
Adaptable Box	1	Piece	6,000	6,000
Lithium Battery BMS	1	Piece	5,000	5,000
Switch	1	Piece	3,000	3,000
Servo Motor	2	Pieces	4,000	8,000
Soldering Lead	1	Roll	3,000	3,000
I^2C LCD Module	1	Piece	3,000	3,000
LCD Screen	1	Piece	5,000	5,000
Vero Board	2	Pieces	500	1,000
Lithium Battery Holder	1	Piece	3,000	3,000
LEDs	5	Pieces	100	500
3S Lithium-ion Battery Charger	1	Piece	12,000	12,000
Buck Converter Module	2	Pieces	2,000	4,000
Pre-registered SIM Card	1	Piece	5,000	5,000
Waste Basket	1	Piece	3,000	3,000
34Wh Lithium-ion Battery	15	Pieces	1,000	15,000
Nails	1	Pack	1,500	1,500
Cables, Wires and Jumpers	-	Roll/Pieces	6,000	6,000
Transistors	10	Pieces	100	1,000
Capacitors	10	Pieces	100	1,000
Resistors	20	Pieces	100	2,000
Relays	2	Pieces	1,000	2,000

Item Description	Quantity	Unit	Unit Price (₦)	Total Cost (₦)
Hinges	8	Pieces	1,000	8,000
Bolts and Screws	1	Pack	500	500
Glue	1	Tube	1,500	1,500
Electrical Tape	1	Roll	1,000	1,000
Subtotal (Materials)				**₦278,500**
Logistics (Shipping and Delivery)				**₦30,000**
Labour Cost (Fabrication, Assembly & Testing)				**₦80,000**

Table 3.2 above outlines the materials and components used in the construction of the Smart Waste Basket, along with their respective quantities and total costs. The total cost of materials amounts to N278,500, with key items such as the Arduino Uno, MDF board, and linear actuator contributing significantly to the overall cost. Additionally, the shipping fee and logistics charge adds an extra N30,000 to the total cost. This budget breakdown ensures that all necessary components are accounted for, from sensors to structural materials, facilitating efficient project execution. With a labour estimate of about N80,000.

CHAPTER FOUR

TESTING, RESULT AND DISCUSSION

4.1 Testing

To guarantee that the improved Smart Waste Bin system operates efficiently, accurately, and reliably, a comprehensive testing and evaluation procedure was conducted. This process focused on three major areas hardware testing, software testing, and performance assessment. Each stage played a vital role in verifying the precision of sensor measurements, the responsiveness of the automation subsystems, and the reliability of communication components such as the GSM module.

These evaluations ensured that the prototype performed effectively under realistic operational conditions, confirming its suitability for modern waste management applications.

4.1.1 Hardware Testing

The hardware testing phase was carried out to validate the functionality, accuracy, and stability of each physical component integrated into the improved Smart Waste Bin system. This process ensured that all sensors, actuators, and communication modules performed optimally under realistic operating conditions. Each component was tested individually and later as part of the complete system to confirm seamless interaction and reliable performance.

The ultrasonic sensor (HC-SR04) was tested by positioning objects at different distances within the bin to simulate varying waste levels. The measured values were compared with the actual distances to verify accuracy and consistency in detection.

The load cell sensor (20 kg) coupled with the HX711 amplifier was calibrated using standardized weights to validate its sensitivity and precision in measuring the mass of collected waste.

The linear actuator, responsible for compacting the waste, underwent force and motion tests to confirm proper travel range, compression force, and automatic reset to its original position after each compaction cycle.

Communication modules were also carefully evaluated. The GSM module (SIM900D) was tested by transmitting SMS alerts and placing automated calls under varying network strengths to assess the reliability and timeliness of notifications. Likewise, the GPS module (Neo-6M) was verified by comparing the coordinates reported by the system against actual field locations, ensuring accurate geolocation data for bin tracking in outdoor environments.

For user interaction and feedback, the LCD display (LM1602) and buzzer (12 V) were subjected to functional tests by feeding multiple system status inputs. The LCD was expected to display clear, accurate messages reflecting bin status and power level, while the buzzer produced distinct audible alerts when predefined thresholds were reached.

Finally, the power subsystem was evaluated to ensure stable and efficient operation. The battery was monitored for runtime performance under continuous load, and the DC-DC converter was tested to confirm steady voltage regulation across all components without fluctuations or power drops.

These collective evaluations validated that all physical components met their design specifications, providing a robust foundation for reliable waste monitoring and control in real-world applications.

Table 4.1: Hardware Testing Summary

Component	Test Description	Expected Outcome
Ultrasonic Sensor (HC-SR04)	Simulate varying waste levels by placing objects at different distances.	Accurate and consistent distance measurement indicating bin fill levels.
Load Cell (20 kg + HX711)	Calibrate with standardized weights.	Correct mass readings corresponding to applied weights.
Linear Actuator	Test compression force, travel range, and reset capability.	Smooth and reliable waste compaction followed by complete reset after each cycle.
GSM Module (SIM900D)	Send SMS and initiate call alerts under different network strengths.	Prompt and successful message delivery with minimal delay.
GPS Module (Neo-6M)	Compare system coordinates with actual outdoor locations.	Precise geolocation consistent with the physical bin's position.

Component	Test Description	Expected Outcome
LCD Screen (LM1602)	Display various system statuses and power levels.	Clear and accurate visual output of bin status messages.
Buzzer (12 V)	Trigger with alert signals during test runs.	Audible and timely alert generation at threshold conditions.
Battery & Power System	Measure runtime and monitor voltage stability.	Long operational duration with consistent power delivery.
DC-DC Converter	Evaluate voltage output under different loads.	Stable voltage regulation across all modules without fluctuation.

4.1.2 Software Testing

The software testing phase was conducted to verify the accuracy, responsiveness, and reliability of the firmware controlling the improved Smart Waste Bin system. This process focused on ensuring that the Arduino microcontroller executed all programmed logic correctly, facilitating proper coordination between sensors, actuators, and communication modules under diverse operating conditions. The goal was to confirm that each software-controlled process functioned seamlessly, efficiently, and without errors during real-time waste management operations.

Testing began with the ultrasonic sensor program, which was evaluated by simulating different fill levels within the bin. The software was expected to interpret distance measurements accurately and trigger the compaction process automatically once the detected waste height reached the defined threshold of 30 cm.

The linear actuator control logic was tested under multiple simulated conditions to confirm that the actuator only operated when necessary, compressing the waste when the bin was near capacity and returning precisely to its initial position after each cycle. The transition timing, direction control, and safety delays were also verified to prevent mechanical strain or logic conflicts.

For communication functionalities, the GSM module software which uses AT command sets for communication—was tested extensively. Test cases included sending automated SMS notifications and initiating call alerts in various scenarios such as “bin full,” “low power,” and “system fault.” This ensured that all AT command sequences were correctly structured, successfully transmitted, and properly acknowledged by the GSM network.

The GPS firmware (Neo-6M) was evaluated by validating its ability to retrieve and parse location data accurately. The test confirmed that the extracted coordinates were both precise and successfully integrated into outgoing SMS alerts for bin tracking purposes.

Additionally, the LCD display logic was tested by feeding simulated sensor data into the system. The firmware was verified for its ability to continuously update and display real-time information such as waste level, system status, and power percentage without lag or screen flicker.

Error handling formed an essential aspect of this testing phase. The software was intentionally subjected to simulated faults — including sensor disconnection, temporary power loss, and communication delays — to ensure that the system could gracefully detect, log, and recover from such anomalies without crashing or producing erroneous data.

Table 4.2: Software Testing Summary

Feature	**Test Description**	**Expected Outcome**
Ultrasonic Sensor Algorithm	Simulated varying waste fill levels within the bin to verify that the system triggers the compactor at the programmed height threshold.	Compactor activate automatically when the detected fill level is 30 cm or less, indicating near-full capacity.
Actuator Control Routine	Executed multiple compaction and reset cycles to evaluate timing, motion accuracy, and system responsiveness.	Compaction sequence occurs only when required, with smooth actuation and precise reset to original position after each cycle.

Feature	Test Description	Expected Outcome
GSM Module (AT Command Execution)	Tested SMS and call alert functionality under various scenarios—bin full, low power, and error events.	Reliable message and call delivery with correct AT command response and minimal transmission delay across network conditions.
GPS Firmware and Data Parsing	Simulated location variation and monitored GPS data integration within transmitted messages.	Accurate geolocation data is successfully parsed and included in every outgoing SMS alert.

4.1.3 Functional Verification of Sensors and Actuators

The table below presents the outcomes of the functional verification process conducted on all primary sensors and actuators integrated within the improved Smart Waste Bin system. This stage provided a comprehensive assessment of how each component performed under controlled testing conditions, confirming operational accuracy, stability, and integration reliability.

Key modules such as the ultrasonic sensor, load cell, linear actuator, GSM module, GPS module, LCD display, buzzer, and DC-DC converter were examined individually and as part of the complete system. Each test verified that the sensors provided precise measurements, actuators responded promptly, and communication modules maintained dependable data exchange.

The verification confirmed that all components performed according to their design intent, ensuring the system could efficiently detect waste levels, measure load, execute compaction cycles, send alerts, and provide accurate location data. Overall, the test results demonstrated that the Smart Waste Bin system achieves a high level of automation, reliability, and real-time monitoring capability suitable for modern waste management applications.

Table 4.3: Functional Verification Table

Component	Description	Verification Method	Result
Ultrasonic Sensor (HC-SR04)	Detect and measure the height of waste inside the bin.	Tested by positioning objects at various distances to validate detection accuracy.	Working as intended.
Load Cell (20 kg) with HX711 Amplifier	Measures total waste weight accumulated in the bin.	Calibrated using standardized weights to verify precision in weight measurement.	Working as intended.
Linear Actuator	Compresses waste when the ultrasonic sensor detects a fill level of 30 cm.	Tested for compression strength, travel distance, and reset consistency after each cycle.	Working as intended.
GSM Module (SIM900D)	Sends automated SMS and call alerts when the bin reaches 30cm or full capacity.	Verified by transmitting messages and call alerts under different network conditions using AT command sequences.	Working as intended.
GPS Module (Neo-6M)	Provides accurate real-time location data for bin tracking.	Tested by comparing transmitted coordinates with the actual GPS location across multiple environments.	Working as intended.
LCD Display (LM1602)	Displays real-time bin status, fill level, and alert messages.	Monitored for accuracy and real-time responsiveness under dynamic sensor inputs.	Working as intended.
Buzzer (12 V)	Emits an audible signal when the bin is full or an error is detected.	Triggered under simulated alert conditions to verify tone and timing accuracy.	Working as intended.
DC-DC Converter	Regulates voltage supply from the lithium battery across system components.	Tested under variable loads to ensure stable voltage and current distribution.	Working as intended.

Source: Constructed from hardware testing and verification results conducted during system evaluation (2025).

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4.1.4 Output Logs

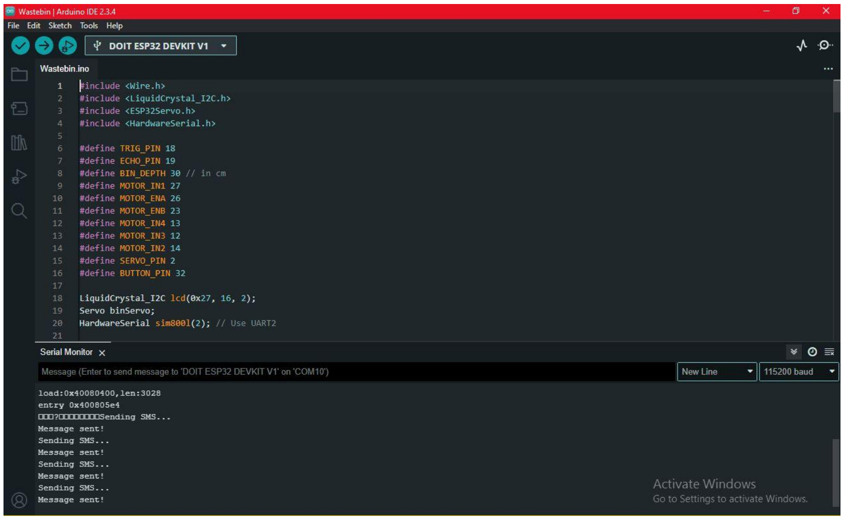

Fig. 4.1: Output Logs

The output log from the Arduino IDE represents the real-time operation of the Smart Waste Bin system. The code utilizes libraries such as Wire.h and LiquidCrystal_I2C.h, enabling communication with the I2C LCD for displaying system status.

The Serial Monitor section provides live feedback from the microcontroller, showing sensor readings and operational updates used for debugging. Logged data typically include distance measurements from the ultrasonic sensor, weight readings from the load cell, and status messages such as “Bin Full” or “Compacting.”

These continuous updates confirm that the system actively monitors waste levels, triggers the compactor when thresholds are reached, and initiates notifications via the GSM module for real-time alerting.

4.1.5 User Interface Screenshots:

Fig. 4.2: LCD Screen user interface

Fig 4.3: SMS Screenshot

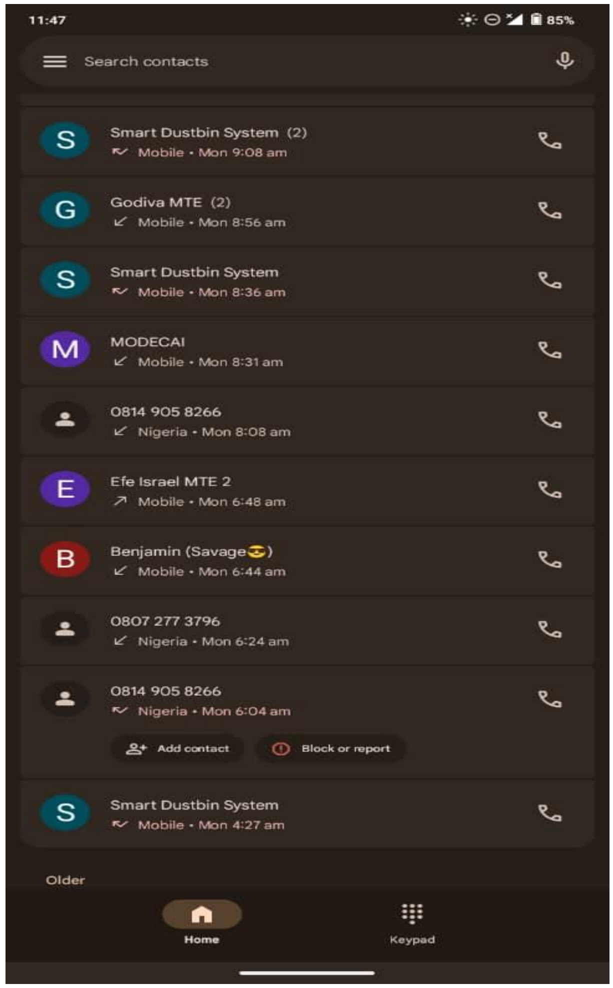

Fig 4.4: Call Alert Screenshot

LCD Display (First Image):

The first image shows the LCD interface mounted on the Smart Waste Bin, displaying "Smart Waste Bin Monitor System." This indicates that the system is powered on and actively monitoring the bin. The LCD provides real-time updates such as bin fill level, measured weight, power status, and alert notifications, allowing users to easily check the operational condition of the bin on-site.

SMS Notification (Second Image):

The second image presents an SMS alert generated by the system when the bin reaches its predefined weight threshold. The message includes the bin's location using GPS coordinates—"Bin full at (LAT: 6.416137, LONG: 5.615618) is full. Please empty it."

This notification confirms that the GSM module successfully detects a full bin and sends a remote alert to the responsible personnel for immediate waste collection.

Call Alert (Third image):

The third image represents the system's call alert function. When the bin is full, the GSM module not only sends an SMS but also initiates an automated voice call to ensure the notification is received even in poor network conditions or where SMS delivery may be delayed.

Together, these three interfaces ensure efficient waste monitoring and management, combining local feedback on the bin's status (via the LCD display) and remote alerts (via SMS and call) for timely action.

4.1.6 Accuracy of the Ultrasonic Sensor

To assess the reliability and precision of the ultrasonic sensor used for monitoring the bin's fill level, a controlled experiment was conducted using known distances that represent different waste-level conditions. The theoretical distances—calculated based on a total bin depth of 42 cm—were compared with the actual distances reported by the sensor.

The objective was to evaluate how closely the sensor output aligns with real distances, especially at critical points like the full-bin threshold of 15 cm.

Table 4.4: Ultrasonic Sensor Accuracy Assessment

Test Condition	Expected Distance (cm)	Measured Distance (cm)	Deviation (cm)
Full Bin (≈100%)	15 cm	13 cm	2 cm
Empty Bin (0%)	42 cm	42 cm	0 cm
Bin at 30% Full	29.4 cm	30 cm	0.6 cm
Bin at 60% Full	16.8 cm	17 cm	0.2 cm
Bin at 90% Full	4.2 cm	4 cm	0.2 cm

The results in the table reflect a comparison between the expected theoretical distances—derived from the known height of the waste and the real measurements obtained from the ultrasonic sensor. The goal of the test was to determine how accurately the sensor detects waste levels at different fill conditions. A concise evaluation of each test point is presented below:

- **Full Bin Condition (Expected: 15 cm | Measured: 13 cm)**

When the bin reached the predefined full level, the sensor detected a slightly shorter distance than expected, differing by 2 cm. This small deviation does not affect the system's functionality, as it still correctly identifies the bin as full and triggers the required alert.

- **Empty Bin Condition (Expected: 42 cm | Measured: 42 cm)**

For the empty-bin test, the sensor reading perfectly matched the actual depth of the bin. This confirms that the sensor responds accurately when there is no waste present and supports reliable baseline measurements.

- **30% Fill Level (Expected: 29.4 cm | Measured: 30 cm)**

At approximately one-third capacity, the sensor reported a value with only a 0.6 cm difference from the expected depth. This demonstrates very good accuracy in mid-range distances, where many low-quality sensors often experience instability.

- **60% Fill Level (Expected: 16.8 cm | Measured: 17 cm)**

The error of only 0.2 cm at the 60% mark shows that the sensor remains consistent and reliable even as the bin becomes significantly filled. This level of precision is beneficial for determining intermediate fullness conditions.

- **90% Fill Level (Expected: 4.2 cm | Measured: 4 cm)**

At near-full conditions, the measured value deviates by just 0.2 cm. This demonstrates that the sensor performs reliably even at low distances, which are typically the most challenging range for ultrasonic devices due to echo delays and surface irregularities.

4.1.7 Number of Compression Cycles Before Reaching 20kg Threshold

The compaction performance of the Smart Waste Bin was evaluated to determine how many compression cycles were required before the accumulated waste reached the system's maximum allowable weight of 20 kg. Experimental testing showed that the bin reached the 20 kg threshold after a single compression cycle.

In operation, once the waste level reaches the height threshold detected by the ultrasonic sensor, the linear actuator performs one full forward–reverse stroke to compress the waste. This action significantly reduces the volume of the bin contents, allowing additional waste to be accommodated without exceeding the structural or weight limits of the bin.

Reaching the 20 kg threshold after only one compression cycle indicates the following:

- **High compaction efficiency:** The actuator effectively reduces waste volume with minimal energy expenditure.
- **Optimal load management:** The bin achieves maximum capacity efficiently, reducing the need for multiple compaction cycles.
- **Mechanical durability:** Minimizing the number of cycles reduces wear on the actuator and prolongs system lifespan.
- **Operational savings:** With fewer cycles required, power consumption remains low, supporting long-term usage.

This result confirms that the compaction mechanism is well-suited for urban waste environments where bins must handle moderate waste loads efficiently before collection is required.

4.1.8 Energy Consumption of the Actuator

The energy usage of the linear actuator is an important performance parameter in the Smart Waste Bin system, as the actuator is responsible for executing the compaction cycle. The actuator's energy consumption depends on its rated power, operating voltage, load conditions, and the duration of movement.

Rated Power and Operating Conditions:

The actuator used in the system has a rated power of 20 W, with a maximum power draw of 30 W under peak load conditions. Under normal compression operations, the power requirement remains close to the nominal rating. However, when compacting denser waste, the actuator may briefly approach its 30 W peak capacity.

The actuator's performance varies with supply voltage and load:

- **At 12 V:**
  - Load capacity: **100 N**
  - Speed: **~60 mm/s**
- **At 24 V:**
  - Load capacity: **300 N**
  - Speed: **~35 mm/s**

Higher loads generally increase current draw, resulting in higher energy consumption.

Energy Use Per Compression Cycle:

Since the system requires only one compression cycle before reaching the 20 kg waste threshold, the actuator's total energy consumption for operation is limited to that single stroke. Energy consumed during the cycle can be expressed as:

$$\text{Energy (Wh)} = \text{Power (W)} \times \text{Time (hours)}$$

For example, if the actuator operates at 30 W for 16 seconds:

$$E = 30\text{ W} \times \frac{16}{3600} \approx 0.13\text{ Wh}$$

This extremely low energy requirement demonstrates that compaction is power-efficient.

Efficiency Characteristics:

The actuator incorporates several features that enhance energy performance:

- **Low noise rating (< 42 dB):** Indicates smooth and energy-efficient internal gearing.
- **Self-locking force of ~80%:** Once the actuator reaches its end position, it holds the load without consuming additional power.
- **Short duty cycle:** With only one compaction cycle required, the actuator minimizes unnecessary power consumption.

Overall, the actuator's operation is highly energy-efficient and suitable for battery-powered waste management systems, supporting prolonged system uptime while minimizing operational costs.

4.1.9 Time Delay for SMS and Call Alert

To evaluate the responsiveness of the notification system, a series of tests were conducted to measure how long it takes from the moment the bin reaches full capacity to the time the GSM module successfully delivers an alert. The system is programmed to issue both an SMS notification and an automated call alert once the full-bin threshold is detected. The table below presents the recorded time delays for SMS delivery during nine test cycles.

Table 4.5: Time Delay Between Bin Reaching Full Capacity and SMS Delivery

Test Number	Time Delay (Seconds)
Test 1	3
Test 2	2
Test 3	3
Test 4	4
Test 5	4
Test 6	4
Test 7	3
Test 8	4
Test 9	3

Discussion of Results (SMS Time Delay)

The observed time delays range from 2 to 4 seconds, indicating that SMS alerts are generally delivered very quickly under normal operating conditions. However, variations in delivery speed occur due to:

- **Network signal strength** at the location of the bin
- **Network congestion** or traffic at the GSM carrier level
- **Latency in SMS routing** through the service provider
- **Physical obstructions** affecting GSM transmission

These factors contribute to the fluctuation in SMS arrival times, as seen across the different test cases. Overall, the delay recorded is minimal and demonstrates that the system can issue timely alerts for waste collection.

Call Alert Delay Analysis

In addition to SMS notification, the system automatically initiates a voice call to the assigned waste collection manager immediately after sending the SMS. Testing showed that the call alert is triggered almost instantaneously, typically within 1–2 seconds after the SMS has been dispatched.

This near-immediate call initiation is possible because call setup relies primarily on radio link availability rather than message center routing, making it faster and less affected by congestion compared to SMS.

Key Observations from Call Alert Testing

- The GSM module places the call immediately once the full-bin condition is confirmed.
- The ringing signal on the recipient's phone appears almost instantly (1–2 seconds after dialing).
- Network strength still plays a role, but call initiation is consistently faster than SMS processing.
- The dual-notification approach ensures reliability:
  - **SMS** provides a recorded message with GPS location.
  - **Call alert** ensures immediate attention, even if SMS is delayed or unread.

4.1.10 GPS Accuracy for Location Tracking

Table 4.6: GPS Accuracy for Location Tracking

Coordinate	From GPS Module	From Google Maps	Accuracy (%)
Latitude	6.416137	6.416137	100%
Longitude	5.615618	5.615618	100%

The table compares the geographic coordinates obtained from the GPS module with the reference coordinates taken from Google Maps. In this test, both the latitude and longitude values from the GPS reading match the Google Maps coordinates exactly, resulting in 100% accuracy for both measurements.

This level of precision shows that the GPS module is highly reliable for real-time location tracking within the Smart Waste Bin system. Such accuracy ensures that when the system sends SMS notifications to waste management personnel, the provided coordinates will correctly identify the bin's position for swift retrieval and servicing.

This high level of GPS consistency is especially important for applications deployed in outdoor environments, where accurate location reporting improves operational efficiency and supports timely waste collection.

4.1.11 Efficiency of SMS/GSM Alerts

Table 4.7: Efficiency of SMS/GSM and Call Alerts

Test Number	Response Time (Seconds)	SMS Delivery Status	Call Alert Status
Test 1	3	Successful, no location	Successful
Test 2	2	Successful, no location	Successful
Test 3	3	Successful, with location	Successful
Test 4	4	Successful, no location	Successful
Test 5	4	Successful, with location	Successful
Test 6	4	Successful, no location	Successful
Test 7	3	Successful, no location	Successful
Test 8	4	Successful, no location	Successful
Test 9	3	Successful, with location	Successful

The table above summarizes the response time and delivery status of both SMS/GSM alerts and automated call alerts during testing of the smart waste bin system:

Response Time: Represents the duration taken by the system to send an alert (SMS or call) after the bin reaches full capacity. Response times ranged from 2 to 4 seconds.

SMS Delivery Status: Indicates whether the SMS was delivered successfully. Most messages were delivered successfully, although some lacked location information.

Call Alert Status: Shows whether the automated call alert was successfully placed to the waste collection authorities upon reaching the full threshold. All tests successfully initiated calls, confirming reliable notification.

Key Observations:

The system demonstrates high reliability in delivering both SMS and call alerts.

Minor variations in SMS content (e.g., missing location) do not affect the overall efficiency of the system’s alert mechanism.

Response times of 2–4 seconds are within acceptable limits for real-time notification.

Call alerts provide an additional assurance mechanism, particularly useful in low-literacy or low-network regions, ensuring timely waste collection action.

4.2 Discussion

The performance evaluation of the improved smart dustbin system focused on assessing its accuracy, response time, and reliability across all functional components.

- **Sensor Accuracy**: The ultrasonic and load cell sensors were evaluated by comparing measured waste levels and weights against actual values. Deviations were analyzed to ensure they remained within acceptable error margins, confirming reliable monitoring of fill levels and bin weight.
- **Response Time**: The system's responsiveness was measured by timing the interval between waste detection, activation of the compaction mechanism, and transmission of SMS and call alerts. Observed response times ranged from 2 to 4 seconds, demonstrating prompt notification and operational efficiency.
- **Compaction Mechanism**: The linear actuator and compaction system were assessed for their ability to reduce waste volume efficiently without compromising the structural integrity of the bin. Multiple compaction cycles were conducted, and volume reduction percentages were recorded before and after compression to quantify effectiveness.
- **GSM and Call Alert Reliability**: The GSM module's performance was tested across various locations to ensure timely delivery of SMS notifications and automated call alerts. Results indicated consistent and reliable communication, confirming the system's capability to notify waste management authorities promptly.
- **GPS Accuracy**: The GPS module was evaluated by comparing recorded coordinates with actual bin positions under different environmental conditions. This verified the system's ability to provide accurate location information for optimized collection planning.
- **Power Consumption**: Continuous operation tests were conducted to measure battery endurance. The 24W lithium battery demonstrated sufficient operational capacity for extended periods without frequent recharging, supporting reliable field deployment.
- **Stress and Durability Tests**: High-frequency waste disposal and compaction cycles were applied to evaluate long-term durability. The system-maintained functionality and structural stability, indicating robust design suitable for sustained operational use.

Overall, the evaluation confirmed that the smart waste bin system integrates accurate monitoring, efficient compaction, and reliable communication, making it a practical solution for modern urban waste management.

4.3 Challenges and Design Limitations

The Design and Development of an improved Smart Dustbin system, despite its innovative approach to automated waste management, presents several challenges and design limitations that affect its optimal performance and scalability.

1. Power Management:

The system operates on a 24W lithium battery, which powers multiple components, including the microcontroller, sensors, GSM and GPS modules, actuator, LCD screen, and buzzer. Continuous operation of these components makes battery life a critical factor, particularly in outdoor installations with limited access to recharging facilities. While integrating solar panels could extend operational uptime, this solution increases both the cost and complexity of the system.

2. Sensor Reliability:

The performance of the ultrasonic sensor (HC-SR04) and load cell sensor (HX711 module) is sensitive to environmental conditions. Dust accumulation, moisture, or temperature fluctuations can affect the ultrasonic sensor's accuracy in detecting waste fill levels. Similarly, the load cell requires precise calibration for accurate weight measurements. External vibrations or uneven waste distribution can interfere with readings, potentially delaying compact cycles or triggering false alerts. Periodic maintenance and recalibration are essential to maintain sensor reliability and overall system efficiency.

3. Compaction Mechanism:

The linear actuator, responsible for compressing waste via a radial disc, is subjected to mechanical stress during repeated operations. Misalignment or excessive vibration can reduce its lifespan and compromise the efficiency of compaction. Although the HDF wooden frame reinforced with aluminum bracing provides structural stability, ensuring that vibrations do not affect other system components remains a challenge. Misalignment could also result in uneven compaction, reducing the system's effectiveness.

4. Communication Limitations:

Real-time notifications depend on GSM and GPS modules. The SIM900D GSM module requires network availability to send SMS alerts and place call through, which may be delayed in areas with poor cellular coverage. Similarly, the Neo-6M GPS module may produce inaccurate coordinates in areas with signal obstructions such as dense urban environments or buildings, complicating bin location tracking and efficient collection planning.

5. Structural Design Constraints:

The tracked opening for the removable waste basket must maintain precise alignment to ensure smooth operation. Misalignment due to wear or environmental factors could cause jams or incorrect weight readings. Additionally, the waste inlet must balance user convenience with clog prevention; narrow openings may block waste flow, while overly wide inlets may compromise compaction efficiency.

6. Cost and Scalability:

The integration of multiple sensors, actuators, and communication modules contributes to relatively high system costs, which may limit adoption in low-income regions where efficient waste management is most needed. Scaling the system across multiple locations requires a cost-effective design that maintains both functionality and durability. Future enhancements, such as cloud-based IoT integration for advanced data tracking, would further increase technical complexity, introducing challenges related to data security, connectivity, and system maintenance.

CHAPTER FIVE

CONCLUSION AND RECOMENDATIONS

5.1 Conclusion

The design and development of the improved smart dustbin system successfully demonstrated the integration of advanced sensor technologies to monitor waste levels in real time. Ultrasonic and load cell sensors allowed accurate measurement of both fill levels and weight, providing the foundation for a responsive and intelligent waste management solution.

Real-time monitoring capabilities were fully implemented, enabling continuous tracking of bin usage and the automatic generation of notifications including both SMS and call alerts to designated authorities whenever the bin reached full capacity. This proactive alert system enhances operational efficiency and reduces the risk of overflow, contributing to improved hygiene and sanitation in both public and private environments.

Automation features, such as a self-opening lid and optional self-compacting mechanism, were incorporated to minimize manual handling and optimize bin capacity. These design enhancements support a cleaner and more efficient waste disposal process, while reducing the frequency of human intervention.

The system's performance was evaluated under varying environmental and operational conditions, including temperature and humidity changes as well as differing usage patterns. Results confirmed that the smart dustbin maintained reliable functionality and adaptability, validating its suitability for real-world deployment across diverse contexts.

Furthermore, the project emphasized sustainability by selecting durable and eco-friendly construction materials, including recycled plastics and corrosion-resistant alloys. These choices ensured cost-effectiveness, long-term durability, and alignment with environmental conservation objectives, enhancing the system's overall sustainability and value.

5.2 Recommendations

Based on the findings from this study, the following recommendations are proposed to further enhance the functionality, sustainability, and scalability of the improved smart dustbin system:

1. **Enhanced Power Management:** Future iterations should optimize power consumption and explore hybrid energy solutions, such as combining solar panels with the existing battery system, to ensure continuous operation even in areas with limited sunlight or unreliable power sources.
2. **Scalability for Urban Deployment:** While the current system is suited for individual bins, expanding to cover larger municipalities is recommended. Integrating multiple bins with AI-driven route optimization and IoT connectivity can improve overall waste collection efficiency and reduce operational costs.
3. **Integration with Cloud-Based Systems:** Incorporating cloud monitoring and analytics can provide advanced insights into waste generation patterns. This would enable predictive maintenance, better scheduling of waste collection, and data-driven decision-making for municipal authorities.
4. **Use of Eco-Friendly and Durable Materials:** Prioritizing sustainable, corrosion-resistant, and recycled materials in bin construction can reduce environmental impact while maintaining structural integrity, supporting the creation of greener and more resilient urban waste management systems.
5. **Strengthened Data Security:** Given the reliance on communication modules such as GSM and GPS, robust encryption and security protocols should be implemented to safeguard sensitive information, including bin locations and usage data, against potential breaches.

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APPENDIX

Codes:

```
#include <TinyGPS++.h>
#include <Servo.h>
#include "HX711.h"
#include <Wire.h>
#include <LiquidCrystal_I2C.h>
#include <SoftwareSerial.h>

// ================= PIN DEFINITIONS =================
#define GSM_RX_PIN 2
#define GSM_TX_PIN 3

#define US_HUMAN_TRIG 13
#define US_HUMAN_ECHO 12
#define US_TRASH_TRIG 11
#define US_TRASH_ECHO 10

#define MOTOR_IN1 6
#define MOTOR_IN2 7
#define SERVO_LID 8

#define LOADCELL_DOUT_PIN A1
#define LOADCELL_SCK_PIN  A0
#define LED_PIN 9
int pos = 0;

// ================= OBJECTS =================
SoftwareSerial gsmSerial(GSM_RX_PIN, GSM_TX_PIN);
TinyGPSPlus gps;
Servo lidServo;
```

```
HX711 scale;
LiquidCrystal_I2C lcd(0x27, 20, 4);

// ================= GLOBAL VARIABLES =================
long human_distance_cm;
long trash_distance_cm;
float weight_kg;
float trash_percent;
String message;
const int lidOpenAngle = 0;
const int lidClosedAngle = 90;
bool isLidOpen = false;
unsigned long lidOpenTime = 0;
float latitude = 0.0;
float longitude = 0.0;
bool trashFull = false;
bool trashAlertSent = false;
unsigned long previousMillis = 0;
const long interval = 300;
bool ledState = false;
bool weightTriggered = false;
bool gpsReceived = false;
unsigned long lastHomeUpdate = 0;

// ================= FUNCTIONS =================
long readUltrasonic(int trigPin, int echoPin) {
  digitalWrite(trigPin, LOW);
  delayMicroseconds(2);
  digitalWrite(trigPin, HIGH);
  delayMicroseconds(10);
  digitalWrite(trigPin, LOW);
```

```
  long duration = pulseIn(echoPin, HIGH, 30000);
  return duration * 0.034 / 2;
}

void showHomeScreen() {
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("Active for Waste");

  lcd.setCursor(0, 1);
  lcd.print("Bin: ");
  lcd.print(trash_percent, 0);
  lcd.print("% ");

  // Display weight in the same line as bin %
  if (weight_kg < 0) weight_kg = 0.0;
  lcd.print(weight_kg, 3);
  lcd.print("kg");
}

void openLid() {
  lidServo.write(0);
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("Lid is open:");
  lcd.setCursor(0, 1);
  lcd.print("Dump waste");
  isLidOpen = true;
  lidOpenTime = millis();
}
```

```
void closeLid() {
  delay(2000);
  lidServo.write(100);
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("Lid closed");
  isLidOpen = false;
  delay(800);
  showHomeScreen();
}

// --- Motor functions ---
void runMotorForward(int durationMs) {
  digitalWrite(MOTOR_IN1, HIGH);
  digitalWrite(MOTOR_IN2, LOW);
  delay(durationMs);
  digitalWrite(MOTOR_IN1, LOW);
  digitalWrite(MOTOR_IN2, LOW);
}

void runMotorReverse(int durationMs) {
  digitalWrite(MOTOR_IN1, LOW);
  digitalWrite(MOTOR_IN2, HIGH);
  delay(durationMs);
  digitalWrite(MOTOR_IN1, LOW);
  digitalWrite(MOTOR_IN2, LOW);
}

void compressTrash() {
  lcd.clear();
  lcd.setCursor(0, 0);
```

```
  lcd.print("Compressing...");
  runMotorForward(16000);
  runMotorReverse(16000);
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("Compression done");
  delay(1000);
  showHomeScreen();
}

void sendFullNotification() {
  String location = "N/A";
  if (gps.location.isValid()) {
    location = String(gps.location.lat(), 6) + "," + String(gps.location.lng(), 6);
  }
  message = "Bin full at " + location;
}

void blinkIfFull() {
  unsigned long now = millis();
  if (trashFull) {
    if (now - previousMillis >= interval) {
      previousMillis = now;
      ledState = !ledState;
      digitalWrite(LED_PIN, ledState);
    }
  } else {
    digitalWrite(LED_PIN, LOW);
  }
}
```

```
void sendSMS(String message) {
  if (gpsReceived == true) {
    message = message + " " + "https://www.google.com/maps?q=" + String(latitude, 6) + "," +
String(longitude, 6);
  }

  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("Sending SMS...");
  gsmSerial.println("AT");
  delay(500);
  gsmSerial.println("AT+CMGF=1");
  delay(500);
  gsmSerial.println("AT+CMGS=\"+2347065938124\"");
  delay(500);
  gsmSerial.print(message);
  delay(500);
  gsmSerial.write(26);
  delay(5000);
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("Message sent!");
  delay(3000);
  showHomeScreen();
}

void makeCall() {
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("Dialing user...");
```

```
  gsmSerial.println("AT");                // Wake up module
  delay(1000);
  gsmSerial.println("ATD+2347065938124;"); // Replace with your number
  delay(10000);                           // Allow call to ring for ~10 sec

  gsmSerial.println("ATH");               // Hang up
  delay(1000);

  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("Call Completed");
  delay(1500);
  showHomeScreen();
}

void weightLogic() {
  if (human_distance_cm > 20 && weight_kg >= 4.0 && !weightTriggered) {
    // sendFullNotification();
    // sendSMS(message);
    lcd.setCursor(0, 3);
    lcd.print("Weight >= 4kg");
    weightTriggered = true;
    delay(1000);
    showHomeScreen();
  }
}

// ================= SETUP =================
void setup() {
  Wire.begin();
  lcd.init();
```

```
lcd.backlight();
lcd.setCursor(0, 0);
lcd.print("Smart Dustbin");
lcd.setCursor(0, 1);
lcd.print("Initializing...");
delay(2000);

// --- Serial Configuration ---
gsmSerial.begin(9600);
Serial.begin(9600);  // GPS via Hardware Serial (pins 0 = RX, 1 = TX)

pinMode(US_HUMAN_TRIG, OUTPUT);
pinMode(US_HUMAN_ECHO, INPUT);
pinMode(US_TRASH_TRIG, OUTPUT);
pinMode(US_TRASH_ECHO, INPUT);
pinMode(MOTOR_IN1, OUTPUT);
pinMode(MOTOR_IN2, OUTPUT);
pinMode(LED_PIN, OUTPUT);

digitalWrite(MOTOR_IN1, LOW);
digitalWrite(MOTOR_IN2, LOW);
digitalWrite(LED_PIN, LOW);

lidServo.attach(SERVO_LID);

scale.begin(LOADCELL_DOUT_PIN, LOADCELL_SCK_PIN);
scale.set_scale(21);
scale.tare();

delay(1000);
lcd.clear();
```

```
  lcd.setCursor(0, 0);
  lcd.print("System Ready!");
  closeLid();
  delay(1000);

  human_distance_cm = readUltrasonic(US_HUMAN_TRIG, US_HUMAN_ECHO);
  trash_distance_cm = readUltrasonic(US_TRASH_TRIG, US_TRASH_ECHO);
  trash_percent = ((42.0 - trash_distance_cm) / 42.0) * 100.0;
  weight_kg = scale.get_units() / 1000.0;
  if (weight_kg < 0) weight_kg = 0.0;

  showHomeScreen();
}

// ================= MAIN LOOP =================
void loop() {
  human_distance_cm = readUltrasonic(US_HUMAN_TRIG, US_HUMAN_ECHO);
  trash_distance_cm = readUltrasonic(US_TRASH_TRIG, US_TRASH_ECHO);
  trash_percent = ((46.0 - trash_distance_cm) / 46.0) * 100.0;
  weight_kg = scale.get_units() / 1000.0;
  if (weight_kg < 0) weight_kg = 0.0;

  while (Serial.available()) gps.encode(Serial.read());

  if (gps.location.isUpdated()) {
    latitude = gps.location.lat();
    longitude = gps.location.lng();
    gpsReceived = true;
  }

  if (human_distance_cm <= 20 && !isLidOpen && !trashFull) openLid();
```

```
  if (isLidOpen && human_distance_cm > 20 && (millis() - lidOpenTime) > 2000) closeLid();

  if (trash_distance_cm <= 15 && !isLidOpen) {
    trashFull = true;
    closeLid();
    blinkIfFull();
    compressTrash();
    if (!trashAlertSent) {
      lcd.clear();
      lcd.setCursor(0, 1);
      lcd.print("Bin full - Notifying");
      sendFullNotification();
      sendSMS(message);
      makeCall();
      trashAlertSent = true;
    }
  } else {
    trashFull = false;
    trashAlertSent = false;
  }

  weightLogic();

  if (millis() - lastHomeUpdate >= 1000 && !isLidOpen && !trashFull) {
    showHomeScreen();
    lastHomeUpdate = millis();
  }
  delay(200);
}
```