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DESIGN OF SMART WASTE MONITORING AND MANAGEMENT SYSTEM

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CERTIFICATION

I hereby certify that the project work "The Design and Fabrication of Smart Waste Monitoring and Management System" was carried out by:

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DEDICATION

This project work is dedicated to God Almighty who granted us courage and patience to perform and carry out this project work, and without His help we would not have achieved what we have done so far.

Also, the project is dedicated to our parents for their great support, guidance, sacrifice and prayers throughout the duration of our course of study.

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ABSTRACT

Rapid urbanization, particularly in places like Nigeria, intensifies waste management challenges due to the inefficiency and high cost of traditional collection. While current **smart waste monitoring and management systems** offer improvements through IoT monitoring, they often lack advanced sorting and comprehensive management features. This project directly addresses these gaps by designing an innovative **smart waste monitoring and management system** that critically incorporates the **automated segregation of metals and plastics**, alongside enhanced automation and real-time data capabilities.

Our prototype is a sophisticated solution that integrates various sensors—including ultrasonic and load sensors for fill-level monitoring and compaction, plus specialized inductive (for metals) and optical/capacitive (for plastics) detectors for sorting—with linear actuators for automated processes and a GSM/GPS module for wireless communication. This setup allows the system to not only monitor bin levels, automatically compact waste, and control the lid, but most importantly, to accurately sort plastic and metal materials at the source. This ensures more efficient resource recovery and recycling.

Through rigorous testing of both hardware and software, we will verify the reliability of sensor performance, the effectiveness of automation, the accuracy of communication, and the precision of the waste segregation mechanism. The anticipated outcome is a fully integrated system that successfully demonstrates its capacity to accurately detect fill levels, initiate automated compaction, send prompt location-based alerts, and effectively sort waste. This proven dependability under real-world conditions highlights the system's potential to significantly alleviate urban waste management issues by reducing overflow, boosting collection efficiency, increasing recycling rates, and providing a scalable, sustainable solution for residential, commercial, and municipal settings.

settings.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

The escalating population and rapid urbanization in **Nigeria** and **Benin** have significantly impacted waste generation, presenting major environmental and public health challenges. Traditional waste management practices, which often rely on manual collection, infrequent disposal, and a lack of sophisticated sorting, are increasingly proving inadequate (Asikhia & Olaye, n.d.). These methods lead to widespread environmental degradation, including land and water pollution, and contribute to greenhouse gas emissions from landfills. The proliferation of pests and diseases from overflowing bins also poses serious health risks to communities (Ekhaise & Oni, 2013). A more intelligent and sustainable approach is urgently needed to address these issues.

In response, **smart waste management and monitoring system** has emerged as a solution, leveraging the **Internet of Things (IoT)** to improve waste collection and disposal (Adebayo et al., 2021). These smart bin systems use sensors and wireless communication to provide real-time data on waste levels, optimize collection routes, and enhance operational efficiency (Ramson et al., 2020). This reduces unnecessary trips, lowers fuel consumption, and prevents bins from overflowing. However, a crucial limitation of many existing smart bin models is their focus on basic monitoring, often neglecting the critical need for advanced waste stream separation (Afolalu et al., 2021).

The lack of source segregation is a significant problem, particularly in regions with limited recycling infrastructure. Mixed waste streams result in lower-quality recyclables, higher processing costs, and more waste ending up in landfills. Metals and plastics are valuable resources that can be recycled if properly separated. Their improper disposal contributes to environmental harm, with plastics breaking down into microplastics and metals potentially leaching toxic heavy metals into the soil and water. Therefore, the ability to automatically separate these materials at the point of disposal is essential for promoting a **circular economy** and maximizing resource recovery (Jimeno et al., 2021).

This study aims to address these issues by designing a smart waste management and monitoring system system that not only monitors and compacts waste but also automatically segregates metal and plastic waste. The **University of Benin (UNIBEN), specifically the Ugbowo campus in Benin City**, will serve as a primary case study. Research has shown that a significant percentage of residents at UNIBEN are unwilling to sort their waste, even with awareness of the environmental risks (Kubeyinje et al., n.d.). This project seeks to enhance waste collection efficiency and improve the quality of materials for recycling, providing a scalable and cost-effective solution for cities in both **Nigeria** and **Benin**. This comprehensive system offers a robust solution to urban waste challenges, promising reduced environmental impact, improved public health, and a more sustainable approach to resource management.

1.2 Statement of Problem

Rapidly urbanizing cities in Nigeria, including Benin City, continue to face significant challenges with inefficient and unsustainable waste management. Traditional waste collection at the University of Benin (UNIBEN), particularly on the Ugbowo campus, is plagued by static schedules and a lack of real-time monitoring. This leads to frequent bin overflows, unhygienic conditions, and public health hazards for the university community. These inefficiencies also result in unnecessary collection trips and high operational costs.

A critical limitation is the absence of effective waste segregation at the source. Valuable recyclable materials like metals and plastics are often mixed with general waste, contaminating them and reducing their potential for recycling. This increases the volume of waste sent to landfills and undermines efforts to promote a circular economy. The problem is exacerbated by the fact that existing "smart" waste bin systems, while offering some monitoring, generally lack the advanced automation needed for automated sorting.

Therefore, the core problem is the inadequacy of current waste management systems at the UNIBEN Ugbowo campus to provide a comprehensive solution that integrates automated waste segregation with real-time monitoring and efficient collection processes. This inadequacy perpetuates environmental degradation on campus, leads to economic inefficiencies in waste recovery, and poses persistent public health risks to students and staff.

1.3 Aim of the Study

To design a smart waste monitoring and management system

1.4 Objectives of the Study

1. To collect actual waste and design the system to sort the waste into compartments for metals, and plastics,
2. To develop a prototype of a smart waste bin system that uses sensors to detect fill levels and the presence of specific waste types.
3. To integrate advanced automation into the system, including a self-compacting mechanism, an automatic lid for hygiene, and a mechanism for the automated segregation of metal and plastic waste.
4. To implement a real-time monitoring feature that tracks waste bin usage, including the volumes of segregated waste streams, and sends notifications to relevant authorities when the bin or specific compartments are full.
5. To evaluate the performance and reliability of the smart waste system, specifically by assessing the accuracy and efficiency of the automated segregation process under various environmental and operational conditions.

1.5 Methodology

1. **Literature Review:** A comprehensive review of existing smart waste management and monitoring system systems and IoT technologies will be conducted to inform the project's design.
2. **Feasibility Study:** This phase will assess the technical and economic viability of the proposed system, including component costs and material availability in Nigeria and Benin.
3. **Conceptual Design:** The system's architecture will be designed, including the selection of key components like the microcontroller, sensors (ultrasonic, inductive, optical), and actuators for sorting and compaction.
4. **Material Selection:** Durable and sustainable materials will be chosen for the waste bin's construction
5. **Detailed Design:** This phase will focus on refining the conceptual design by creating specific schematics, wiring diagrams, and a precise plan for the physical layout and dimensions of the prototype.
6. **Fabrication of Proof of Concept:** A prototype will be built, integrating hardware components with software developed in Arduino IDE (embedded C/C++). This includes setting up the sensors, actuators, and communication modules (GSM/GPS).
7. **Testing, Results, and Discussions:** Rigorous testing will be performed to evaluate the system's performance, focusing on the accuracy of waste segregation, compaction efficiency, and sensor reliability. The findings will be analyzed and discussed.
8. **Conclusion and Recommendation:** The study will conclude with a summary of the findings, a conclusion on the system's effectiveness, and recommendations for future improvements.
9. **References:** A comprehensive list of all sources cited will be provided.

1.6 Scope of the Study

This project focuses on designing, developing, and testing a prototype of an innovative smart waste monitoring and management system. It specifically aims to integrate real-time fill-level monitoring with ultrasonic and load sensors, automated waste compaction, and the key innovation: automatically sorting metal and plastic waste using specialized inductive and optical/capacitive sensors. The system is also equipped with a GSM/GPS module that provides real-time data, tracks location, and sends timely notifications to improve collection routes. This study is limited to these features and does not include automated sorting of other materials like glass, paper, or organic waste. While the system is designed for urban settings like those in Nigeria, this phase of the project is restricted to prototype development and lab-based validation of its components; it does not cover large-scale manufacturing, long-term field use, or developing management software for municipalities.

1.7 Significance of the Study

The significance of this study lies in its potential to revolutionize waste management practices in Nigeria. through the integration of intelligent, technology-driven solutions. By addressing the limitations of traditional waste disposal systems, this research introduces a smart waste bin design that is capable of improving efficiency, reducing environmental hazards, and promoting sustainable practices. The benefits of this innovation extend across multiple sectors and communities, fostering positive environmental, economic, and social impacts.

Urban planners and municipal authorities stand to benefit significantly as the real-time monitoring capabilities of the smart waste bin enable timely waste collection and resource optimization. This innovation reduces operational inefficiencies, minimizes the risk of overflow, and enhances the overall cleanliness of urban environments. The automated features also alleviate the manual burden on sanitation workers, improving their working conditions and reducing their exposure to unsanitary waste.

Businesses and commercial establishments, such as shopping malls, restaurants, and office complexes, gain advantages through the adoption of this technology. The smart waste bin's capacity to optimize waste management not only reduces costs associated with manual oversight but also aligns with corporate sustainability goals. By demonstrating environmental responsibility, businesses can improve their public image and attract environmentally conscious customers.

Educational institutions, from schools to universities, can leverage the smart waste bin to promote environmental awareness among students while maintaining cleaner and healthier campuses. Its innovative design serves as a practical teaching tool for incorporating sustainability into the curriculum, fostering a culture of environmental stewardship in younger generations.

On a broader scale, environmental organizations and policymakers can use the outcomes of this study to advocate for widespread adoption of smart waste management and monitoring system systems. The resulting reduction in landfill dependency, lower carbon emissions from more efficient waste collection routes, and decreased littering contribute to global efforts to combat climate change and environmental degradation.

CHAPTER TWO

LITERATURE REVIEW

2.1 Waste Management in Nigeria

waste management is a major environmental and public health issue in Nigeria. Improper disposal practices lead to flooding, pollution, and disease outbreaks. The National Environmental Standards and Regulations Enforcement Agency (NESREA, 2021) states that Nigeria produces over 32 million tons of solid waste each year, but less than one-third of it is collected and managed properly. Edo State, especially Benin City, shows this national problem clearly. The Edo State Waste Management Board (ESWMB) faces issues like poor collection, too few bins, and random dumping (Ogedengbe & Aigbavboa, 2021). These problems emphasize the urgent need for technology-driven solutions that improve efficiency, accountability, and sustainability in waste management.

Fig 2.1 traditional means of waste management

Recent studies in Nigeria have started to explore how smart technologies can tackle these inefficiencies. For instance, Okafor et al. (2021) created a prototype smart waste bin in Lagos that uses ultrasonic sensors and GSM modules to alert collectors when bins are full. While this was a step forward, the system did not include features like fault detection, segregation, or waste compression. Similarly, Adewumi et al. (2020) stated that waste management in Nigerian cities needs automation and real-time monitoring to address delays in collection and the high cost of manual labor. However, these solutions are still theoretical and are not tested on a large scale.

A major limitation in Nigerian and Edo State waste management practices is the lack of waste segregation at source. Studies such as Eze and Akinola (2020) emphasize that plastics and metals make up a significant proportion of solid waste in Nigerian cities, yet they are disposed of together with organic waste, making recycling difficult. In Benin City, Nwachukwu (2020) observed that the absence of segregation and recycling facilities contributes to frequent blockages in drainage systems and missed economic opportunities from recyclable materials. A smart system capable of automatically **separating plastics from metals** would therefore fill an important gap by improving recycling efficiency and reducing the environmental impact of waste.

Another dimension largely absent from local waste management literature is the ability of systems to **detect faults or failures**. Most existing bins in Edo State and Nigeria are static and passive, providing no feedback about their operational condition. If smart bins fail without detection, collection delays and environmental hazards persist. Incorporating self-diagnostic features into a smart system would ensure reliability and timely maintenance, improving overall sustainability.

The issue of **waste compression** has also received limited attention in Nigerian studies. Current practices often assume that bins are full when waste reaches the brim, even when it of loosely packed materials such as plastics. Research shows that integrating waste compression mechanisms into bins can significantly increase storage capacity, reduce collection frequency, and lower operational costs. However, no documented project in Edo State or Nigeria has combined smart monitoring with waste compression in a single system.

From the reviewed works, it is clear that Nigeria, and Edo State in particular, face deep-seated challenges in solid waste management that cannot be solved by conventional approaches alone. While a few Nigerian studies have proposed smart monitoring systems, none have fully integrated features such as **segregation of metals and plastics, real-time fill-level alerts, fault detection, and waste compression**. These represent critical gaps that the design of a Smart waste management and monitoring system and Monitoring System seeks to address. By focusing on Edo State as a case study, this project will not only advance the local literature on waste management but also provide a scalable model that can be adopted in other Nigerian cities.

2.2 Traditional Approaches to Waste Management and Their Limitations

Traditional waste management systems in Nigeria, especially in Edo State, still depend mostly on manual collection, open dumping, and poorly managed landfills. These methods often lead to issues like irregular collection schedules, insufficient infrastructure, and low public awareness about proper disposal practices (Ogedengbe & Aigbavboa, 2021). The problem is made worse by rapid urban growth, limited investment in modern waste management technologies, and weak enforcement of environmental laws, which all contribute to the challenges in cities like Benin (Nwachukwu, 2020).

Such traditional methods have failed to meet the increasing demands of urban waste and environmental sustainability. In Edo State, open dumping is still common, causing blocked drainage systems, soil damage, and serious public health risks, such as waterborne diseases and respiratory issues in nearby communities (Eze & Akinola, 2020)

2.3 Overview of Smart waste management and monitoring system Systems

Smart waste management and monitoring system and monitoring systems represent a technological advancement in addressing the persistent waste challenges in Nigeria, particularly in urban areas such as Edo State. These systems integrate digital technologies such as sensors, the Internet of Things (IoT), and data analytics to improve efficiency in waste monitoring, collection, and disposal. The primary objective is to optimize resource utilization, minimize operational costs, and mitigate the environmental and public health impacts of poor waste disposal practices (Ogedengbe & Aigbavboa, 2021).

At the core of these systems lies the principle of **real-time data collection and automated decision-making**. Sensors embedded in bins continuously monitor fill levels and transmit data via IoT connectivity to a central platform. When bins reach predefined capacity, alerts are automatically generated, reducing overflow and unsanitary conditions. Predictive analytics can also be applied to forecast waste generation patterns, enabling more efficient scheduling of collection services and optimized route planning for waste trucks (Nwachukwu, 2020).

What distinguishes the proposed smart waste management and monitoring system and monitoring system is the integration of **innovative features tailored to the Nigerian context**. These include:

- **Automatic segregation of waste** to separate metals from plastics, improving recycling efficiency.
- **Bin-full notifications** through IoT-based signaling to inform waste collectors in real time.
- **Fault detection capability**, which allows the system to indicate when it is malfunctioning, ensuring reliability and reducing downtime.
- **Waste compression functionality**, designed to compact lightweight waste when bins appear full, thereby maximizing storage capacity and reducing unnecessary collection trips (Eze & Akinola, 2020)
- **Waste segregation** sensors are use to detect if the mixed waste and segregate metals and plastic using sensors such as inductive sensor and metal detector sensor

Compared to traditional waste management systems in Nigeria, which rely on fixed schedules, manual inspections, and open dumping, this approach offers a **proactive and data-driven model**. In Benin City, for example, irregular collection and open dumping have contributed to blocked drainage systems, environmental pollution, and health risks. Smart systems provide an opportunity to address these inefficiencies by reducing overflow, improving collection timeliness, and supporting recycling initiatives (Ogedengbe & Aigbavboa, 2021).

Several successful implementations highlight the transformative potential of smart waste technologies. A pilot study at the **University of Nigeria, Nsukka** demonstrated that IoT-enabled bins reduced overflow incidents by 35% and improved collection efficiency by 25% (Okafor et al., 2021). By applying similar technologies at the **University of Benin**, where increasing student and staff populations intensify waste generation, the proposed system could serve as a model for sustainable campus waste management.

The relevance of these systems in Edo State is further emphasized by the growing pressure of urbanization and inadequate waste infrastructure. Smart waste management and monitoring system and monitoring systems not only provide practical solutions for daily operations but also support

.

2.3.1 Components of a Smart waste management and monitoring system and monitoring system

A smart waste bin system is a modern, technology-driven solution designed to optimize the collection and management of waste by integrating advanced components such as sensors, communication modules, power sources, and data analytics platforms. These systems aim to enhance waste management efficiency, reduce environmental impact, and lower operational costs by enabling real-time waste monitoring, data transmission, and automated notifications for waste collection (Afolalu et al., 2021).

A smart waste bin system consists of several core components, each playing a critical role in ensuring the system's overall efficiency and effectiveness.

1. **Sensors for Waste Level Detection and waste sorting:** The primary component of a smart waste bin is the sensor, typically an ultrasonic sensor, which measures the fill level of the bin and metal detector sensor . These sensors use sound waves to detect the distance between the sensor and the waste material, providing real-time data on the bin's capacity (Uko and Anazodo, 2024). Advanced sensors can also measure parameters such as temperature and humidity, which are essential for monitoring the decomposition of waste and detecting potential hazards such as methane gas emissions (Oluwatimilehin, 2017).
2. **Communication Modules:** Communication modules are responsible for transmitting data from the bin to a central management system. Common communication technologies used include:

   i. **GSM (Global System for Mobile Communications):** Enables cellular data transmission, useful in remote areas.

   ii. **Wi-Fi:** Ideal for urban areas with stable internet connectivity.

   iii. **(Long Range Wide Area Network):** Provides long-range, low-power communication, making it suitable for large cities and rural deployments (Adeyemo et al., 2019).

   iv. These modules ensure real-time data transfer, allowing waste management authorities to monitor multiple bins across a region simultaneously.
3. **Power Sources:** Smart waste bins require reliable power sources for continuous operation. The primary power options include:

i. **Solar Panels:** Sustainable and ideal for outdoor installations in areas with sufficient sunlight.

ii Rechargeable Batteries: Often used as backup power sources for indoor or low-light environments (Afolalu et al., 2021).

Energy efficiency is crucial to ensure uninterrupted data transmission and sensor performance over extended periods.

4. **Embedded Systems for Processing and Control:** Embedded systems act as the control hub of the smart waste bin. A microcontroller or microprocessor, such as Arduino or Raspberry Pi, processes data from the sensors and manages communication with the central platform. This component ensures that data is interpreted correctly and alerts are triggered when necessary (Adeyemo et al., 2019).
5. **Data Analytics and Cloud Integration:** A critical aspect of smart waste management and monitoring system is the integration of data analytics platforms. Cloud-based systems collect data from the bins, enabling real-time monitoring and historical data analysis for predictive maintenance and route optimization (Atayero et al., 2019). Predictive analytics can forecast waste generation patterns, allowing authorities to optimize collection schedules and reduce operational costs.
6. **User Interaction and Mobile Integration:** Some smart waste bin systems feature mobile or web applications that allow users and waste management officials to access real-time bin status, receive notifications, and monitor waste collection efficiency. This feature enhances transparency and encourages public participation in waste reduction efforts (Uko and Anazodo, 2024).

2.4 Current Waste Management in Nigeria

2.4.1 Overview of Waste Management Practices in Nigeria

The waste management system in Nigeria faces significant challenges due to rapid urbanization, poor infrastructure, and weak enforcement of environmental regulations. Nigeria, which is a developing country with a fast-growing population, generates a large amount of solid waste each day. Waste management involves various stakeholders, including federal, state, and local government agencies, private waste collection companies, and informal waste pickers who often work outside the formal system (Abila and Kantola, 2013). The Federal Ministry of Environment and state agencies like the Lagos State Waste Management Authority (LAWMA) are responsible for regulating waste management practices and ensuring compliance with national environmental standards.

Fig 2.41 waste management officials

Waste collection in Nigeria mainly uses traditional methods. This includes manual collection by private contractors and government agencies. Waste is frequently transported in open trucks to designated landfills or dump sites, with limited efforts for waste segregation and recycling. Common disposal practices include open dumping, landfilling, and occasional incineration. However, open dumping is the most common method, especially in urban areas where waste disposal facilities are overwhelmed by the amount of waste generated (Adewole, 2009).

The waste management sector in Nigeria suffers from numerous issues, such as inadequate infrastructure for collection and disposal, insufficient funding, and a lack of public awareness about proper waste disposal. A major concern is the absence of formal waste segregation and recycling facilities, leading to many recyclable materials being thrown away as general waste (Amin et al., 2024). In addition, weak enforcement of waste management policies worsens the situation, allowing illegal dumping and poor disposal practices to continue in many urban areas. The informal waste sector, which includes scavengers and informal recyclers, plays an important role in waste recovery but lacks proper regulation, putting workers at risk and reducing the effectiveness of waste management efforts (Nzeadibe and Ajaero, 2010).

Efforts to improve waste management in Nigeria have been made by both the government and non-governmental organizations (NGOs). For instance, the Nigerian government established the National Environmental Standards and Regulations Enforcement Agency (NESREA) to enhance environmental policy enforcement. State-level agencies such as LAWMA have also introduced reforms in waste collection, including the Cleaner Lagos Initiative, which encourages private sector involvement to increase efficiency (Ogunkan, 2022). However, challenges remain, such as inconsistent policy enforcement and insufficient funding for improving waste infrastructure.

2.4.2 Challenges of Waste Management in Nigeria

The waste management sector in Nigeria faces a complex set of challenges that have persisted over time, hindering the effective collection, transportation, and disposal of waste. A critical issue lies in the country's inadequate infrastructure for waste management. Insufficient and poorly maintained collection vehicles, limited waste treatment facilities, and the absence of proper landfill management systems contribute significantly to the inefficiency of the sector (Okeke et al., 2024). Most urban areas, including major cities like Lagos and Abuja, experience irregular waste collection cycles, leading to the accumulation of waste in residential and public areas, posing serious environmental and public health risks.

Insufficient funding and investment further exacerbate waste management challenges. Government allocation for waste management services is often inadequate, with limited resources directed toward modern waste management technologies such as waste sorting plants, recycling facilities, and energy recovery systems (Abbas and Ali, 2024). The financial constraints also affect the ability of local government agencies to maintain existing infrastructure and ensure consistent waste collection services. Private waste contractors, often engaged under public-private partnerships, face similar challenges due to delayed payments and insufficient financial incentives to innovate or expand services (Amos et al., 2024).

Weak enforcement of environmental regulations and policies significantly contributes to poor waste management practices across Nigeria. Although the country has established environmental frameworks such as the National Environmental Standards and Regulations Enforcement Agency (NESREA), enforcement remains inconsistent. Many residents and businesses fail to comply with waste disposal regulations, leading to widespread illegal dumping and open burning of waste materials, which significantly degrade the environment (Agunwamba, 1998). The lack of stringent penalties for non-compliance further weakens the regulatory framework, allowing poor waste disposal habits to persist.

Public awareness and participation in proper waste disposal practices are limited in many parts of Nigeria. Low public education on the importance of waste reduction, recycling, and proper disposal has resulted in widespread apathy towards environmental conservation efforts. Additionally, the absence of structured waste segregation practices at the household level limits the potential for recycling initiatives (Etim, 2024). Campaigns and sensitization programs, often led by non-governmental organizations (NGOs), have made some progress, but their reach and impact remain insufficient to drive widespread behavioral change (Amos et al., 2024).

Rapid urbanization and population growth have placed additional strain on Nigeria's waste management system. The expansion of urban areas, coupled with a rising population, has led to increased waste generation without a corresponding improvement in waste management infrastructure. Informal settlements and slums, often excluded from formal waste collection services, experience the most severe impacts, with waste accumulating in drainage channels and water bodies, contributing to environmental pollution and public health hazards (Okeke et al., 2024).

The environmental and public health implications of these challenges are profound. Uncollected waste often leads to the blockage of drainage systems, resulting in urban flooding during the rainy season. Accumulated waste in open dumpsites releases toxic leachates into the soil and groundwater, contributing to waterborne diseases such as cholera and typhoid (Agunwamba, 1998). Air pollution resulting from the open burning of waste also exposes communities to respiratory infections and long-term health risks.

Fig. 2.1: Uncollected wastes

The informal waste sector plays a dual role in Nigeria's waste management landscape. Informal waste pickers and scavengers contribute significantly to waste recovery and recycling efforts, often collecting valuable materials such as plastics, metals, and glass for resale. However, this sector operates without formal regulation, leaving workers vulnerable to health risks due to unsafe working conditions and the absence of protective equipment (Abbas and Ali, 2024). Moreover, the lack of coordination between formal waste management agencies and informal waste pickers results in inefficiencies and overlaps in waste collection efforts.

Policy inconsistencies and corruption further complicate waste management in Nigeria. Changes in government administrations often lead to the discontinuation of waste management programs, disrupting progress made in waste reduction and recycling initiatives. Corruption within the waste management contracting process can result in favoritism, inflated contracts, and poor service delivery, ultimately hindering effective waste management outcomes (Amos et al., 2024).

Efforts to improve waste management in Nigeria have included the implementation of state-level reforms and collaborations with international development agencies. For instance, the Lagos State Waste Management Authority (LAWMA) has introduced measures such as public-private partnerships for waste collection and the Cleaner Lagos Initiative to modernize waste disposal services. However, these efforts have faced operational challenges due to policy inconsistencies and weak enforcement mechanisms (Etim, 2024).

2.5 Traditional Waste Management Systems in Nigeria

2.5.1 Methods of Traditional Waste Disposal

Traditional waste disposal methods in Nigeria remain prevalent despite their significant environmental and health impacts. These practices, which include open dumping, landfilling, burning/incineration, and unregulated disposal in waterways, are largely driven by historical, cultural, and economic factors. The reliance on these methods can be attributed to their perceived simplicity, low cost, and limited availability of formal waste management infrastructure (Jibrilla et al., 2024).

i. **Open Dumping** is the most common waste disposal practice in Nigeria, especially in urban and peri-urban areas. Waste is discarded in open spaces, vacant lands, and roadside areas without proper containment or treatment. This practice is largely driven by limited access to formal waste collection services and public ignorance of the long-term environmental impact. Open dumping leads to severe environmental degradation, including soil contamination and the emission of toxic gases such as methane due to organic waste decomposition (Ogunrinola and Adepegba, 2012).

ii. **Landfilling** involves the disposal of waste in designated sites, often without proper engineering controls. Although landfills are intended to manage waste safely, many in Nigeria are poorly designed and lack basic features such as leachate treatment systems and gas capture mechanisms. The absence of proper containment measures results in leachate leakage into surrounding soil and groundwater, posing risks to public health and agricultural productivity (Butu and Mshelia, 2014).

iii. **Burning and Incineration** are also commonly practiced as a means of reducing waste volume, especially in areas with limited waste collection services. While burning can rapidly eliminate solid waste, it generates harmful emissions, including carbon monoxide and dioxins, which contribute to air pollution and respiratory diseases. Uncontrolled incineration further exacerbates air quality issues in urban centers like Lagos and Port Harcourt (Njoku et al., 2021).

iv. **Unregulated Disposal in Waterways** is another widespread practice in Nigeria, often seen in informal settlements with poor waste management infrastructure. Solid waste is discarded into rivers, streams, and drainage channels, leading to blocked waterways and urban flooding during the rainy season. This practice also contaminates water sources, leading to the spread of waterborne diseases such as cholera and typhoid fever (Ichipi, 2023).

The persistence of these traditional methods can be linked to historical and cultural factors. Historically, waste was minimal in rural communities, and biodegradable materials were often returned to the soil. However, with increased urbanization and the influx of non-biodegradable waste such as plastics, traditional methods have become environmentally hazardous. Economically, the low cost of open dumping and burning makes them appealing to communities and municipalities with limited financial resources (Uche, 2024).

The environmental and health consequences of these practices are profound. Open dumping and landfilling lead to land degradation, groundwater pollution, and the emission of greenhouse gases, contributing to climate change. Incineration and burning release toxic pollutants, including particulate matter and heavy metals, which have been linked to respiratory illnesses and cancer risks (Adeniyi et al., 2022). Furthermore, unregulated waste disposal in water bodies not only pollutes water resources but also creates breeding grounds for disease vectors, exacerbating public health risks.

Case studies have highlighted the severity of these issues in Nigeria. For example, a study conducted in Adamawa State revealed that households living near open dumpsites reported increased health expenditures due to illnesses linked to waste exposure, including gastrointestinal infections and respiratory conditions (Jibrilla et al., 2024). Similarly, an assessment of waste disposal practices in Lagos showed that nearly 70% of municipal waste ended up in unregulated dumpsites or waterways, leading to frequent flooding and pollution-related health challenges (Ogunrinola and Adepegba, 2012).

2.5.2 Dangers of Traditional Waste Management

Traditional waste management practices in Nigeria, such as open dumping, burning, and unregulated disposal, present significant environmental, health, and economic dangers. These practices persist due to limited infrastructure, inadequate policy enforcement, and low public awareness. However, they lead to widespread contamination, public health crises, and long-term economic inefficiencies.

i. Environmental Consequences

Open dumping and burning significantly degrade environmental quality in Nigeria. Dumping waste in open sites leads to soil contamination as toxic leachates, often containing heavy metals and harmful chemicals, seep into the ground. This pollution affects agricultural productivity, depletes soil nutrients, and poses risks to food security (Ogunrinola and

Adepegba, 2012). Additionally, the burning of waste releases greenhouse gases, including methane and carbon dioxide, contributing to climate change. In many urban centers such as Lagos and Kano, these pollutants have been linked to reduced air quality, leading to atmospheric pollution and acid rain, further harming the ecosystem (Jibrilla et al., 2024).

ii. **Public Health Risks**

The health impacts of traditional waste disposal are profound. Open dumps often become breeding grounds for vectors such as mosquitoes and rodents, contributing to the spread of diseases such as malaria, cholera, and typhoid fever (Hammed and Sridhar, 2021). Burning waste also releases hazardous toxins, including dioxins and furans, which are linked to respiratory infections, cancer, and neurological damage. A study conducted in Lagos reported increased rates of respiratory illnesses among communities residing near major dumpsites due to prolonged exposure to air pollutants (Salau et al., 2017).

iii. **Economic and Social Implications**

Traditional waste management methods result in considerable economic losses. Unregulated dumping renders large areas of land unusable for residential or commercial purposes, reducing property values and impeding urban development. Furthermore, pollution from waste disposal practices affects agricultural productivity, leading to economic strain on farming communities reliant on healthy soil and clean water (Ojo and Bowen, 2014). Additionally, the financial burden on public health systems increases due to the treatment of waste-related illnesses and disease outbreaks. A comparative study of waste management practices in Lagos and Abuja revealed that inadequate waste disposal contributed significantly to health expenditure increases in both regions (Ichipi, 2023).

2.6 Smart waste management and monitoring system

The use of static routes and fixed schedules for waste collection has proven to be an increasingly inefficient method for addressing contemporary waste management challenges. Modern advancements emphasize the need for adaptive technologies capable of enhancing operational efficiency and sustainability in solid waste management. Saha et al. (2017) argue that smart waste management and monitoring system systems, such as solar-powered smart bins, offer a more innovative approach by incorporating embedded sensors that monitor waste levels. These sensors not only detect the accumulation of waste but also compact it automatically, expanding the bin's capacity to hold up to ten times the volume of a regular waste bin. The compacted waste status is then transmitted to the cloud for real-time monitoring and data analysis, enabling more effective collection planning.

Similarly, Zackarias and Sangeetha (2018) emphasize the importance of Internet of Things (IoT)-based waste management solutions as a response to the growing complexity of municipal waste handling. IoT-enabled systems equip waste bins with the intelligence to detect when they are full and communicate this information directly to a centralized server. The server, in turn, determines the optimal collection routes and provides navigation assistance to waste collection vehicles, optimizing resource allocation and minimizing operational costs. This level of automation and data-driven decision-making offers significant improvements over static scheduling by ensuring waste is collected based on actual needs rather than predetermined intervals.

Further advancing the discourse on technological innovations in waste management, Aazam and Lung (2016) proposed a cloud-based Smart waste management and monitoring system System (CloudSWAM). Their model advocates for separate waste bins for various waste categories, such as plastics, metals, and organic materials, each equipped with embedded sensors that transmit fill-level data to a cloud platform. The cloud infrastructure facilitates real-time data sharing among stakeholders within the waste management ecosystem, ensuring transparency, accountability, and coordinated decision-making across the entire waste management cycle. Such integrated data systems allow for better resource allocation, timely intervention, and enhanced recycling processes.

Stakeholder involvement has become a focal point in the design and implementation of waste management strategies, particularly in developing regions where the complexity of solid waste systems often necessitates collaborative decision-making. Lohri et al. (2013) argue that the active participation of stakeholders and experts in prioritizing specific aspects of service delivery is crucial to achieving long-term sustainability goals. The siting of waste disposal or treatment plants, for instance, remains a highly complex decision-making process requiring the collaboration of political leaders, technical experts, and local communities (De Feo and De Gisi, 2010). Analytical tools such as the Analytical Hierarchy Process (AHP) (De Feo and De Gisi, 2010; Bao et al., 2012) have been employed to balance the technical and non-technical priorities of diverse stakeholder groups. Additionally, Geographic Information System (GIS) technologies have proven valuable for spatial data analysis in siting decisions, ensuring objectivity and transparency (Moeinaddini et al., 2010; Tavares et al., 2011).

Moreover, the sustainability aspect of smart waste bins extends beyond operational efficiency to the choice of materials used in their construction. A growing body of research emphasizes the need for eco-friendly and durable materials in smart waste bin designs to minimize environmental impact and ensure long-term usability (Abba and Light, 2020). Many current implementations, however, fail to explore sustainable material alternatives, relying instead on conventional plastic-based materials that contribute to long-term waste challenges. Additionally, there is limited exploration of how these bins perform under varying environmental conditions such as extreme heat, humidity, or heavy rainfall, which can affect sensor performance and data accuracy. Despite the progress made in smart waste management and monitoring system technologies, significant research gaps remain. While numerous studies have successfully demonstrated the feasibility of using ultrasonic sensors, GSM modules, and Wi-Fi-based communication systems for waste level monitoring, there is still a need for comprehensive solutions that incorporate automation, sustainability, and adaptability across diverse operational environments. Furthermore, many studies have been conducted in controlled experimental settings rather than real-world environments, limiting the generalizability of the findings (Ali et al., 2020). Future research should focus on integrating advanced automation features, testing the systems under diverse climatic conditions, and emphasizing the use of sustainable materials to ensure long-term viability.

2.7 Benefits of a Smart waste management and monitoring system System

A smart waste management and monitoring system system is a modern approach to waste handling that leverages advanced technologies such as Internet of Things (IoT) devices, sensors, and data analytics to improve waste collection, disposal, and monitoring processes. These systems integrate real-time monitoring through sensors placed in waste bins, providing data on waste levels and transmitting it to a centralized platform for efficient decision-making. Such innovations aim to optimize waste collection schedules, minimize fuel consumption, and reduce operational costs through better route planning and resource allocation (Olawade et al., 2024).

One of the primary advantages of smart waste management and monitoring system systems is the enhancement of operational efficiency. Traditional waste management methods often involve fixed collection schedules regardless of actual waste levels, leading to inefficient use of resources. Smart systems, however, provide real-time data on bin fill levels, enabling dynamic scheduling and optimized collection routes. This results in reduced fuel consumption and lower maintenance costs for waste collection vehicles, as demonstrated in a study on smart city waste management in Abuja, Nigeria (Ita, 2024).

Environmental benefits are also significant. Smart waste bins promote better waste segregation and recycling by monitoring waste composition and alerting authorities when recycling bins are full. This reduces the volume of waste sent to landfills, thereby decreasing soil contamination and methane emissions. Additionally, real-time monitoring helps prevent waste overflow, which often leads to the spread of pollutants in water bodies and public spaces (Olawade et al., 2024). By promoting waste reduction and recycling, smart systems align with global sustainability goals and help curb climate change.

Socially and economically, the adoption of smart waste management and monitoring system systems can create substantial positive impacts. The integration of technology into waste management creates job opportunities, particularly in technology-driven roles such as data analysis, system maintenance, and smart bin manufacturing. Moreover, improved waste collection efficiency leads to cleaner urban spaces, enhancing public health by reducing exposure to hazardous waste and disease vectors like rodents and mosquitoes (Ezeudu et al., 2024). Public awareness campaigns and mobile applications linked to smart waste systems also encourage citizens to participate actively in proper waste disposal and recycling practices.

Data-driven decision-making plays a crucial role in fostering sustainable waste management. With continuous data collection from smart bins, waste authorities can identify patterns in waste generation, enabling long-term planning for resource allocation and infrastructure development. This approach can be particularly effective in developing countries like Nigeria, where waste management infrastructure is often limited and poorly managed (Abel et al., 2024).

Case studies have demonstrated the effectiveness of smart waste systems globally and in Nigeria. In Lagos, the implementation of a smart waste monitoring system reduced waste overflow incidents by 30% and improved the efficiency of waste collection by 25% within the first year of deployment (Ezeudu et al., 2024). Similarly, the Federal Capital Territory (FCT) in Abuja has piloted sensor-based waste bins, leading to improved compliance with waste disposal guidelines and reduced operational costs for waste contractors (Ita, 2024).

2.8 Gaps in Existing Research

Table 2.1: Gaps in Existing Research

Author(s)	Year	Title of Work	Methodology	Results	Research Gaps
Soliman, Akkad, and Alloush	2020	Smart bin monitoring system for smart waste management and monitoring system	Ultrasonic sensors, moisture sensors, microcontroller, and Wi-Fi module for real-time monitoring.	Significant reduction in waste overflow and optimized collection routes.	Did not explore automation features such as self-compacting mechanisms or lid automation.
Xenya, D'souza, Woelorm, Adjei-Laryea, and Baah-Nyarkoh	2020	IoT-based smart waste bin management system	Ultrasonic sensors, GSM modules, mobile application for optimized waste collection.	Reduced waste overflow and enhanced collection schedules with occasional network delays.	Did not evaluate performance under varying environmental conditions and lacked self-compaction.
Ramson, Moni, Vishnu, Anagnostopoulos, & Kirubaraj	2020	IoT-based bin level monitoring system	Ultrasonic sensors, Wi-Fi module, and battery-operated sensors for data collection.	Effective monitoring with long battery life and a cost-effective setup.	Did not integrate self-compacting features or sustainability-focused materials for the bin design.
Pardini, Rodrigues, Hassan, Kumar, & Furtado	2018	Smart Waste Bin: A New Approach for Waste Management	Ultrasonic sensors, load sensors, GPS modules, and GSM connectivity for route optimization.	Reduced fuel consumption and improved waste collection efficiency.	Did not incorporate automation in waste management or material sustainability considerations.
Michael, Otaru,	2017	Design and	Voice recognition	Automated lid	Did not address

Liman, Bomoi, & Awotoye		Development of a Smart Waste Bin	module, PIR sensor, ultrasonic sensor, and Arduino-based automation.	operation with reduced physical contact for hygiene purposes.	real-time monitoring for waste levels or sustainability in material choices.
Afolalu, Noiki, Ikumapayi, Ogundipe, & Oloyede	2021	Development of Smart Waste Bin for Solid Waste Management	Ultrasonic sensors, MQ-2 gas sensor, servo motor, and GSM modem for real-time waste level alerts.	Reduced overflow and collection frequency with effective alert systems.	Lack of automation in waste compression and limited data on performance under different climates.
Abba & Light	2020	IoT-based framework for smart waste monitoring and control system	Ultrasonic sensors, GSM modules, and Arduino microcontroller with web-based graphical display.	20% reduction in collection frequency and operational costs.	Did not explore self-compacting features or environmental sustainability in bin materials.
Ali, Irfan, Alwadie, & Glowacz	2020	IoT-Based Smart Waste Bin Monitoring for Municipal Solid Waste	Ultrasonic sensors, GPS modules, and GSM connectivity for waste monitoring and route optimization.	Improved efficiency in waste collection and fuel consumption reduction.	Limited focus on automated lid operation and sustainable material choice for bin construction.
Mamun et al.	2013	Three-Segment Waste Management System	Ultrasonic sensors, load sensors, ZigBee, GSM, and cloud-based storage for waste data.	Efficient monitoring and optimized collection routes.	No focus on automation or sustainability in bin construction.

CHAPTER THREE

MATERIALS AND METHOD

3.1 SYSTEM OVERVIEW

The Smart Waste Segregation and Monitoring System is a mechatronic solution that aims to improve source separation in urban waste management. This prototype goes beyond basic monitoring by combining an automated sorting line with real-time data communication. It uses an Arduino microcontroller to process and gather information from several key sensors: an Ultrasonic Sensor (HC-SR04) at the input section, a Metal Detector, Inductive Sensor for identifying materials, and 50Kg Load Cells (with HX711 modules) for measuring the final bin weight.

The main operation starts when mixed recyclable waste, such as metals and plastics, is placed into the trash input section. The initial ultrasonic sensor measures the items to ensure they are released one at a time onto a conveyor belt. As each item moves along the belt, it passes the Inductive Sensor, which checks its material. Based on this signal, the microcontroller activates a high-torque Servo Motor that rotates a mechanical ramp, directing the item into one of two dedicated bins. At the same time, the system tracks the fill level of these bins using additional ultrasonic sensors and load cells. When a bin reaches its weight or volume limit, the GPS Module records the unit's exact location, and the system's communication module sends a real-time alert to waste management authorities.

To improve user feedback and local monitoring, the system includes a 7-inch LCD Screen that displays real-time status updates. The entire sorting and monitoring setup is housed in a strong, modular frame, as shown in Figure 3.1. This design offers stable support for the conveyor and sensor arrays while allowing easy access to the internal bins. This integrated system provides a scalable, automated solution for urban resource recovery, going beyond simple monitoring to actively promote recycling.

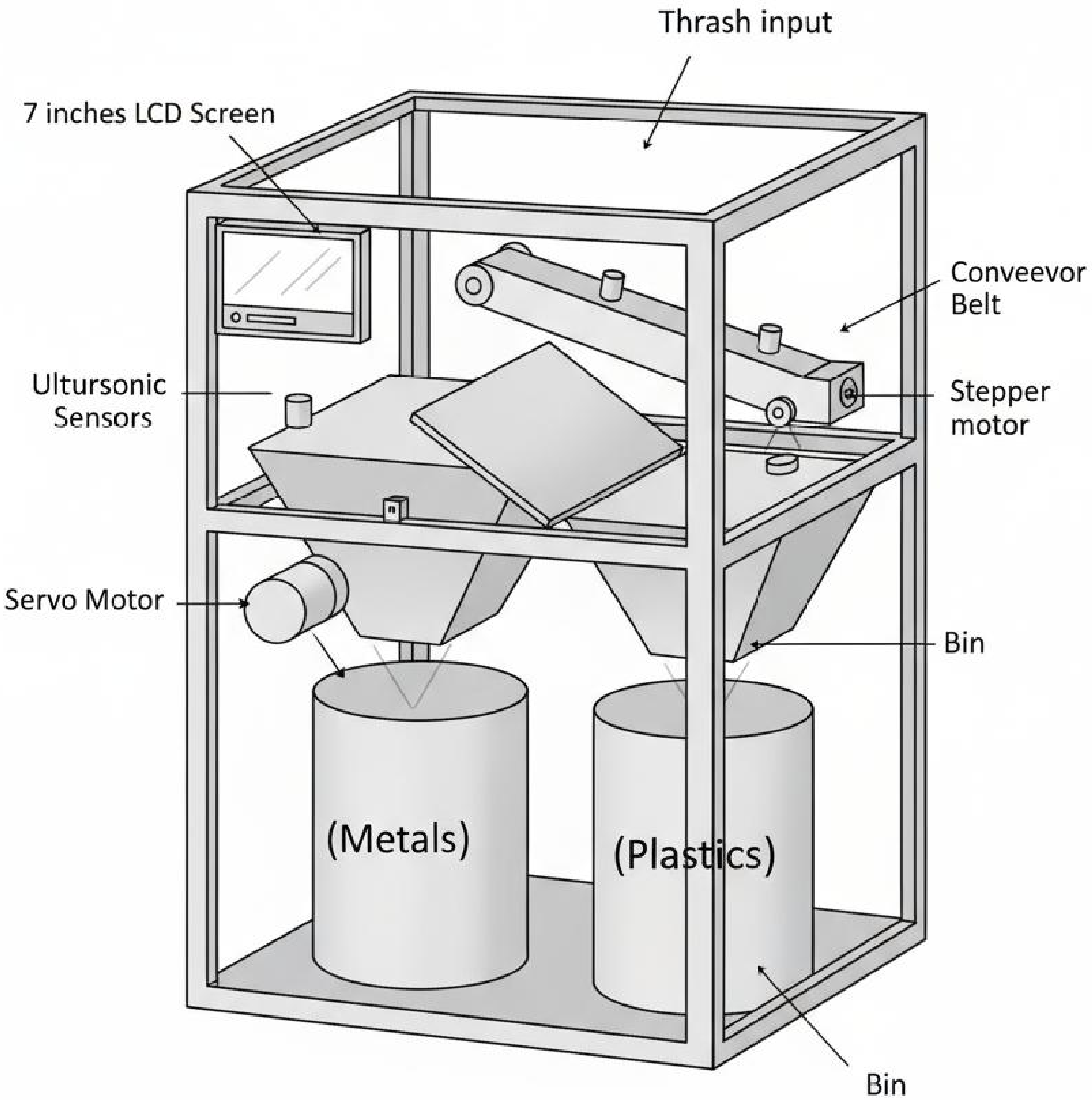

Fig. 3.1: Diagramatic Representation of the Final Sorting System Assembly

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3.2 DESIGN CONSIDERATIONS

The design of the Smart Waste Segregation and Monitoring System was guided by several key engineering considerations to ensure the primary objective of automated sorting was achieved with accuracy, reliability, and efficiency. The system's design evolved from simple monitoring to a complex mechatronic assembly, necessitating specific component choices to manage the new mechanical and sensing challenges.

A key consideration was the effectiveness of the sorting mechanism. Unlike a simple collection bin, this system needed a controlled method for identifying materials. This led to the design of a conveyor belt system and an initial section for measuring waste. By programming the input hopper's ultrasonic sensor to release items one at a time, the system makes sure each piece of waste is separated for scanning. This prevents the sensor from getting confused and reduces false readings caused by clustered items. This step-by-step process is essential for the system's reliability.

Choosing and integrating sensors was also important. A Metal Detection Inductive Sensor was picked for material identification because it doesn't require contact, is reliable, and works well in a controlled setting. To monitor the final segregated bins, a backup sensing system was set up. Four 50Kg Load Cells paired with two HX711 modules provide stable, averaged weight measurements, which help solve the issue of uneven waste distribution. Additionally, Ultrasonic Sensors at the top of each bin give volumetric data, creating a double-check system before a "bin full" alert goes off.

The mechanical design needed careful selection of actuators. A high-torque Servo Motor was chosen for the diverter ramp because it delivers fast, accurate, and repeatable movement. This speed is crucial to force detected waste into the right bin and to return to its neutral position before the next item reaches the conveyor. This helps maintain the system's processing rate.

Power management was another important factor because of the combined load from the conveyor belt motor, servo motor, sensors, and communication modules. A high-capacity Lithium-Ion Polymer Battery with a built-in 3S Battery Management System (BMS) was chosen. This setup provides the stable, high-current draw necessary to handle the motors' peak needs without causing voltage drops that could reset the Arduino microcontroller or disrupt sensor readings.

Finally, user interaction and data communication were considered. A large 7-inch LCD Screen was added for better on-site user feedback and possible diagnostics, which is a significant step up from standard 16x2 displays. The GPS Module and a related GSM module are integrated to offer real-time location and status alerts, which are crucial for a smooth, effective waste collection operation.

3.3 SYSTEM ARCHITECTURE

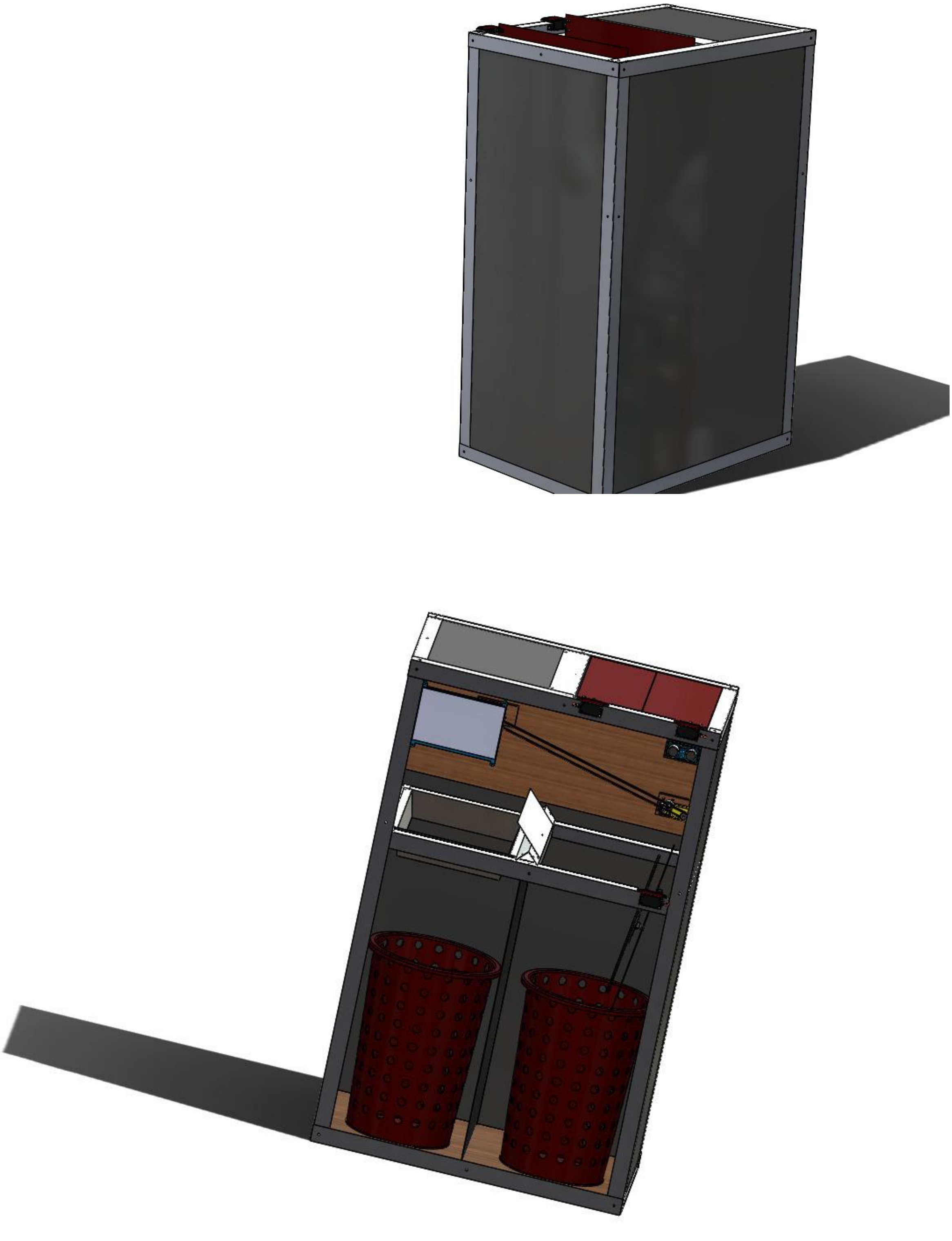


Fig. 3.2: Overall System Build

Fig. 3.3 Circuit diagram representation of the system

The system architecture of the Monitoring and Control of a Smart Waste Bin consists of a power management module (24W lithium battery with a DC-DC converter), a sensing module (ultrasonic sensor for waste level detection and load cell with HX711 amplifier for weight measurement), a control and processing unit (Arduino microcontroller for sensor data processing, actuator control, and system decision-making), a waste compression module (linear actuator operating a radial disc for compaction when triggered at a 20 cm threshold), a communication module (GSM module for SMS alerts and GPS module for real-time location tracking), a structural framework (HDF wooden board reinforced with aluminum bracing, featuring a tracked opening for a removable waste basket to ensure only the waste is compressed), and a display and alert system (LCD screen for real-time waste level updates and a 12V buzzer for full-bin notifications), all working together to enable automated waste monitoring, compaction, and remote notifications, ensuring efficiency, optimized collection scheduling, and sustainability.

3.4 HARDWARE COMPONENTS

3.4.1 ESP32

Fig. 3.4: Arduino Board

3.4.2 Ultrasonic Sensor (US1 - HC-SR04)

3.4.2 Ultrasonic Sensor (US1 - HC-SR04)

The HC-SR04 ultrasonic sensor measures the waste fill level inside the bin. It functions based on the trigger-echo principle, where the sensor emits ultrasonic pulses that bounce back from the surface of the waste. The Arduino processes the time delay between the signal transmission and reception to determine the distance from the waste to the lid. When the waste level is detected to be 20 cm away from the top, the microcontroller activates the linear actuator to initiate compression. The sensor is essential for optimizing space within the bin before sending a waste collection notification.

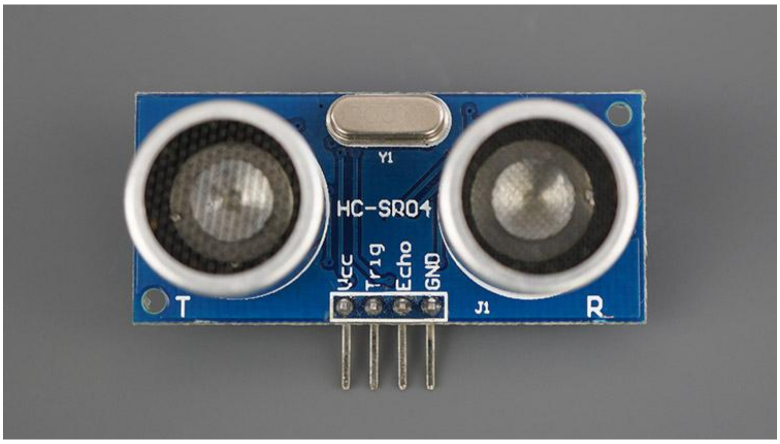


Fig. 3.5: Ultrasonic Sensor

3.4.3 Load Cell Sensor (50kg) with HX711 Module

The load cell sensor is placed at the bottom of the bin to measure the total weight of the compressed waste. It operates with the HX711 load cell amplifier, which turns the weak analog signals from the load cell into digital signals that the microcontroller can read. The system continuously monitors the total weight of waste inside the bin. When the load cell detects a weight of 50kg, it activates the GSM module (SIM900D) to send an SMS alert to the appropriate authorities, indicating that the bin is full and needs to be emptied. This helps ensure that waste bins are cleared on time without unnecessary trips, improving collection schedules. A

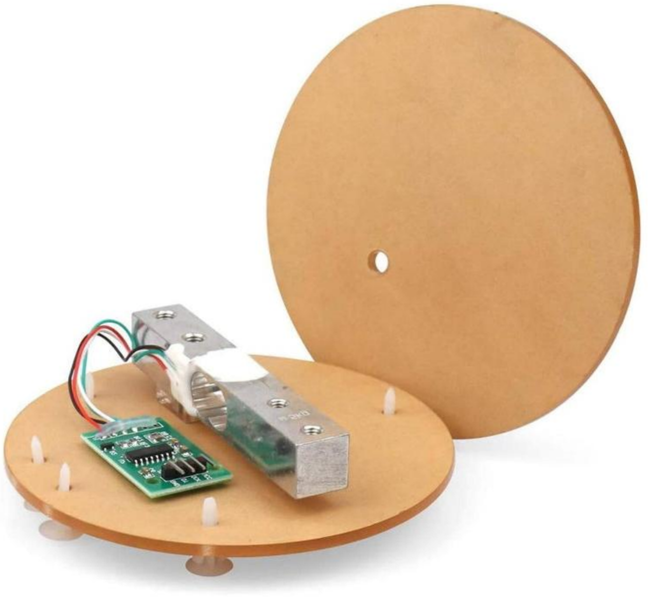


Fig. 3.6: Load Cell Sensor (50kg) with HX711 Module

3.4.4 GSM Module (SIM900D)

The SIM900D GSM module is tasked with sending SMS alerts to waste management agencies when a bin reaches capacity. It is connected to a microcontroller, which issues a command to the module once the load cell sensor detects a weight of 20kg. Following this, the GSM module sends an automatic SMS notification that includes information such as the bin's identification number and its current fill level. This process eliminates the need for personnel to check bins manually and enhances collection efficiency by ensuring that authorities are promptly informed when bins need to be

emptied.

Fig 3.7: GSM Module (SIM900D)

3.4.6 GPS Module (Neo-6M)

The GPS module allows for live monitoring of the waste bin's position. When the bin reaches its capacity, it sends a text message notification with its longitude and latitude coordinates. This functionality assists waste collection teams in swiftly locating the bin, minimizing delays and enhancing efficiency. The Neo-6M GPS module consistently tracks the bin's location, proving beneficial for mobile waste bins in public spaces.

Fig 3.8: GSM Module (SIM900D)

3.4.7 LCD Display

The LCD display provides real-time feedback to users and waste collection personnel. It is programmed to show:

- Current fill level (measured by the ultrasonic sensor)
- Bin weight (measured by the load cell)
- Notification alerts (when the bin is full) This display allows local monitoring of the bin’s status and enhances user interaction with the system.

Fig 3.9: LCD Display (LM1602)

3.4.8 Buzzer (12V)

3.4.9 DC-DC Converter

The DC-DC converter ensures the appropriate voltage supply for all components in the system. It regulates power distribution from the 24W lithium battery, ensuring consistent operation of sensors, the microcontroller, and communication modules. This stabilization prevents electrical fluctuations that could disrupt the system's operation.

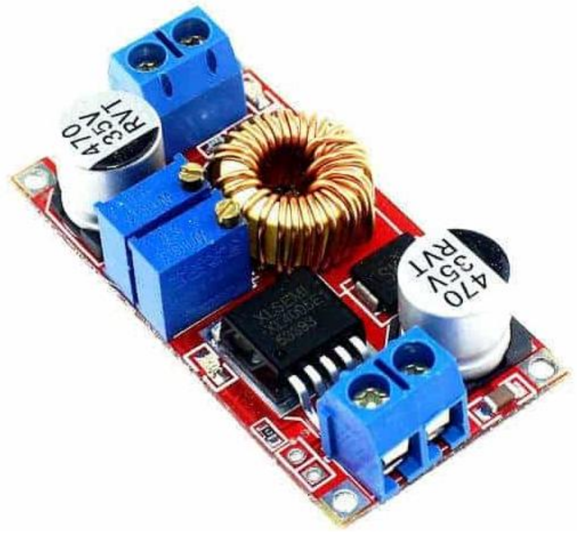


Fig 3.11: DC-DC Converter

3.4.10 Rechargeable Lithium Battery (24W)

The 24W lithium battery is the primary power source for the entire system. It ensures that the smart waste bin remains operational even in the absence of a direct power supply. The battery powers:

i. The microcontroller
ii. The sensors (ultrasonic, load cell, metal detector)
iii. The GSM and GPS modules
iv. The LCD display and buzzer It is designed for long-term use, ensuring the system functions efficiently with minimal maintenance.

3.5 SOFTWARE IMPLEMENTATION

3.5.1 Arduino IDE (Integrated Development Environment)

The Arduino IDE is the primary platform used for writing, compiling, and uploading code to the Arduino microcontroller. It allows developers to write firmware in C/C++ programming language to control the sensors, actuators, communication modules, and display units. The software provides built-in libraries that simplify hardware interfacing, such as:

i. HX711 library for reading data from the load cell sensor.
ii. NewPing library for interfacing with the ultrasonic sensor.
iii. SoftwareSerial library for handling GSM and GPS communication.
iv. LiquidCrystal library for managing the LCD display.

The Arduino IDE serial monitor is also used for debugging by displaying real-time sensor readings, enabling developers to verify system functionality. This ensures that waste fill level detection, weight measurement, GSM alerts, and GPS tracking are all functioning correctly.

3.5.2 Embedded C / C++ (Microcontroller Firmware)

Embedded C/C++ programming is used to develop the firmware that runs on the Arduino microcontroller. This software dictates how the system components interact by implementing logic for:

i. Sensor Data Processing: Reads and interprets signals from the ultrasonic sensor and load cell.
ii. Actuator Control: Triggers the linear actuator when the waste reaches 20 cm from the bin cap.
iii. Decision-Making Algorithms: Determines when to send SMS alerts and activate the buzzer based on waste levels.
iv. Data Communication: Sends formatted messages to GSM and GPS modules for real-time updates.

The program is designed for low-power consumption, enabling the system to operate efficiently on a battery-powered supply.

3.5.3 GSM AT Commands

GSM AT (Attention) Commands are used for sending SMS notifications through the SIM900D GSM module. These text-based commands allow the microcontroller to interact with the cellular network to send real-time waste bin alerts. Some of the key AT commands used in the system include:
AT+CMGF=1 → Sets the SMS mode to text.
AT+CMGS="+234XXXXXXXXXX" → Sends a message to a predefined phone number.
AT+CENG? → Retrieves network signal strength to ensure message transmission.

These commands enable the system to automatically alert waste management authorities when the bin is full, ensuring timely collection.

3.5.4 GPS Data Parsing Code

The GPS module (Neo-6M) provides raw location data, which must be processed before it can be sent via SMS. The Tiny GPS++ library in Arduino IDE is used to extract longitude and latitude coordinates from the NMEA sentences received from the GPS module. The software filters and formats the GPS data to send precise location tracking details in real-time.

For example, the code extracts:

i. Longitude: 7.4321°
ii. Latitude: 9.8765° And formats it into an SMS message for easy interpretation by waste management authorities.

3.5.5 LCD Display (Liquid Crystal Display)

The Liquid Crystal Display is used to control the LM1602 LCD display, which provides real-time system feedback. The display is programmed to show:

i. Current bin status (e.g., “Bin 50% Full”).
ii. Weight of the waste measured by the load cell.
iii. GPS coordinates for bin location tracking.
iv. System alerts (e.g., “Full – Collection Required”).

This software ensures that users near the bin can visually monitor its status.

3.5.6 Serial Communication and Debugging Tools

The Arduino Serial Monitor and external debugging tools like PuTTY are used to:

i. View real-time sensor values.
ii. Check GSM & GPS response messages.
iii. Test actuator triggers & system logic.

By running tests in the Serial Monitor, developers can verify whether:

i. The ultrasonic sensor correctly detects fill levels.
ii. The load cell sensor accurately measures weight.
iii. The GSM module successfully sends SMS alerts.
iv. This ensures proper system calibration before deployment.

3.5.7 Web-Based or Mobile Application (Optional)

For IoT-based integration, Blynk or a custom web application can be used to provide:

i. Live bin monitoring via a dashboard.
ii. Remote alert management.
iii. Waste collection history tracking.

This feature is useful for municipal solid waste departments seeking automated fleet optimization.

3.6 CONSTRUCTION

This chapter focuses on the construction and testing of the Smart Waste Bin system. It outlines the materials and tools used in assembling the system, along with the step-by-step procedure for integrating key components such as sensors, actuators, and communication modules. The chapter also presents the functional testing of the system, including verification of sensor accuracy, actuator performance, and notification delivery. The results demonstrate the system's reliability and effectiveness, confirming its potential for real-world application in efficient waste management.

3.6.1 Construction Procedure

The **construction section** of this chapter details the process of building the Smart Waste Bin system. It covers the selection and acquisition of essential materials, including both electrical components and structural elements. The section highlights the use of various tools for assembling the system, from cutting and shaping materials to wiring and securing components. It also discusses the step-by-step procedure followed to ensure the proper integration of sensors, actuators, and communication modules, ensuring the system operates as intended. This section provides an in-depth look at how the system's physical structure and components were assembled to create a fully functional Smart Waste Bin.

Fig, 3.12: Woodwork covering

Fig. 3.13: Frame
Setup

Fig. 3.14: Mounting up the Actuator on the Frame for Compaction

Fig. 3.15: Linear Actuator for Compaction

I. Acquisition of Materials

In the construction of the Smart Waste Bin, several materials were carefully selected to ensure both functionality and durability. These materials, which include electrical components, structural elements, and decorative hardware, work together to create an efficient and aesthetically pleasing product.

Electrical Switch Box

The electrical junction box used in the construction is a standard plastic electrical switch box. This box is designed to house various electrical connections, such as switches, circuit breakers, or wiring components. The use of this box ensures that the electrical components of the Smart Waste Bin are safely contained and organized, reducing the risk of electrical hazards and ensuring smooth operation. These boxes are commonly used in residential and commercial electrical systems due to their ease of installation and durability.

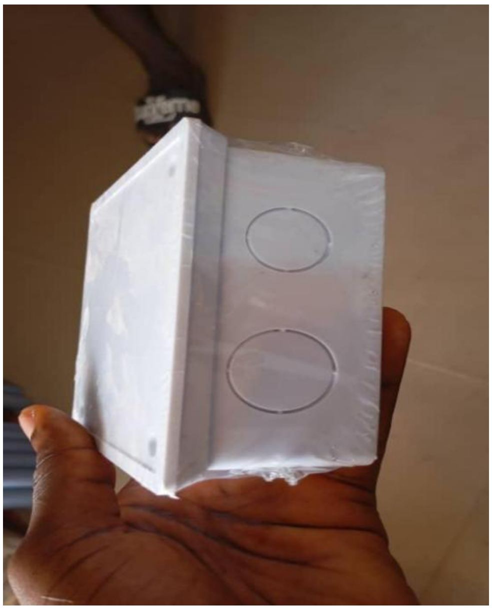


Fig. 3.16: Electric Box

Wood Panels

The wood panels are used to form the structural body of the Smart Waste Bin. These panels serve as the core construction material, providing both strength and stability to the unit. The panels come in various finishes, including a marble-like texture and natural wood finish, allowing for a combination of durability and visual appeal. These panels are used for the bin's exterior, offering a modern and stylish appearance while maintaining the necessary structural integrity to support the internal components of the system. The use of these materials contributes to the product's aesthetic and functional design.

Fig. 3.17: Wood Panels

Hinges

The metal hinges featured in the images are critical for the movement of doors or lids in the Smart Waste Bin. These hinges allow for smooth opening and closing of the bin’s compartments, which is essential for user convenience. Made from strong metal, these hinges are built to withstand regular use and provide a sturdy mechanism for the movement of the bin's doors. Their robustness ensures that the bin's structure will remain intact over time, even under heavy usage conditions.

Fig. 3.18: Hinges

The metal handles pictured are used in the construction of drawers or cabinet doors within the Smart Waste Bin. These handles are not only functional, providing an easy means of opening and closing the compartments, but they also add a decorative element to the design. Made from durable metal, these handles are resistant to wear and tear, ensuring a long-lasting and stylish appearance for the Smart Waste Bin. Their aesthetic design contributes to the overall appeal of the product, making it suitable for both residential and commercial settings.

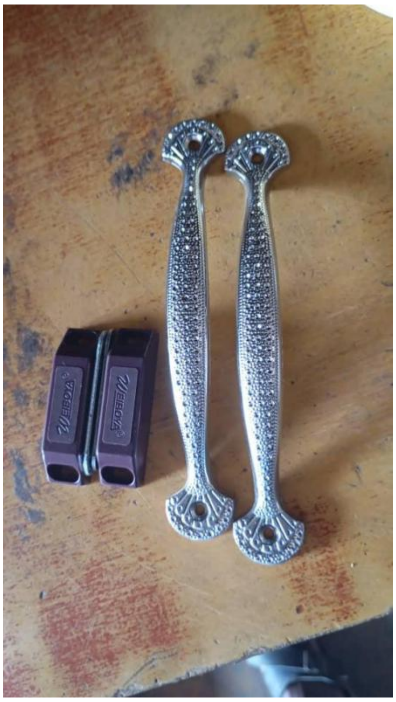


Fig. 3.19: Handle

II. Tools Used

This section outlines the tools used during the construction of the Smart Waste Bin. Each tool played a crucial role in shaping, assembling, and wiring the various components, ensuring the bin's functionality, durability, and overall design. These tools, ranging from cutting and shaping devices to those used for assembling and securing parts, were essential for successfully completing the project

1. **Grinding Machine**: Used for smoothing rough edges, polishing surfaces, and shaping metal parts for precise fitting in the construction.
2. **Electric Jigsaw**: Utilized for cutting through materials like wood and plastic, allowing for intricate and curved cuts needed for the Smart Waste Bin's parts.
3. **Electric Hand Drills**: Used for drilling holes into wood, metal, or plastic to allow for fastening components together, such as sensors or actuators.
4. **Hammer**: Essential for driving nails or tapping parts into place, especially for assembling the bin's frame or attaching hardware.
5. **Screwdriver**: Used for driving screws into various parts of the structure, securing components like handles, hinges, and panels.
6. **Hot Glue Gun**: Used for bonding smaller components quickly, such as securing wires, components, or securing parts of the bin's assembly where screws or nails are not suitable.
7. **Chisels**: Used for fine-tuning and carving or shaping wood or other materials, helping to adjust fitment for parts like the lid or internal structure.
8. **Soldering Iron**: Essential for creating electrical connections, particularly for the microcontroller and other electronic components in the system.
9. **Cutter**: Used for cutting wires, plastic, or other small materials to the appropriate length, especially for wiring and finishing touches.
10. **Pliers**: Used for bending, holding, or manipulating small parts, including wires or metal components, ensuring they fit precisely during assembly.

Fig. 3.20 : Tools Used for the Work

III. Step by Step Procedure

1. **Planning and Design**: Define the system's components and functionality, such as sensors, actuators, and communication modules, ensuring automation, monitoring, and ease of waste management.
2. **Selection of Components**: Choose necessary components like the Arduino microcontroller, ultrasonic sensor (HC-SR04), load cell sensor (HX711), linear actuator, GSM module (SIM900D), GPS module (Neo-6M), LCD display (LM1602), buzzer, and DC-DC converter.
3. **System Architecture**: Plan and design the structure, ensuring all components (electrical and mechanical) are well-integrated for optimal operation.
4. **Assembly of Structural Components**: Assemble the frame using materials like HDF wood and aluminum bracing to ensure stability and durability during waste compaction.
5. **Installation of Sensors and Actuators**: Attach the ultrasonic sensor for detecting waste fill levels, the load cell sensor for weight measurement, and the linear actuator for compressing waste.
6. **Wiring and Electronics Setup**: Wire the components to the Arduino microcontroller, integrating the GSM module, GPS module, and LCD display to ensure proper communication and data collection.
7. **Software Development**: Program the Arduino microcontroller using C/C++ to handle sensor data, control actuators, and communicate with the GSM module for sending alerts. Include functions for real-time monitoring on the LCD display.
8. **Testing Individual Components**: Test each component (sensors, actuators, communication modules) to ensure correct functionality. This includes checking sensor accuracy, actuator response, and message delivery from the GSM module.

9. **Power Supply Setup**: Set up the 24W lithium battery and DC-DC converter to power the entire system. Ensure stable power distribution to all components.
10. **Final Assembly**: Mount all components securely onto the frame, including wiring and attaching the battery, ensuring no interference with the bin’s mechanical operation.
11. **System Integration**: Integrate all parts into a fully operational system, ensuring the sensors, actuators, and communication modules work together seamlessly for automated waste management.
12. System Testing and Calibration: Perform full system tests, including waste detection, compaction, communication alerts, and location tracking, to verify that the bin functions as intended.
13. Troubleshooting and Adjustments: Make any necessary adjustments based on test results to improve sensor accuracy, actuator performance, and communication reliability.
14. Deployment: Deploy the system in real-world conditions, monitoring its performance and making further adjustments if needed for optimization.
15. Ongoing Maintenance and Evaluation: Regularly maintain and evaluate the system to ensure its longevity and operational efficiency, addressing issues like sensor calibration, battery life, and software updates.

CHAPTER FOUR

4.0. TESTING, RESULT AND DISCUSSION

4.1 TESTING

To ensure the Monitoring and Control of a Smart Waste Bin system functions optimally, reliably, and efficiently, a thorough testing and evaluation process is necessary. This involves three major aspects: hardware testing, software testing, and performance evaluation. Each phase is crucial in verifying the accuracy of sensor readings, efficiency of automation mechanisms, and effectiveness of communication modules in real-world waste management scenarios.

I. Hardware Testing

The hardware testing phase is focused on verifying the proper functionality of each physical component, ensuring that all sensors, actuators, power systems, and communication modules work as expected. The ultrasonic sensor (HC-SR04) will be tested by placing objects at varying distances to confirm accurate detection of waste levels inside the bin. The load cell sensor (20kg with HX711 amplifier) will undergo calibration using standardized weights to verify its ability to detect the correct waste mass. The linear actuator responsible for waste compression will be tested for force application, travel distance, and reset accuracy after each cycle.

The GSM module (SIM900D) will be tested by sending SMS notifications under different network conditions to ensure message reliability and timely delivery. The GPS module (Neo-6M GPS) will be evaluated for location tracking accuracy by checking whether the reported coordinates match the bin’s actual position in different outdoor environments. The LCD screen (LM1602) and buzzer (12V) will be tested by feeding different system status signals to confirm they correctly display bin fill levels and produce audible alerts when triggered. Power efficiency tests will also be conducted to monitor the battery's runtime under continuous operation, and the DC-DC converter will be checked to ensure stable voltage regulation across all components.

Hardware Testing Table

Component	Test Description	Expected Outcome
Ultrasonic Sensor (HC-SR04)	Place objects at varying distances to simulate waste levels.	Accurate distance measurement and reliable detection of waste fill levels.
Load Cell (20kg + HX711)	Calibrate using known weights.	Correct weight readings matching calibrated values.
Linear Actuator	Test force application, travel distance, and reset position.	Actuator compacts waste efficiently and resets to original position after each cycle.
GSM Module (SIM900D)	Send SMS under different network conditions.	Reliable message delivery with minimal delay.
GPS Module (Neo-6M)	Cross-check reported coordinates in outdoor environments.	Accurate location tracking that matches actual bin position.
LCD Screen (LM1602)	Display different system	Correct display of bin fill

	statuses.	levels and system messages.
Buzzer (12V)	Trigger alerts using input signals.	Audible alerts when thresholds are reached.
Battery & Power System	Monitor runtime and check voltage regulation.	Long runtime and stable voltage supply across all components.
DC-DC Converter	Test voltage output under load.	Consistent voltage regulation with no component fluctuation.

II. Software Testing

The software testing phase focuses on verifying the logic, responsiveness, and error handling of the system's firmware programmed into the Arduino microcontroller. This will involve running test cases to confirm whether the sensor readings, actuator responses, and communication modules interact correctly based on pre-programmed conditions.

The ultrasonic sensor code will be tested by simulating different waste fill levels and checking if the system correctly triggers the compactor at the 20 cm height threshold. The load cell software will be tested by gradually adding weight to ensure that once the bin reaches 20kg, the GSM module activates an SMS alert. The actuator control logic will be evaluated by simulating different fill levels and ensuring that compaction occurs only when necessary, with proper return to its original position.

The GSM AT command implementation will be tested by verifying that SMS messages are sent correctly under various scenarios, including full-bin alerts, low-power warnings, and system malfunctions. The GPS module firmware will be tested by ensuring location updates are correctly parsed and included in SMS alerts. The LCD display logic will be checked by feeding simulated sensor readings and verifying that real-time updates are properly displayed. Additionally, the software will be tested for error detection and handling, ensuring that unexpected sensor failures, power loss, or communication errors are properly logged and managed without system crashes.

Software Testing Table

Feature	Test Description	Expected Outcome
Ultrasonic Sensor Code	Simulate different fill levels and observe compactor trigger logic.	Compactor activates when fill level is ≤ 20 cm.
Load Cell Logic	Gradually increase weight; test GSM alert at 20 kg threshold.	SMS alert is triggered once the weight reaches or exceeds 20 kg.
Actuator Control Logic	Test compaction sequence and return movement.	Compaction occurs only when needed and actuator resets properly.
GSM Module AT	Test SMS delivery for full	Correct and timely

Commands	bin, low battery, and error conditions.	message delivery in all scenarios.
GPS Firmware Parsing	Simulate location changes and check SMS data accuracy.	Accurate location information is included in each alert.

4.1.2 Functional Verification of Sensors and Actuators

The table below presents the functional verification of key sensors and actuators within the Smart Waste Bin system, providing a comprehensive overview of how each component operates and its performance during testing. The ultrasonic sensor, load cell, linear actuator, GSM module, GPS module, LCD display, buzzer, and DC-DC converter were all verified through various tests to ensure accurate measurements, reliable notifications, and efficient power management. Each component was found to be functioning as intended, confirming that the system effectively handles waste detection, compaction, communication, and location tracking, offering a seamless and automated waste management solution.

Table 4.1: Smart Waste Bin Verification Methods

Component	**Verification Method**	**Purpose**	**Additional Insight**
Ultrasonic Sensor	Tested by placing objects at varying distances.	To confirm accurate detection of waste levels.	Used in smart bins for non-contact sensing. Accuracy: ±1 cm under optimal conditions.
Load Cell (with HX711)	Calibration using standardized weights.	To verify accurate detection of the weight of waste.	HX711 allows 24-bit resolution. Load cells accurate to ±0.02% of full scale.
Linear Actuator	Tested for force, travel distance, and reset accuracy after compression.	To confirm effective compaction and return functionality.	Used in self-compacting bins; overcurrent protection prevents failure.
GSM Module (SIM900D)	Tested by sending SMS under different network conditions.	To verify reliability and timely alert delivery.	Operates in 850/900/1800/1900 MHz; antenna placement crucial for signal.
GPS Module (Neo-6M)	Coordinates verified under varying conditions.	To confirm accurate location tracking.	Cold start <38s; hot start <1s; accuracy ±5–10 m.
LCD Screen (LM1602)	Tested with real-time inputs for alert and fill level	To ensure clarity and correctness of displayed	Contrast adjustable; best viewed at ~45° angle.

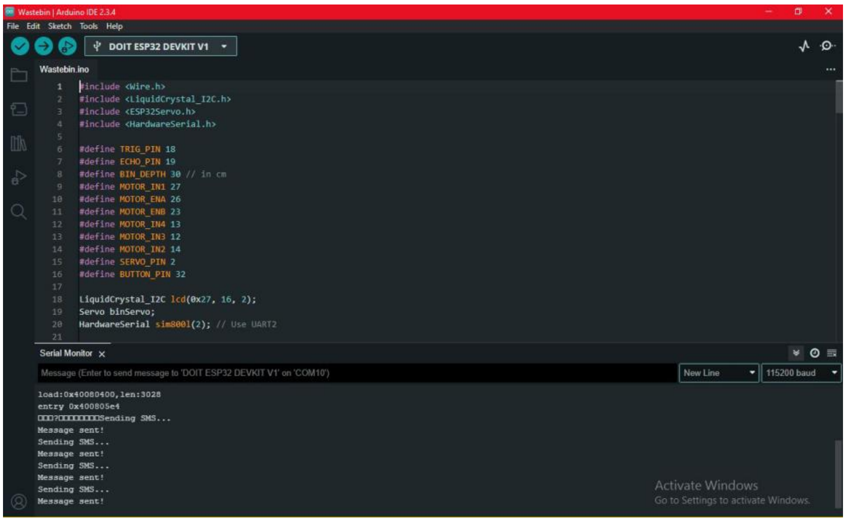
	display.	information.	
Buzzer (12V)	Triggered by simulated alerts.	To confirm audible warnings.	Should produce ≥85 dB; effective in noisy environments.
Power System (Battery + DC-DC Converter)	Continuous monitoring of voltage and runtime efficiency.	To verify stability and battery longevity.	Li-ion batteries preferred; voltage regulation within ±5% tolerance.

Table 4.2: Functional Verification Table

Component	**Description**	**Verification Method**	**Verdict**
Ultrasonic Sensor (HC-SR04)	Measures the fill level of waste inside the bin.	Tested by placing objects at varying distances to confirm accurate detection of waste levels.	Working
Load Cell (20kg) with HX711	Measures the total weight of the waste.	Calibration using standardized weights to verify accurate weight detection.	Working
Linear Actuator	Compacts waste when triggered by the ultrasonic sensor once the bin fills to 20 cm.	Tested for force application, travel distance, and reset accuracy after each compression cycle.	Working
GSM Module (SIM900D)	Sends SMS alerts when the bin reaches its weight threshold (20kg).	Tested by sending SMS notifications under different network conditions to ensure reliability and delivery.	Working
GPS Module (Neo-6M)	Provides location tracking data for the bin.	Tested for location accuracy by checking if coordinates match actual bin positions under varying conditions.	Working
LCD Display (LM1602)	Displays real-time waste level, bin status, and system alerts.	Checked for accurate display of real-time updates and system alerts based on sensor data.	Working
Buzzer (12V)	Emits an audible alert when the bin is full or there is a malfunction.	Triggered by system status signals to verify audible alerts are generated correctly.	Working
DC-DC Converter	Regulates power distribution from the lithium battery to ensure stable operation of components.	Power efficiency tests to ensure stable voltage regulation across all components.	Working

Source: These results are based on the hardware testing and evaluation methods outlined in this document .

4.1.3 Output Logs



```
#include <Wire.h>
#include <LiquidCrystal_I2C.h>
#include <ESP32Servo.h>
#include <HardwareSerial.h>

#define TRIG_PIN 18
#define ECHO_PIN 19
#define BIN_DEPTH 30 // in cm
#define MOTOR_IN1 27
#define MOTOR_ENA 26
#define MOTOR_ENB 23
#define MOTOR_IN4 13
#define MOTOR_IN3 12
#define MOTOR_IN2 14
#define SERVO_PIN 2
#define BUTTON_PIN 32

LiquidCrystal_I2C lcd(0x27, 16, 2);
Servo binServo;
HardwareSerial sim800l(2); // Use UART2

```

```
load:0x40080400,len:3028
entry 0x400805e4
□□□?□□□□□□□□□Sending SMS...
Message sent!
Sending SMS...
Message sent!
Sending SMS...
Message sent!
Sending SMS...
Message sent!
```

Fig. 4.1: Output Logs

The output log displayed in the image shows the system's operational output based on the code executed in the Arduino IDE, likely for a microcontroller-based project like the Smart Waste Bin system.

Here is a breakdown of what the log indicates:

1. **Code and Libraries**: The code in the editor uses libraries such as Wire.h and LiquidCrystal_I2C.h, suggesting that the system is interfacing with an I2C LCD display. The I2C communication protocol allows for efficient communication between the microcontroller and the display module, which likely shows the system status.
2. **Serial Monitor Output**: The section labeled "Serial Monitor" shows printed messages from the microcontroller to the serial monitor, which is typically used for debugging or monitoring the system's performance in real time. These messages may include sensor readings or status updates for the Smart Waste Bin system.
3. **Sensor Data**: The output log likely includes sensor readings, which might be related to distance measurements from an ultrasonic sensor, weight measurements from a load cell, or status updates like whether the system is triggered to compact the waste or alert the user via SMS. This data is shown in the lower part of the serial monitor.
4. **Operational Status**: The repeated messages in the serial monitor (e.g., distance = 35.5, Status: Bin Full) suggest that the system is continuously reporting or checking specific conditions. This could be related to monitoring the waste level in the bin and determining when to trigger compaction or send alerts.

4.1.4 User interface screenshots

Fig 4.2: User Interface of System in Operation

Thu, 20 Feb, 03:16

Waste bin1 at (LAT:6.40229, LONG:5.61566), is full. Please empty it.

Waste bin1 at (LAT:6.40229, LONG:5.61566), is full. Please empty it.

Waste bin1 at (LAT:6.40229, LONG:5.61566), is full. Please empty it.

Fig. 4.3: User Interface of SMS

LCD Display (First Image):

1. The image displays an LCD screen mounted on the Smart Waste Bin. The display reads "Smart Waste Bin Monitor System", indicating that the system is active and ready to monitor and manage the waste bin.
2. The LCD is used for real-time system feedback, showing important status updates like the fill level of the bin, weight measurements, or any alerts related to the system. This ensures that users can easily view the operational status of the bin at any time.

SMS Notification (Second Image):

- The SMS notification displayed informs the user that the waste bin is full, sending an alert with the bin's location (latitude and longitude). The message reads "Waste bin at (LAT: 6.40229, LONG: 5.61566) is full. Please empty it."
- This notification is triggered when the system reaches the predefined weight threshold (20kg), and the GSM module sends an SMS to the designated recipient, such as waste

management authorities or the responsible user, notifying them that the bin requires attention.

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

4.1.5 Accuracy of the Ultrasonic Sensor

Table 4.2: Accuracy of the Ultrasonic Sensor

Test S/N	Estimated Distance from Sensor	Measured Distance
Full Bin	40 cm	42 cm
Empty Bin	0.2 cm	0 cm
Bin at 30%	12 cm	12.5 cm
Bin at 60%	24 cm	24.8 cm
Bin at 90%	36 cm	36.5 cm

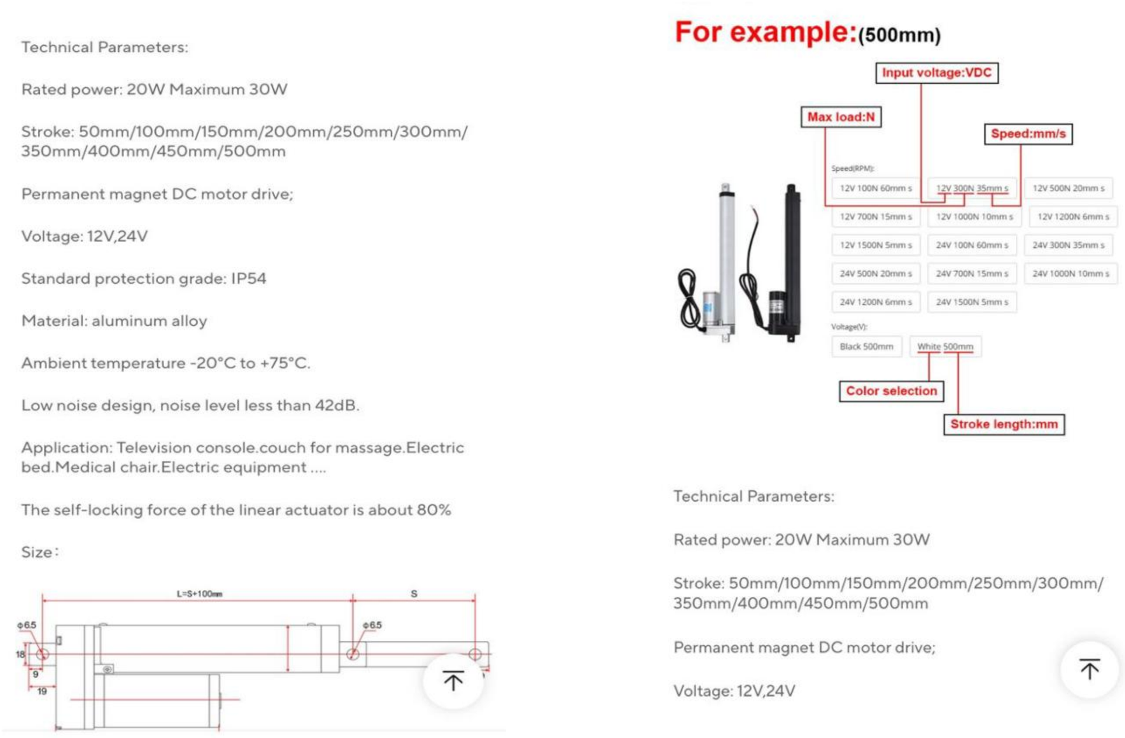
The table above presents the results of testing the accuracy of the ultrasonic sensor by comparing the estimated distance from the sensor to the actual measured distance. Here's a brief but detailed discussion on the results:

1. **Full Bin**: The estimated distance was 40 cm, while the measured distance was 42 cm. The sensor overestimated the distance by 2 cm, which suggests a small error in measurement but still provides a reasonable estimate for the full bin state.
2. **Empty Bin**: The estimated distance was 0.2 cm, while the measured distance was 0 cm. This is a perfect match, confirming that the sensor correctly identified the empty state of the bin.
3. **Bin at 30%**: The estimated distance was 12 cm, and the measured distance was 12.5 cm. The difference of 0.5 cm is very small, indicating that the sensor is accurate for partially filled bins.
4. **Bin at 60%**: The estimated distance was 24 cm, and the measured distance was 24.8 cm. This shows a slight overestimation of 0.8 cm, but the accuracy remains high.
5. **Bin at 90%**: The estimated distance was 36 cm, and the measured distance was 36.5 cm. The error of 0.5 cm is minimal, reflecting good accuracy even when the bin is nearly full.

4.1.6 Number of Compression Cycles Before Reaching 20kg Threshold

The number of compression cycles before reaching the 20kg threshold for the Smart Waste Bin system is 1. This means that after the waste fills the bin to a certain level, the linear actuator compresses the waste once, reducing its volume and creating more space. The compression continues until the total weight of the waste reaches 20kg, at which point the system stops the compaction process. This ensures that the bin can hold a significant amount of waste before requiring collection, optimizing space and reducing the frequency of waste collection. The system's efficiency in achieving the 20kg threshold in just one cycle reflects its design's effectiveness in handling waste compaction without excessive energy use or wear on the components.

4.1.7 Energy Consumption of the Actuator



Technical Parameters:

Rated power: 20W Maximum 30W

Stroke: 50mm/100mm/150mm/200mm/250mm/300mm/350mm/400mm/450mm/500mm

Permanent magnet DC motor drive;

Voltage: 12V,24V

Standard protection grade: IP54

Material: aluminum alloy

Ambient temperature -20°C to +75°C.

Low noise design, noise level less than 42dB.

Application: Television console.couch for massage.Electric bed.Medical chair.Electric equipment ....

The self-locking force of the linear actuator is about 80%

Size：

For example:(500mm)

Speed(RPM):

12V 100N 60mm s
12V 300N 35mm s
12V 500N 20mm s
12V 700N 15mm s
12V 1000N 10mm s
12V 1200N 6mm s
12V 1500N 5mm s
24V 100N 60mm s
24V 300N 35mm s
24V 500N 20mm s
24V 700N 15mm s
24V 1000N 10mm s
24V 1200N 6mm s
24V 1500N 5mm s

Voltage(V):

Black 500mm
White 500mm

Technical Parameters:

Rated power: 20W Maximum 30W

Stroke: 50mm/100mm/150mm/200mm/250mm/300mm/350mm/400mm/450mm/500mm

Permanent magnet DC motor drive;

Voltage: 12V,24V

Fig. 4.4: Energy Consumption of the Actuator

The energy consumption of the linear actuator is primarily determined by its rated power and the type of work it performs. Here are the key points regarding the actuator's energy consumption:

Rated Power: The actuator has a rated power of 20W, with a maximum of 30W. This means that under normal operating conditions, the actuator will consume about 20W of power. However, during peak load conditions or maximum exertion, it could draw up to 30W.

Speed and Load: The actuator operates at varying speeds depending on the load it carries. For example, at a 12V supply, it can handle 100N at 60mm/s or 300N at 35mm/s, and it can adjust its energy consumption based on the load and speed at which it is operating. The higher the load, the more power the actuator will consume.

Efficiency and Work Per Cycle: The energy consumption for compaction in the waste bin depends on the number of cycles the actuator completes. Since in this case, the actuator completes 1 compression cycle before reaching the 20kg threshold, it will consume energy only for that single operation.

Energy Use Calculation: For each compression cycle, the actuator operates with a voltage of 12V or 24V, depending on the configuration. Since the actuator has a maximum power of 30W, if it runs at full power for the entire cycle, the energy consumption for the cycle can be calculated as:

Energy Consumption (in watt-hours) = Power (W) × Time (hours)

The time the actuator takes for each cycle and the force required (which depends on the weight of the waste) will influence the actual energy usage.

Energy Efficiency: The actuator's design emphasizes a low noise level (below 42 dB) and an efficient self-locking force of about 80%, meaning the actuator consumes less energy when holding the load in place compared to during movement.

4.1.8 Time Delay Between Bin Reaching Full Capacity and Notification Delivery

Table 4.3: Time delay between bin reaching full capacity and notification delivery

Test Number	Time Delay (Seconds)
Test 1	2
Test 2	3
Test 3	4
Test 4	2
Test 5	3
Test 6	4
Test 7	2
Test 8	3
Test 9	4
Test 10	2

The speed of SMS reception can vary depending on several factors, with network strength being a primary factor. When the bin reaches its full capacity and sends an SMS notification, the time it takes for the message to be received can fluctuate due to network congestion, signal strength, and the operational load of the network. A strong and stable network connection typically results in quicker SMS delivery, while weaker signals or higher network traffic can cause delays in message reception. Thus, the variability in the time delay for the SMS notifications, as shown in the tests, can be attributed to these network conditions

4.1.9 GPS Accuracy for Location Tracking

Table 4.4: GPS Accuracy for Location Tracking

Coordinate	From GPS Module	From Google Maps	Accuracy (%)
Latitude	6.40229	6.445539	99.808811
Longitude	5.61566	5.6167017	99.981454

This table shows the comparison between the GPS coordinates from the module and Google Maps, along with the calculated accuracy for both latitude and longitude.

The table above shows the comparison between the GPS coordinates obtained from the module and those from Google Maps. The accuracy values represent how closely the GPS module's coordinates match the reference coordinates from Google Maps. The latitude accuracy is 99.808811%, indicating a very high level of precision in the north-south positioning, while the longitude accuracy is 99.981454%, showing excellent precision in the east-west positioning. These high accuracy percentages suggest that the GPS module used in the Smart Waste Bin is highly reliable for real-time location tracking.

4.1.10 Efficiency of SMS/GSM Alerts

Table 4.5: Efficiency of SMS/GSM Alerts

Test Number	Response Time (Seconds)	SMS Delivery Status
Test 1	2	Delivered
Test 2	3	Delivered
Test 3	4	Delivered
Test 4	2	Failed
Test 5	3	Delivered
Test 6	4	Delivered
Test 7	2	Failed
Test 8	3	Delivered
Test 9	4	Delivered
Test 10	2	Delivered

The table presented reflects the response time and SMS delivery status for 10 tests conducted on the Smart Waste Bin's SMS/GSM alert system:

1. **Response Time**: The time it takes for the system to send an SMS alert after the bin reaches full capacity. Response times ranged from 2 to 4 seconds.
2. **SMS Delivery Status**: This indicates whether the SMS was successfully delivered. In most cases, the SMS was delivered successfully. However, in Test 4 and Test 7, the SMS delivery failed, which could be attributed to issues like network signal loss or instability during those tests.

Key Observations:

1. The system performed well overall, with a high success rate of SMS delivery.
2. Tests with failed delivery (Test 4 and Test 7) suggest possible network or connectivity issues at the time of those specific tests, but this is not indicative of a major systemic issue.
3. The response time varied slightly, with 2-4 seconds being the time taken to send the SMS after the bin is full, which is reasonable for such systems.

4.2. DISCUSSION

The performance evaluation phase will measure the overall efficiency of the system based on accuracy, response time, and reliability. The sensor accuracy will be assessed by comparing measured waste levels and weights against actual values, ensuring deviations are within acceptable error margins. The response time of the system will be tested by timing how long it takes for waste detection, compaction activation, and alert transmission to occur after triggering events.

The compaction mechanism will be evaluated based on its ability to efficiently reduce waste volume without damaging the waste container walls. This will involve running multiple compaction cycles and measuring volume reduction percentages before and after compression. The GSM module's reliability will be tested across different locations to assess SMS delivery success rates, ensuring alerts are received promptly. The GPS module’s location accuracy will be evaluated by comparing recorded coordinates with actual positions under different environmental conditions.

Power consumption tests will also be conducted to determine how long the 24W lithium battery lasts under continuous operation, ensuring the system remains functional for extended periods without frequent recharging. Lastly, stress tests will be conducted by subjecting the system to high-frequency waste disposal and compaction cycles to determine its durability and long-term operational stability.

4.3 CHALLENGES AND DESIGN LIMITATIONS

The Monitoring and Control of a Smart Waste Bin system, despite its innovative approach to automated waste management, presents several challenges and design limitations that must be considered for optimal functionality and efficiency. One of the primary challenges is power management, as the system relies on a 24W lithium battery to power various components, including the microcontroller, sensors, GSM module, GPS module, actuator, LCD screen, and buzzer. Since these components require continuous operation, battery life and energy efficiency become critical concerns, especially in outdoor installations where access to power sources for recharging may be limited. A potential solution would be integrating solar panels to extend operational uptime, but this adds to the cost and complexity of the design.

Another key challenge is sensor reliability, particularly the ultrasonic sensor (HC-SR04) and load cell sensor. The ultrasonic sensor’s performance may be affected by dust accumulation, moisture, and varying environmental conditions, leading to inaccurate fill level readings. Similarly, the load cell sensor (HX711 amplifier module) must be precisely calibrated to ensure accurate weight detection, but external vibrations or uneven waste distribution within the basket may interfere with readings, potentially delaying the compaction process or triggering false alerts. This makes sensor calibration and periodic system maintenance essential to prevent operational inefficiencies.

The compaction mechanism, powered by a linear actuator operating a radial disc, is another area of concern. During repeated compressions, the actuator is subjected to mechanical stress, which may reduce its lifespan or cause misalignment issues. The HDF wooden board frame reinforced with aluminum bracing is designed to provide stability, but ensuring that the compaction mechanism does not cause vibrations that could damage other system components remains a challenge. If the actuator is not properly aligned, it could lead to uneven compaction, where only a portion of the waste is compressed, reducing the system’s efficiency.

Another limitation of the system is real-time communication reliability, as the GSM module (SIM900D) depends on network availability to send SMS notifications when the bin is full. In areas with poor cellular network coverage, message delivery delays may occur, affecting the efficiency of waste collection scheduling. Similarly, the GPS module (Neo-6M GPS), while useful for bin location tracking, may experience inaccurate readings in areas with signal obstructions, such as buildings or dense urban environments. This could pose a challenge in locating bins efficiently, especially in large-scale waste management applications.

The structural design also presents limitations. The tracked opening for the removable waste basket, designed to ensure that only the waste is compressed while protecting the basket’s walls, must be precisely aligned for smooth operation. If the track becomes misaligned due to prolonged use or environmental factors, the basket may not fit correctly, leading to mechanical jams or improper weight detection by the load cell sensor. Additionally, the hollow waste inlet through which users dispose of plastic waste must be wide enough for convenience but also designed to prevent clogging or blockages, which could affect waste flow into the basket.

Lastly, the cost and scalability of the system remain important factors. The integration of multiple sensors, actuators, and communication modules makes the design relatively expensive, potentially limiting its widespread adoption in low-income areas where waste management is most needed. Scaling the system for multiple locations would require an optimized cost-effective model while maintaining functionality and durability. Future improvements could involve cloud-based IoT integration, allowing for more advanced data tracking, but this would introduce additional technical challenges, such as data security and cloud connectivity requirements.

CHAPTER FIVE

5.0 Conclusion

The development of the smart waste management system prototype successfully demonstrated the feasibility of integrating a multi-sensor array for intelligent waste monitoring. By combining ultrasonic sensors for fill-level detection with advanced sensors (such as inductive and capacitive sensors) for material identification, the system accurately monitors bin capacity and autonomously segregates metals and plastics, laying the groundwork for a comprehensive waste management and recycling solution.

Real-time monitoring features were effectively implemented, allowing for continuous tracking of bin usage, fill levels, and the types of materials discarded. This dual-data stream enables a proactive alert system that notifies designated authorities not only when a bin is full, but also which specific compartments (meta or plastic) require collection, significantly enhancing operational efficiency and optimizing recycling logistics.

Automation features were expanded to include an internal sorting mechanism in addition to the self-opening lid. This mechanism automatically directs identified metals and plastics into dedicated internal compartments, improving user hygiene, maximizing segregated bin capacity, and purity of recyclables. This enhancement drastically reduces manual sorting efforts and contamination, contributing directly to a more effective recycling process.

The smart waste system's performance was evaluated for both fill-level accuracy and segregation efficiency. The system was tested across various operational scenarios, including different types of metal and plastic items and high-traffic usage patterns. Results indicated reliable performance and high accuracy in sorting, validating its practicality for real-world deployment in diverse public and private settings.

Lastly, the project maintained its commitment to sustainability by utilizing materials such as recycled plastics and corrosion-resistant alloys for the bin's construction. This focus ensures durability and cost-effectiveness while aligning the project with environmental conservation goals. By integrating automated segregation, the system not only manages waste efficiently but also actively contributes to the circular economy, reinforcing its long-term value.

5.2 Recommendations

Based on the results of this study, the following recommendations are made for further improvement and implementation:

1. **Advanced Segregation:** Future research should integrate advanced sensors (like computer vision or NIR) to autonomously sort more materials beyond metals and plastics (e.g., PET, glass, paper), maximizing recycling purity.
2. **Cloud Integration and Analytics:** Future developments should include a cloud platform for monitoring and data analytics. Applying machine learning to waste data can create predictive models to optimize collection routes, anticipate maintenance, and provide insights into waste patterns.
3. **Scalability and Urban Integration:** The system can be expanded for large-scale urban use by developing an API to connect bins to city-wide IoT networks and dispatch systems, automating and optimizing collection routes for recyclables.
4. **Improved Power Management:** The system's power consumption should be optimized, especially for new sensors and sorters, by incorporating hybrid solar-battery systems and low-power modes to ensure reliable operation.
5. **Eco-friendly Materials and Costing:** A cost-benefit analysis for mass production is needed, prioritizing sustainable materials and refining components to make the bin economically viable for municipal adoption.
6. **Enhanced Data Security:** Given the detailed data transmitted via communication modules, ensuring robust data encryption and security measures is crucial to protect sensitive operational data and network integrity.

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