Sudan University of Science and Technology

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Waste Control and Monitoring Using Long-Range Wide Area Network

A Research Submitted in Partial fulfillment for the Requirements of the Degree of B.Tech. (Honors) in Electronics Engineering

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بسم الله الرحمن الرحيم

قال تعالى:

﴿اقْرَأْ بِاسْمِ رَبِّكَ الَّذِي خَلَقَ ۝ خَلَقَ الْإِنسَانَ مِنْ عَلَقٍ ۝
اقْرَأْ وَرَبُّكَ الْأَكْرَمُ ۝ الَّذِي عَلَّمَ بِالْقَلَمِ ۝ عَلَّمَ الْإِنسَانَ مَا لَمْ
يَعْلَمْ ۝﴾

سورة العلق (1-5)

DECLARATION

I hereby declare that the research titled “Waste Control and Monitoring Using Long-Range Wide Area Network” is the result of our original work, carried out under the guidance and supervision of [Prof. Rashid]. This research represents the design and simulation of intelligent waste management systems that integrate sensors, actuators, LoRaWAN communication, Node-RED, Wokwi, and a cloud-based dashboard for real-time waste monitoring, classification, compression, sterilization, and location tracking.

We affirm that all sources of information and references used in this research have been properly acknowledged and cited. This work has not been submitted in whole or part for any other academic degree or professional qualification. We are also proud that this research was presented at the International Conference on Intelligent Systems and Artificial Intelligence Application (ISAA), at the University of Nizwa, Sultanate of Oman.

ACKNOLEDGMENTS

First and foremost, we express our gratitude to Almighty Allah, who has granted us the strength, patience, determination, and wisdom throughout this journey. We praise Him for making this achievement possible. We would also like to express our deepest gratitude to Prof. Rashid, our supervisor, for his continuous guidance, invaluable advice, constructive feedback, and unwavering support throughout every stage of this journey. We would also like to extend our sincere appreciation to our university, Sudan University of Science and Technology, for providing us with the knowledge, facilities, and academic environment that supported this work.

Our heartfelt thanks go to our own efforts, dedication, time, and energy that we invested in this project to be presented in the best possible way. Also, thanks go to our families and friends for their endless patience, encouragement, and moral support throughout our journey.

Finally, we express our gratitude to everyone who contributed, directly or indirectly, to the completion of this research. And we pray that Allah makes our knowledge beneficial and allows us to benefit others through it.

Dedication

"In honor of every dreamer who faces challenges with determination, and with heartfelt appreciation to our families, whose faith in us gave us the strength to continue and achieve our goals"

Abstract

Traditional waste collection methods often result in inefficient collection schedules, increased operational costs, and environmental pollution. To address these challenges and enhance waste management, this project proposes the use of a Long-Range Wide Area Network (LoRaWAN)-based system for the monitoring, sorting, sterilizing, and compressing of waste. All bins (nodes) collect real-time environmental data with the help of sensors and send it using LoRa to the Cluster Head, which serves as a local gateway. The Cluster Head gathers and sends the information to a cloud-based Network Server (Node-RED) via the Internet. The information is then communicated and sent through the MQTT protocol to a Dashboard to monitor and make decisions in real-time. The system also incorporates GPS-based location tracking and notification services to optimize waste collection operations. The proposed system contributes to reducing unnecessary collection trips, improving operational efficiency, and supporting sustainable environmental management. Simulation results confirmed that the system is efficient in all tasks, sending an alert when the container is full, when harmful gases are detected, and/or when the bin is rotated or moved. It also represents the position of the bin perfectly and offers live information. The proposed system contributes to reducing unnecessary collection trips, improving operational efficiency, and supporting sustainable environmental management.

الخلاصة

تؤدي الطرق التقليدية لجمع النفايات الى جداول جمع غير فعالة وزيادة في التكاليف التشغيلية وتلوث بيئي. لمواجهة هذه التحديات وتحسين إدارة النفايات يقترح هذا المشروع استخدام نظام قائم على شبكة (واسعة النطاق طويلة المدى ومنخفضـــة الطاقة). تقوم جميع صـــناديق النفايات(العقد) بجمع البيانات البيئية في الوقت الفعلي بمساعدة أجهزة الاستشعار وإرسالها باستخدام تقنية "لورا" الى رأس المجموعة الذي يعمل كبوابة محلية. يقوم رئيس المجموعة بجمع المعلومات وإرسالها إلى خادم شبكة سحابي عبر الإنترنت. ثم يتم نقل المعلومات وإرســـالها عبر بروتوكول نقل البيانات الى لوحة التحكم لمراقبة الوضـــع واتخاذ القرارات في الوقت الفعلي. كما يشـــتمل النظام على خدمات تتبع الموقع والإشـــعارات القائمة على نظام تحديد المواقع العالمي لتحسين عمليات جمع النفايات. ويساهم النظام المقترح في تقليل رحلات الجمع غير الضـــرورية، وتحســـين الكفاءة التشـــغيلية، ودعم الإدارة البيئية المســـتدامة. أكدت نتائج المحاكاة أن النظام فعال في جميع المهام، حيث يرســـل تنبيهًا عند امتلاء الحاوية، أو عند اكتشـــاف غازات ضـــارة، أو عند تدوير الحاوية أو تحريكها. كما أنه يحدد موقع الحاوية بدقة ويوفر معلومات مباشـــرة. ويســـاهم النظام المقترح في تقليل رحلات الجمع، وتحسين الكفاءة التشغيلية، ودعم الإدارة البيئية المستدامة.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Background

In recent years, there has been a booming growth of solid waste and environmental pollution due to urbanization and population growth to create the current cities with weak ecology [1]. The conventional approaches to managing wastes like scheduled garbage collection have become ineffective and fuel and manpower consuming [2]. When the collection of garbage is done once a week, it may spill over and cover the area. Poor waste management also causes floods, bad smell and poor air pollution that are detrimental to human health [3]. As such, a remote monitoring system is required that can notify the waste management company on the amount of garbage in the bins. In Sudan, there is rapid urbanization and poor solid waste management infrastructure, which result in accumulation of wastes in the streets, resulting in health and environmental issues, particularly in large cities such as Khartoum [4]. Hence, we need an emergency strategy to keep our country and cities clean and environmentally friendly.

Every year, we can observe the advent of a great number of technologies [5, 6]. The Internet Of Things (IoT) is in the process of having a significant change; it is a web of interacting devices that have the ability of gathering data without the involvement of a human being and combining embedded devices with networks and information technology [7, 8].

Most existing smart bins rely on Wi-Fi and GSM, which are unsuitable for large, developing areas and do not include recycling or monitoring of gases and Odors inside the bin [9]. Therefore, there was a need to find effective system solutions to reduce operating costs and unnecessary trips, support recycling and sustainability, and minimize environmental pollution [10, 11]. This project presents an effective system using Long Range Wide Area Network (LoRaWAN*)* technology for long-range and low-power communication. The system includes monitoring of fullness levels, gas and odour detection devices, and a compression system to increase bin capacity [12]. It also supports a sorting system for environmental sustainability and recycling.

1.2 problem statement

Waste management is the task of handling solid wastes and provides a wide range of solutions for recycling the objects that can be used again. Improper disposal of wastes can generate unhygienic conditions which will in turn cause pollution of

the environment and outbreak of many diseases. Thus, proper management of solid wastes is required to protect public health and environment [13].
As a result, recycling rates decrease, transport and unloading costs increase, and environmental degradation also occurs, which affects the health of the population.
In many urban areas, trash bins overflow due to inefficient waste collection schedules and absence of real-time monitoring systems. When bins are not full, unnecessary collection leads to waste of fuel and manpower, while delayed collection causes waste to spread around the area, resulting in environmental pollution and health risk to the public therefore, the lack of accurate and real time information about bin status leads to inefficient waste management operation [14].
Many current smart solutions either have a high cost or use energy sources that are not environmentally friendly or do not provide mechanisms to track the location, which limits their implementation on a large scale, especially in environments with limited resources.

1.3 The Objectives and Aims

the main aim of system to enhance waste management efficiency, optimized waste collection and real-time monitoring, the objectives of this research are:

1) Cost reduction: Minimize costs by reducing unnecessary waste collection trips.
2) Real-time monitoring: Continuously monitor bins status.
3) Improve public health: Reduces unpleasant odours, insects and environmental pollution.
4) User convenience: Provides an easy way for user to dispose of waste.
5) efficient waste collection.
6) Date-driven management: Collect and analyse data to support better decision-making.
7) Environmental sustainability: promote cleaner environments and reduce fuel consumption.

1.4 Research Questions

1) What is the importance of Smart Bins in improving public health?
2) What is the theory of automation and remote management in Smart Bins?
3) Can we serve user convenience?
4) Is it an efficient way to collect waste? And how?
5) Determine whether it is an expensive or economical method and explain?
6) How do we enhance recycling?
7) What is the main objective of smart bins?
8) In one sentence describe data-driven management through smart bins?

9) What are the requirements for smart cities?

1.5 Significance of the study

This study is significant as it contributes to the advancement of sustainable waste management practices through the development of a Smart Bin system that integrates renewable energy, recycling, and sensor-based monitoring. By addressing the pressing challenge of increasing urban waste, the project provides a practical and innovative solution that combines efficiency, environmental responsibility, and modern technology. The system enhances waste management by ensuring efficient collection, enabling real-time monitoring, and supporting automated segregation of waste materials. For governments, municipalities, and waste management companies, the Smart Bin offers substantial benefits, including cost reduction by minimizing unnecessary collection trips, optimizing manpower and resources, and streamlining logistics [15]. These improvements not only reduce operational expenses but also help authorities allocate resources more effectively in other areas of urban development. From a community perspective, the system promotes public health and environmental cleanliness by preventing overflowing bins, reducing unpleasant Odors, and minimizing pest infestations often associated with unmanaged waste. Furthermore, by encouraging proper waste disposal practices and recycling, the project fosters a culture of environmental responsibility among citizens. Environmentally, the study emphasizes the importance of integrating technology with green initiatives. The use of renewable solar energy reduces dependency on non-renewable sources, supports recycling initiatives, and lowers the overall carbon footprint of waste management operations. This aligns with global sustainability goals and contributes to building eco-friendly and resilient cities [16]. Academically, the study provides valuable insights into the application of the IoT within the broader context of smart cities. It highlights how emerging technologies can be leveraged to address real-world environmental challenges. Moreover, it serves as a reference point for future researchers and practitioners interested in exploring the intersection of smart technologies, sustainability, and urban development. By bridging theoretical knowledge with practical application, the study enriches the academic discourse and paves the way for further innovation in environmental sustainability.

1.6 Scope and Limitations

Scope:
The scope of this project encompasses the design, simulation, and evaluation of a smart waste bin that focuses on automated waste segregation into three categories: metal, plastic, and organic matter. Furthermore, it provides a compression system that activates when the bin reaches proposed Fill Levels.

The bin integrates sensors to identify deposited items and channels them into appropriate compartments. It also incorporates a ventilation and sterilization system to eliminate Odors and maintain hygiene. Each bin sends the data collected from sensors to cluster head via LoRaWAN and transmits it via Internet using MQTT Protocol to the nearest Network Server to connect to a mobile application for the cleaners providing real-time information on fill levels, alerts when the bin is moved, and notifications when maintenance is required. Additionally, the bin is solar-powered and thus best suited for use outdoors in open areas like parks, university campuses, airports or main roads. The project does not sort paper or glass waste and does not perform actual recycling processes; it sorts the waste to some extent only. It is not designed for industrial scale use like factories or large production centres.

Limitations:

The System tested in simulation only. Therefore, no real hardware calibration and environmental factors are not considered. The accuracy of waste classification may be reduced when dealing with dirt, mixed materials, which may not get identified by available sensors. The bin currently sorts only three types of waste, excluding materials like paper, glass or textiles like tissue. Solar energy ensures sustainability; its effectiveness can be limited in areas with poor sunlight exposure or changing weather conditions. Expansion using high-precision sensors and cameras is expensive and significantly increases the cost of implementation, which limits scalability.

1.7 Organization of the thesis

This Research contains five chapters as shown below:

Chapter One: Introduction chapter, this chapter presents background of our study, problem theory, Questions, aims and objective, significance of the study, scope and organization of the thesis.

Chapter Two: Literature Review Here we show you an old study review related to our project, IoT applications and the gap that we aim to solve in this project.

Chapter Three: Methodology Our third chapter covers in fine detail system design, hardware components and software.

Chapter four: it represents how the system works, simulation of the smart bin and results obtained.

Chapter Five: Conclusion we present a summary of our project and suggest other ideas for similar projects in the next coming years.

Chapter 2

Literature Review

2.1 Introduction

Nowadays the whole world is turning into environmental sanitation and sustainable development considering economic factors. Wastes are one of the most dangerous threats today because of the rapid renaissance, population growth and industrial evolution. Somehow governments in big cities and countries tried many ways to reduce the side effects of this progress and evolution but it’s not enough. We need to start from our own streets and neighbourhoods, also increasing awareness among citizens of all ages.

Waste management is a term that refers to all the ways in which waste is collected starting from our own houses, streets, facilities, reaching every foundation and space in the city. Streets play the most crucial role, as they reflect the overall outlook of the city. Citizens spend half of their day on it going to work, school or going back home, even in entertainment ways you will cross minimum 2-4 main street in your day with a cup of coffee in your hands or something to eat, if we don’t raise our awareness and help our government the pollution will become more threatening.

Traditional waste management and collecting are no longer effective because of high levels of waste in cities, and it is impractical. Researchers and Inventors tried to discover new ways starting from recycling bins and talked about the economic and environmental value of recycling. Many countries adopted separate baskets in the streets and elsewhere but also it is impractical and inefficient. Smart Waste Management (SWM) is a new term used in the last few years mixed between technology and environmental sustainability, using IoT in bins and recycling has become effective and more user-friendly.

IoT Smart Waste Bins are basic and important components of building and developing smart cities and. Waste is one of the biggest challenges in every country in the world. Every year hundreds of technologies and ways to collect waste and make cities green and more sustainable but every way has its own difficulties and disadvantages.

The IoT is a network of embedded sensors and services connected; it has many uses in our modern world today. The way it works is by collecting data and information and making a response in a certain way such as in smart houses, agriculture and many other applications.

Here we use it to make our streets green and sustainable, also raising citizens' awareness. It works in a very simple way for all ages and kinds of people; it will be distributed in all main streets. Simply, when someone approaches the container cover it will open automatically to throw your waste inside and immediately

close, what happens inside is the sensors will sort the contents into three parts (metal, plastic and organic) for recycling. There is also a waste compression system to save space in containers.
In conclusion our IoT Smart waste bins will solve the traditional and un efficient way in collecting waste and recycling and will reduce the government budget been used in this area and give us other benefits such as improve efficiency, reducing spread of harmful gases, provide comfort to users, extend life of the infrastructure and it’s a very important step towards more sustainable and civilized cities.

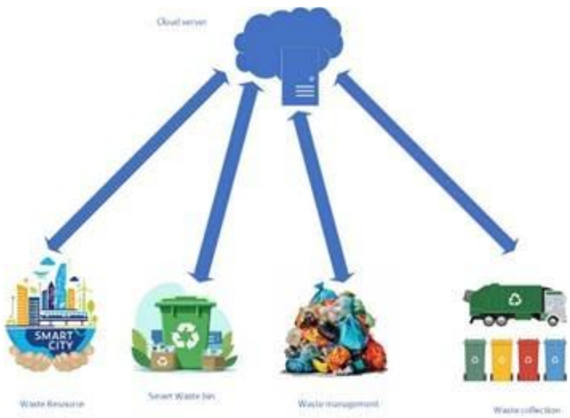


Figure 2.1 Smart waste management system

2.2 IoT in Waste Management

Waste management has been identified as a critical problem underpinning the vision of sustainable cities. Several researchers have proposed smart waste management solutions using IoT technologies to tackle this challenge over the years.
In 2021, a unique smart waste management (SWM) system was proposed using Blockchain and the IoT to simplify waste segregation with the help of smart bins. Rewards were distributed to users for proper waste disposal in smart waste bins using smart contracts deployed on the Matic test network [17]. Although the system was focused primarily on incentive-based methods and was distinguished by transparency, traceability, safety, and smart waste sorting, important operational and environmental aspects such as– sterilization and ventilation mechanisms to ensure public health, reliance on a sustainable energy source, and improvement of capacity efficiency through pressure mechanisms– were neglected.
In another paper in 2021, a system was presented in which the unfilled level and geographical location of a trash bin were measured, the data were processed and then transmitted to a LoRa WAN gateway. The gateway functioned as a concentrator for the Trash Bin Level Monitoring Unit (TBLMU) and was used to relay data between the TBLMU and the IoT-TBLM server [14]. The system was

effective in providing long-range communication, low energy consumption, and reliable data transfer; However, it was limited by its narrow focus on level detection and location tracking, while important features such as automated waste segregation, sterilization, ventilation mechanisms, and integration with a mobile application for real-time monitoring and maintenance alerts were not incorporated.

In a recent study 2025, an IoT-based smart dustbin system was designed to optimize waste management through automated real-time monitoring. The system incorporated sensors for waste level detection, user interaction, and fire hazard detection, with the key novelty being the use of three MQ gas sensors for toxic gas detection, a GSM-based notification system was also implemented to provide alerts [18]. The system was effective in enabling real-time monitoring, early warnings of toxic gases and fire hazards; However, it faced challenges related to power consumption and dependence on Wi-Fi
connectivity. Unlike this system, the proposed smart bin focuses not only on monitoring but also on automatic waste segregation, GPS tracking, as well as sustainable operation through solar energy.

2.3 Smart Waste Bin Concepts and Evolution

2.3.1 Concepts:

Environmental pollution and waste accumulation in the streets made researchers and governments looking for more advanced solutions. Here they began using IoT technologies in this major because of its benefits and ease of use.

They invented a fundamental concept of smart waste bin revolving around sensors to sense type of waste, another type of sensor to detect movement around the containers and open the cover for the citizens when they need to, also a bad Odour detector for harmful gases and air purification. The most important notion has been improved is the organic waste segregation for use in energy and fertilizers. All the components are connected to a cloud to organize unloading operations and collect more efficient data, also solar panels and batteries have been used in recent studies and to make it more economical.

Besides all this a 60% and 80% waste compaction stages will apply to save more space and reduce the number of trips to transport waste. A notification will appear when the container is full even after computation the truck will locate the container and arrive at the destination to extract the waste easily.

2.3.2 Evolution

Building smart cities requires a lot of modern systems to enhance environmental health and sustainable development.

A waste management system has been developed to manage the entire process of waste collection Through a specifically designed RFID tag with weight sensing capabilities and detect the amount of urban waste produced by every citizen [19].
Another system has been implemented using logic, sensors and Arduino UNO microcontroller, The sensors, logics, microcontrollers and IoT module ensures that the clearing of trash bins is maintained by signalling the trash levels and henceforth acknowledge the individuals not to spill the waste outside of the trash bin [20].
The solar panel has been used in smart waste segregation with image processing that helped in managing to segregate four types and also, they used GSM module to generate SMS notification once the bin reached its maximum capacity [21].
A LoRa WAN (long range low power) technology used for this type of purpose and improved fairness in the waste management and minimized both total distance and achieving fairness.

2.4 Public Health and Environmental Benefits

In recent years, smart waste management systems, especially IoT technology-based systems, have been researched as environmentally friendly solutions since waste management has been most widely identified not only as an ecological issue but also as a critical determinant of public health. Unsustainable disposal and accumulation of wastes have been linked to the spread of infectious diseases, water and land pollution, and emission of toxic gases that cause harm to human beings' health.
In 2024, a review was conducted to evaluate the efficacy of waste management methods such as gasification, pyrolysis, compaction, and incineration in the battle against waste clogging and breeding grounds of associated mosquitoes [22].
The study also assessed waste-derived water containers as breeding grounds for Aedes aegypti mosquitoes by assessing larval density in ten dengue- endemic regions using the Container Index (CI). High CI values were recorded in Dire Dawa, Ethiopia (54%), and Tamil Nadu, India (32.2%), a significant risk for dengue transmission was indicated, while a low CI value of 0.15% was seen in Rawalpindi, Pakistan, correlating with reduced incidence of dengue. The results confirmed that inadequately managed waste points, especially those with stagnant water, significantly increased mosquito breeding.
Consequently, effective waste management practices, supported by community participation and policy frameworks, were deemed essential to control dengue outbreaks. Unmanaged waste, especially materials that accumulate stagnant water, can create breeding grounds for mosquitoes and increase disease transmission [22]. This highlights the necessity of a waste monitoring system to prevent overflowing, as well as a ventilation and sterilization mechanisms to eliminate the possibility of Odors generation and insects breeding.

Poorly managed waste leads to negative environmental consequences. Malaysia generates more than 39,000 tons of municipal solid waste per day, and a large portion of this waste is still disposed of in landfills. Inefficient collection systems, including fixed schedules and non-optimized routes, contribute to reduced collection efficiency and waste overflow [23]. Consequently, trucks were under-utilized, and some regions were left unserved. Hence, the need for an efficient, intelligent, and automated waste management system to ensure trucks reach containers on time was highlighted. In particular, the world's population is expected to reach 9.9 billion by 2050, representing an increase of more than 25% compared to 7.8 billion recorded in 2020, and as large number of people being gradually concentrated in cities, the amount of waste is expected to increase to 2.2 billion tons worldwide by 2025 [24].

It has been indicated in several studies that less than 5% of global greenhouse gas emissions are contributed by the waste management sectors, with a more recent assessment estimating around 3.4% of total emissions [25][26]. Another approach to waste management focuses on energy recovery from organic solid waste. In one study [14], anaerobic digestion was used for household waste consisting of 80.4% organics.

Biogas with a methane content of 57.35% and carbon dioxide of 32.4% was produced by the process for 70 days and amounted to 9 Liters. The upgraded biogas was estimated to generate 1235.27 kWh of primary energy per ton of waste while 6.34 tCO_2eq emissions was avoided, representing a 77.54% reduction compared to landfilling. This demonstrates the necessity for a system that speeds up the process of sorting waste for recycling by enhancing efficiency in operation. Such systems offer the public health and environmental benefits of lowered disease vectors, greenhouse gas emissions, and the encouragement of recycling activities that conserve natural resources.

2.5 Automation and Remote Management Theories

Automation is a key concept in the smart bin management systems, by operating processes (e.g., waste sorting, fullness of bins) without the need for direct human intervention, it’s also dependent on control systems theory, which follows the principle of inputs, processing, outputs, and feedback.

Sensors collect data (bin fill levels or waste type), and the microcontroller processes this information to generate actions (activating motors to sort waste or turning on filtration units). This approach reduces the need for direct human intervention besides increasing accuracy and efficiency.

Remote management, on the other hand, is based on the IoT. It allows bin data (e.g., GPS location, fill status, or unauthorized movement) to be transmitted to central servers or mobile applications. Such connectivity enables real time monitoring, route optimization for collection, and reduced operational costs and improving system reliability.

According to Ramson et al. (2022), sensors integrated with IoT enabled microcontrollers were used to automate waste segregation and monitoring processes without human involvement [27]. However, it was noted that most existing works focused on only one aspect, either automation or remote monitoring, while very few systems integrated both in a cost-effective manner.
Furthermore, sustainability concerns, such as renewable energy integration and Odor management, were largely unaddressed. Other studies also reported additional contributions, including waste recycling, the use of clean energy (e.g., solar panels), and the implementation of GPS systems to enhance safety, as well as the deployment of monitoring units to track the fullness of bins.
Building on these previous studies, efforts in the current project were directed towards developing a more comprehensive and sustainable smart bin. Key improvements were proposed to combine automation with predictive and remote monitoring, thereby enabling real time tracking of bin status, forecasting of fill levels, and the integration of Odor control and self-sanitization units to enhance public health and prevent the spread of diseases.

2.6 Efficiency and user convenience

Previous studies described dynamic scheduling and waste collection as manual processes, but the use of the IoT has made them more efficient.
A smart bin was developed that sent alerts to municipal authorities so arrangements could be made to replace the bin.
Additionally, features were also introduced automatic door closing with the help of motors using ultrasonic sensors when the bin was full, and detection of surrounding objects using an infrared sensor, which in turn can prevent waste from accumulating around the bin [28].
To address the existing issues of waste management an automated waste management system based on the IoT was proposed. Sensor activated and internet-connected garbage bins were designed to collect information about fill level, location, and other information. Waste collectors were provided with optimized route schedule, bin locations, and waste status via a web or mobile app. This information helped them identify priority areas that might require urgent cleaning [29].
Previous studies have focused on waste collection efficiency, bin fill levels, methods for determining optimal routes, and how to notify the municipal authorities. However, they have not focused primarily on user convenience , such as ensuring container sizes are appropriate for all ages, providing adequate ventilation to prevent unpleasant Odors, using screens that display motivational and educational messages about the environment and the importance of keeping it clean, and providing containers with dim lighting at night to facilitate visibility.

2.7 Economic perspective

In recent years, the amount of solid waste in cities has been reported to be increasing due to the lack of proper waste management systems. All types of waste being disposed of in large quantities without any segregation. Governments around the world have been struggling with sustainable collection and treatment. Waste segregation and subsequent collection have been shown to increase the burden on authorities, preventing them from taking appropriate steps to recycle and treat waste.

According to a study conducted by the Planning Commission Task Force, out of 100%, approximately 52% of waste was classified as biodegradable and 32% as non-biodegradable. The proportion of recyclable waste such as plastic, paper, glass, was determined 16%. If this waste is collected conclusively, the biodegradable portion can be used for composting, and the recyclable products can be used to make new products. This has not only been reported to generate revenue for the government but has also been shown to reduce environmental pollution [30].

It was reported that from the amount of garbage collected daily, there is a potential of nearly 1,800 Kcal/Kg of energy could have been produced [31]. Previous studies have highlighted the many economic benefits of effective waste management, it has been suggested that waste can be harnessed to produce new products through recycling, energy generation and composting, which in turn reduces environmental pollution and provides revenue opportunities for government. In addition we have proposed incorporating a compacting mechanism into smart bins as innovation to enhance economic efficiency.

Compacting waste increases the bin's capacity without increasing its volume, reducing the frequency collection, this reduces labour and fuel consumption for collection vehicles. Furthermore, this approach not only reduces transportation cost but also extends the life of waste collection infrastructure.

2.8 Management Smart bin and Recycling

Smart city developments have focused heavily on smart bins as tools to improve waste management and recycling in cities. These bins help solve the problems of outdated waste systems by providing real- time monitoring, automated sorting, and a better recycling process.

Recycling enhancement is another critical focus of smart bin research. Smart bins are increasingly being designed with automated segregation features to separate biodegradable, recyclable, and non-recyclable waste at the source. One study proposed a prototype capable of real-time waste categorization, thereby improving recycling rates and reducing the burden on landfill sites [32]. In addition, the use of cloud computing and data analytics allows authorities to track recycling programs. Such systems also provide valuable insights into citizen

behaviour regarding recycling, which can guide policy decisions for sustainable urban planning [33].
Overall, the review concluded that smart insurance is an effective part of improving the logistics of collecting and recycling medical records. By combining the IoT with accounting, it is used to identify data, and these electronics contribute significantly to achieving economic goals and data management for waste.

2.9 Data-Driven Waste

Recent studies have shown that the adoption of data-driven waste management systems has become an important step towards achieving sustainable and efficient urban waste solutions.
Using IoT, wireless communications, and cloud analytics, these systems can automate waste bin monitoring, optimize collection routes, and encourage recycling practices.
For example, one study evaluated IoT-based sensor node designs and LoRa technology for solid waste management and found that LoRa technology provided reliable, low-power, and long-range communications. This not only extended battery life but also ensured smooth operation for large-scale city use [34].
In another case, a smart waste management system was developed that combined IOT sensors with artificial intelligence to handle the heavy demands during peak seasons. Ultrasonic gas sensors were used to measure the fullness of the cabinet, while gas sensors detected harmful substances, allowing for action after multiple people have been present [35].
These studies highlight how the transition from large smart communications to a city data set of adaptive, emerging, and larger resources is aimed at achieving sustainability.

2.10 Smart Cities and Infrastructure Requirements

Smart cities are growing rapidly, and digital technology is now at their core. The Internet of Things, artificial intelligence, and data systems connect everything to healthcare, transportation, energy, and even governance. By placing sensors and networks within the city itself, massive amounts of real-time data are being collected. This data enables cities to respond quickly and adapt, making management more agile and efficient.
Building a smart city is not only about physical structures. It also depends on digital connectivity, smooth system integration, and resilience. Managed platforms for the IoT are essential, as they save water and improve traffic flow efficiency [36].

Smart cities require neural networks and pipelines, and now digital domains require connectivity, compatibility, electronics, and flexibility. IoT technology will play a significant role in this, encompassing efficient tracking, traffic flow, and the management of vital resources such as energy. A key challenge is ensuring that these interconnected systems remain secure and reliable, particularly when deployed at large scale [37].
Cities are also moving toward so-called digital twins. Imagine them as virtual copies of real buildings, roads, or systems. Using these twins, planners can run simulations, test new mobility solutions, or predict how infrastructure will evolve before they are implemented. These twins combine IoT sensor data, 3D models, and real-time analytics to optimize choices in areas such as transportation, congestion, and energy consumption [38].
It can highlight the smart solutions needed for scalable and adaptable infrastructure. For example, advanced simulation tools enable optimizing public transportation routes, predicting traffic flows, and accessing performance data and information under different social and convenience choices. These will not only enhance access to justice but also contribute to achieving sustainable goals by measuring congestion, reducing emissions, and thus achieving fairness in services [39].

2.11 Related Works

Several studies, including Catarinucci, Ramson et al., recent studies in 2025, and Sossounova and Boras, focused on waste monitoring systems to improve waste collection efficiency. Catarinucci proposed a model in an innovative radio frequency identification (RFID) sensor equipped with low-cost weight sensors and a cloud-based software system capable of managing the collected data [19]. Similarly, Ramson et al. introduced a LoRaWAN IoT-enabled Trash Bin Level Monitoring System (IoT-TBLMS) using an ultrasonic sensor, a GPS module, LoRaWAN communication, and solar energy to monitor bin fill level and geolocation in real time [39]. More recent studies in 2025 proposed IoT-based systems that include an ultrasonic sensor, an infrared sensor, a hazard detection sensor, and three MQ gas sensors to detect harmful gases. The system is connected to a web-based dashboard and GSM-based SMS [40]. In addition, Sossounova and Boras (2022) conducted a systematic review of 173 preliminary studies on smart waste management systems powered by the IoT. They categorized the systems into city-level systems focused on data analytics, route optimization, and incentive models, and smart bin-level systems that rely on sensors such as ultrasonic, infrared, and RFID/NFC technology to detect and monitor bin fill levels. The review highlighted the importance of real-time notifications, improved waste collection routes, and citizen engagement through blockchain-based rewards [14]. However, the existing system focused on monitoring waste levels and lacked features such as automated waste segregation.

Some researchers, including Joel (2021) and a recent study In (2024) focused on improving waste segregation and automated sorting processes. Joel (2021) proposed an improved smart container design that includes automated lid control, color-coded containers, audible alerts, and real-time analytics via the ThingSpeak cloud platform. An alert is sent via SMS to the local municipality when a container overflows or the gas level reaches a certain threshold [20]. Similarly, a study in 2024 demonstrated the integration of AI with IoT technologies to automatically identify waste types such as glass, plastic, and metal. The system used ultrasonic sensors, GPS, and GSM technologies for bin geolocation [41]. However, the existing system did not rely on a conventional power source, lacked integrated management platforms, and had limited consideration of large-scale deployment cost and sustainability.

Some studies, including a study in (2024) and another smart waste management study, focused on efficient waste collection and communication technologies. A study in (2024) explored the use of LoRa technology to optimize waste collection routes by considering the total distance covered by collection trucks and distance distribution among individual trucks. The results were evaluated through numerical simulation, demonstrating the potential of LoRa-based communication in improving collection efficiency [42]. Another proposed smart waste management system integrates smart containers, a cloud server, a GSM unit management system/mobile platform, an online control and monitoring system, a location tracking system, a vehicle tracking system, and an online scheduling system [43]. However, the studies did not consider citizen participation and relied on multiple platforms rather than a unified management platform.

Several studies, including research published in India (2023) by M. Suresh Kumar et al., focused on sustainability and environmental considerations in waste management systems. Research published in India (2023) highlighted the impact of population growth and urbanization on increasing pollution and challenges in waste management. The study proposed IoT-based waste management involving sensors, transportation, and recycling processes. The study emphasized the problem of overflowing bins, which can lead to environmental and health hazards such as unpleasant odour and the spread of insects. It also discussed converting waste into electricity or fertilizer and enhancing sustainability [44]. Similarly, M. Suresh Kumar et al. proposed an intelligent waste management system that integrates hardware and software components. The system consists of an Arduino Uno microcontroller, ultrasonic sensors to monitor waste levels, an odour detector, and a GSM module for sending instant alerts via SMS. It incorporates solar power for a sustainable energy supply and an on-site organic waste decomposition unit. A dedicated mobile application was also developed to provide real-time notifications [45]. However, studies did not address features such as container sterilization and recycling.

2.12 Summary

The reviewed studies consistently emphasize the role of IoT, AI, and wireless communication in enhancing smart waste management. Most of the works focused on monitoring bin fill levels, sending real-time alerts, and optimizing waste collection routes. Several systems also integrated cloud platforms, GSM, and GPS for improved data management and location tracking, while some advanced models explored automated segregation of recyclable waste types. Overall, the literature agrees that these technologies improve operational efficiency, reduce overflow, and contribute to cleaner urban environments. Despite these advancements, recurring limitations appear across the studies.

Many systems remain restricted to monitoring and notifications without integrating comprehensive features such as Odor control and sanitation mechanisms. Few works have addressed renewable energy integration, cost-effectiveness, or scalability for large-scale deployment. In addition, waste compression and deeper recycling strategies are largely overlooked, and limited attention has been given to stakeholder integration within broader smart city infrastructures. These gaps highlight areas where existing solutions remain incomplete.

This research aims to address these shortcomings by developing a more comprehensive smart bin system that not only provides automated segregation and real-time remote management but also incorporates odour and sanitation control, solar energy integration, and cost-effective design. In addition, the proposed system will feature a mobile application to allow authorities to monitor bin status remotely, and a waste compression mechanism to reduce volume and improve recycling efficiency. By combining these features, the system seeks to deliver a sustainable, holistic solution to the persistent challenges identified in prior studies.

Chapter 3

Methodology

3.1Introduction

In this chapter, we focus on system design in both hardware and software. Our project aims to create a sustainable environment by enhancing waste management using IoT technology [46] and LoRaWAN (long-range, low-power wireless communication) for communication modules [47]. It covers the system design, networking, data management, and deployment setup. The chapter furnishes a step-by-step, detailed description of the project design and technologies used to develop it. It will also explain the overall system architecture and evaluation procedure.

3.2 Research Design

This research represents an experimental and simulation-based design to describe an IoT smart waste bin that is programmed to monitor and evaluate waste levels, detect hazards and harmful gases, segregation, which is the most important term in sustainability [48], and send data to the system cloud.

The project begins with problem identification; our problem is the inefficient waste collection system in Khartoum that affects environmental sustainability and the health system. After that, we will move to a literature review to understand existing smart waste collection systems and more sustainable technologies such as harmful gas detection, ventilation, and other additions will be explained in the following headings, using an ESP32 microcontroller and LoRaWAN technology.

Then, the system architecture will be designed to connect all the components logically and tested in the simulation phase to ensure accurate data transmission at every step. Finally, data analysis and evaluation will assess the performance of the system in energy efficiency, system effectiveness, and communication reliability. This research will provide a clear vision of the system's effectiveness, besides economic value, to applies to the city due to the efforts made by governments and environmental institutions, but the waste management system still has difficulties.[49]

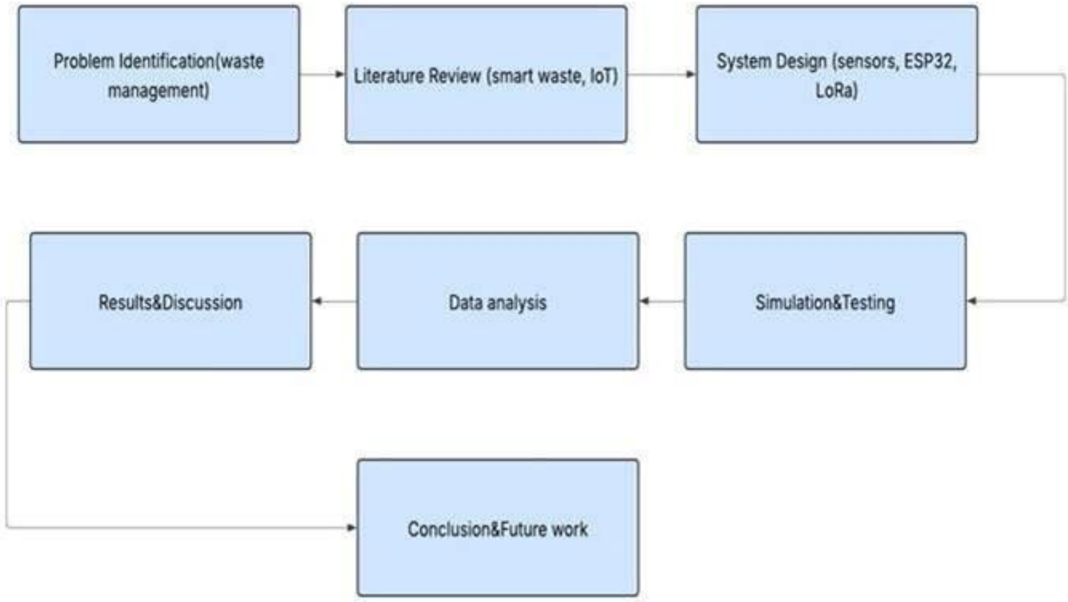


Figure 3.1 Research design

3.3 System Architecture Overview

The system architecture of the smart waste bin is designed to manage and control waste collection using IoT technology. The system architecture consisting of four main layers: sensing, processing, communication, and application.

Stage one: Sensing Layer

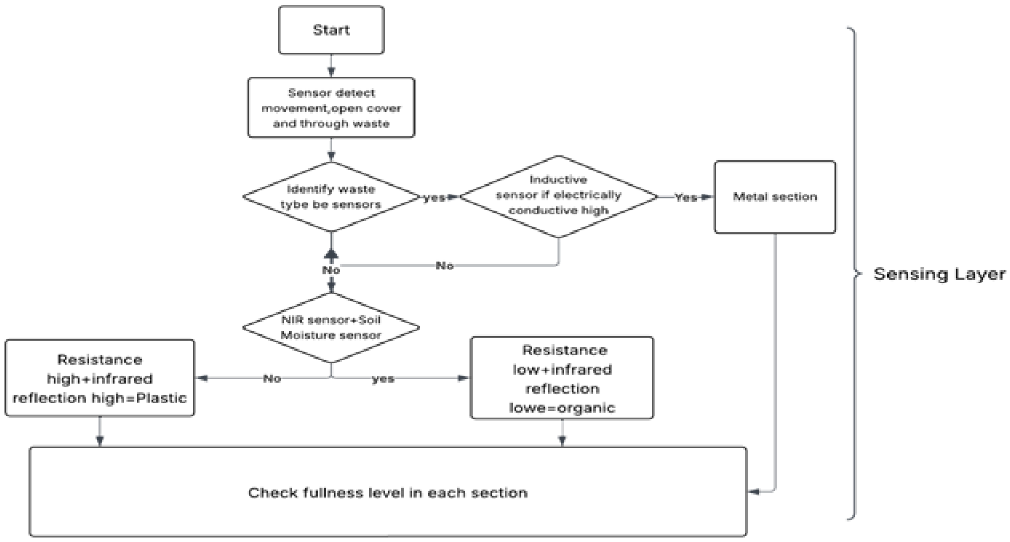


Figure 3.2 Sensing layer

The first and most important layer, this layer includes sensors inside the bin such as an inductive metal sensor, soil moisture sensor, gas sensor, NIR sensor, and other sensors grouped together to perform multiple tasks such as sensing waste level, segregation, detecting movement, and other tasks beside collect real-time data about waste conditions inside the bin. The process starts with the HC-SR04 sensor to detect movement and open the container door for the user to through wastes in the detection area; inside the detection area, three sensors are placed to detect waste type, inductive sensor to detect metal and direct it to the metal section. NIR and soil moisture sensors segregate plastic and organic waste to their sections (e.g., low resistance and low infrared reflection direct waste to the organic section). Load cell sensor S type senses containers' weight to measure fullness level in three sections.

Stage Two: Processing layer

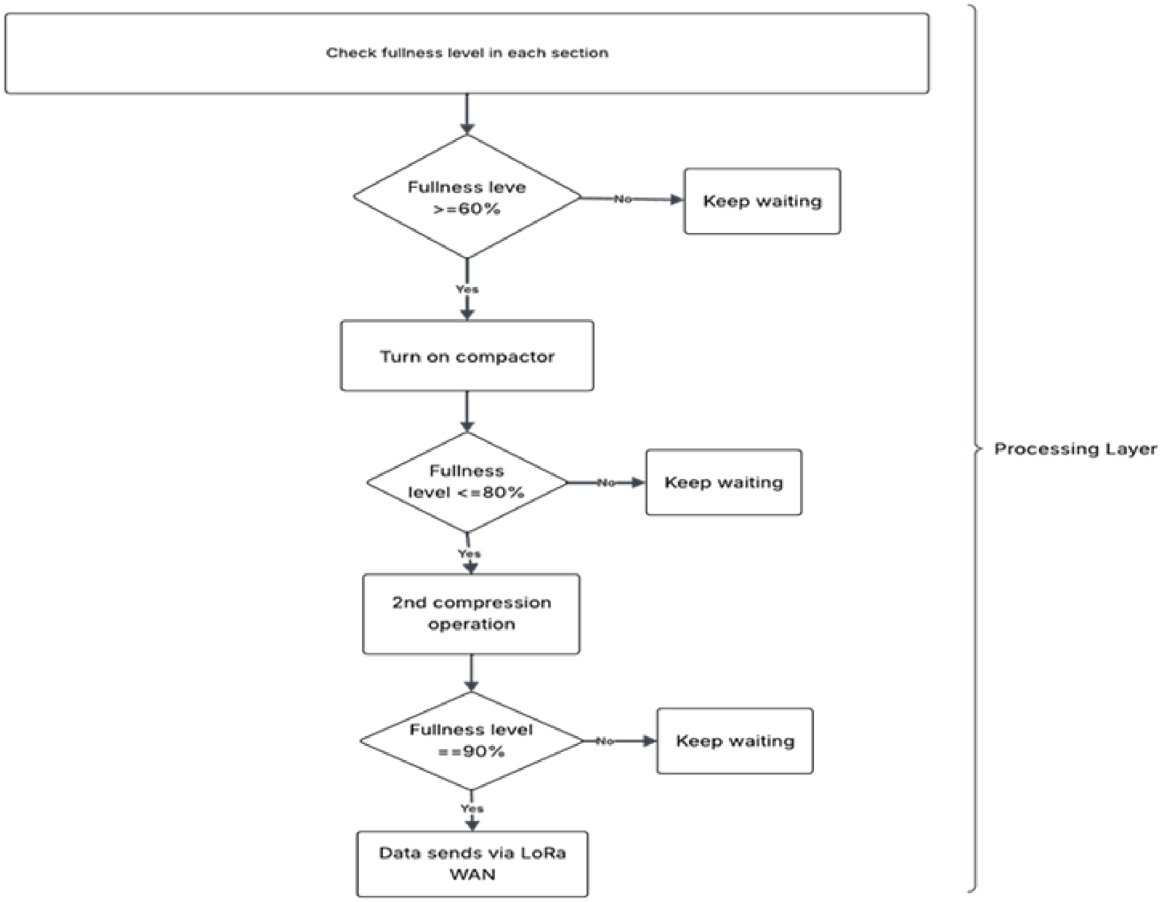


Figure 3.3 Processing layer

The TTGO T-Beam ESP-32 is our microcontroller and the processing unit; it collects data from the sensors, filters data, and takes the right actions (e.g., activate the compression unit in the metal and plastic sections when 60% full). Also, it collects data to transmit to the cloud via LoRa; simply, it is the heart of the bin and system.

Stage Three: Communication and Mobile application

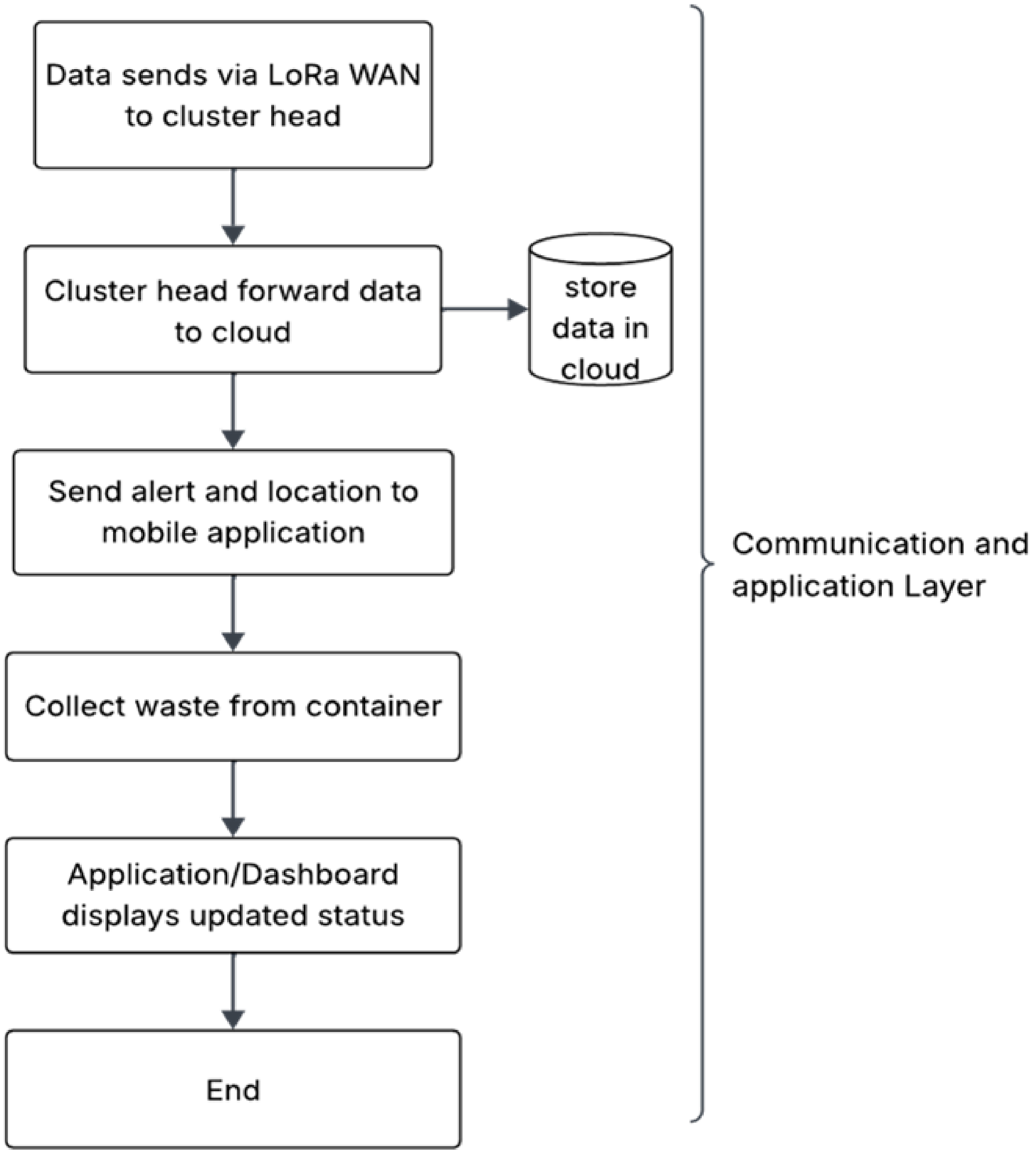


Figure 3.4: Communication and Mobile application

Our system uses a communication module to transmit data that contains LoRaWAN and cluster head methods to transmit processed data. It will ensure reliable data transfer to the smart bin and cloud platform. It includes a cloud and a user mobile application. The cloud stores collected data, while the mobile application provides bin fill levels, bin condition, hazards, and alerts. Also, when a bin is 100%, the application will provide the user with the data and location. Data is sent via LoRa to the cluster head to forward data to the cloud platform and store it. Alerts are sent with the container location to mobile applications to collect waste, and then the application/dashboard shows updated status and keeps monitoring. The system architecture ensures an efficient and automated waste management system to clear the urban environment, reduce the disadvantages of manual waste collection methods, and make the city more environmentally sustainable.

3.4 Software Design

Software design integrates embedded programming, cloud computing, and data visualization tools to enable real-time monitoring, efficient data transfer, and intelligent waste management decision-making. The system uses a modular software architecture, integrating sensor systems, communication protocols, and cloud integration to collect, process, and visualize data from distributed smart bins.

3.4.1 Embedded Programming

The embedded software was developed and simulated for the TTGO T-Beam microcontroller, which integrates an ESP32 processor, a LoRa SX1276 module, and a NEO-6M GPS receiver. The firmware controls sensor readings, data processing, and wireless communication between the smart Bins. Each smart bin is equipped with multiple sensors, including an S-type load cell (for waste weight measurement), an MQ-135 gas sensor (for air quality monitoring), a LIS3DH accelerometer (for motion and tilt detection), an NIR AS7265x spectrum sensor (for material classification), and a soil moisture sensor (for organic waste identification) [57].

The microcontroller reads the values from these sensors via analogue or digital interfaces; filters noise and compiles the data into JSON packets.

A local decision-making algorithm determines the waste classification and bin status. For example, if the ultrasonic sensor detects a fill level above 90%, the " bin Full " flag is set, triggering a LoRa transmission to the cluster head. Similarly, abnormal gas readings or bin tilt trigger event-based messages for real-time alerts [58].

The embedded firmware logic follows a periodic sampling cycle (e.g., every 10 minutes), supported by interrupt-based actions for critical events. Power is optimized through the ESP32's deep sleep modes, and data is queued for transmission via the LoRa SX1276 module using a low-power, long-range data frame [59].

3.4.2 Cloud Integration Using LoRa-WAN

The proposed smart waste bin system utilizes LoRa-WAN connectivity combined with a cluster-based cloud architecture, enabling efficient, reliable, and long-range data transmission. Each cluster head (node) operates using a TTGO T-Beam (ESP32) microcontroller, which i uh ncorporates an ESP32 processor, a LoRa SX1276 transceiver, and a NEO-6M GPS module in an integrated board.

This integration reduces wiring complexity, ensures stable connectivity, and provides support for Wi-Fi, Bluetooth, and battery charging, making it ideal for solar-powered outdoor smart waste bins [60].

Each node collects environmental data (such as waste level, air quality, and location) and transmits it wirelessly via LoRa to a dedicated cluster head (CH). The CH acts as a local gateway, combining data from multiple nearby bins forming a LoRa cluster—and transmits the collected information to a cloud server (Node-RED) over the internet.

Visualization Layer (Node-RED Dashboard)

The processed data is displayed on the Node-RED dashboard, providing an interactive and real-time monitoring interface for the waste management authority. Through this dashboard, users can visualize key parameters such as bin fill levels, gas concentrations, and the geographic locations of smart bins.

The dashboard also supports dynamic alerts and graphical indicators that notify operators when a bin approaches critical levels (e.g., over 90% fill), enabling timely waste collection and improving operational efficiency [62].

The LoRa-WAN architecture based on these datasets provides scalability and flexibility, with each cluster operating semi-autonomously with minimal power consumption. It also enables local analytics and decision-making without overloading the central cloud infrastructure [63].

Example of Cluster-Based Data Format


```
{
"Cluster_ID": "C-02",
"Gateway_ID": "GW_05",
"Nodes": [
{
"Bin_ID": "BIN_201",
"Waste_Level": 88,
"Gas_Value": 690,
"Waste_Type": "Organic",
```

"Latitude": 15.50894,
"Longitude": 32.54281,
"Timestamp": "2025-10-20T09:15:00Z"
},
{
"Bin_ID": "BIN_202",
"Waste_Level": 72,
"Gas_Value": 412,
"Waste_Type": "Plastic",
"Latitude": 15.50981,
"Longitude": 32.54137,
"Timestamp": "2025-10-20T09:15:00Z"
}
]
}

Explanation: The JSON data structure represents a single dataset containing multiple bins, each reporting sensor readings, coordinates, and timestamps. The cluster Head uploads these buckets to the Node-RED cloud for analysis and visualization.

3.4.3Web Application Interface

The system includes a responsive web dashboard that enables users, especially waste management agencies, to monitor all bins and collections in real time.

The interface is designed using the Node-RED dashboard user interface, integrated via MQTT subscriptions. Each bin is visually displayed with indicators for Percentage full level (using colour codes: green, yellow, red), gas quality index (from MQ-135 readings), GPS location plotted on a live map and Operational status (active, offline, full, maintenance).

Users can access historical records, receive real-time notifications (such as "Bin 12 is full" or "Abnormal gas detected"), and track waste collection routes. The system design also allows for future expansion to include a mobile application that supports instant push notifications, using the same MQTT-based data channels for synchronization [64].

This interface ensures improved decision-making, faster response times, and optimized waste collection scheduling.

The dashboard's modular design allows authorized personnel, such as municipal operators and technicians, to access specific information relevant to their responsibilities. The integration of time series data storage supports the analysis of current and historical trends, improving operational planning and decision-making [65].

3.5 Network and Communication Protocols

The proposed Smart Waste Management System employs LoRa (long Range) technology integrated with TTGO T-Beam microcontroller, LoRaWAN has wireless communications system allowing long-range.

low-power and low-throughput communications and it provides a medium access control mechanism, enabling many end devices to communicate with a gateway using the LoRa modulation. [66]

According to standard LoRaWAN Class A specifications the system operates using spreading factor 10 (SF10), and 125kHz bandwidth for 868 MHz frequency, 4/5 coding rate and Qos level 1 to ensure the lowest power consumption.[67]

The power consumption for a single packet transmission is approximately 0.24 J for 608.2 mS end to end latency. These parameters are selected to balance between communication range and energy efficiency to enhance transmission reliability while maintaining efficient data throughput.

The parameters and classification of operative operation thresholds of the proposed smart waste bin were set in terms of empirical results of simulation and practice that were widely used in the system of environmental monitoring and smart waste management.

The TTGO T-Beam (ESP32) was chosen as the main microcontroller because it integrates multiple essential components (ESP32 processor, LoRa SX1276 module, and GPS (NEO-6M) into one compact board.

This reduces wiring complexity and ensures stable communication between bins and the cluster head through LoRa, it also supports Wi-Fi, Bluetooth, and battery charging, making it ideal for solar-powered outdoor smart bin systems. Each bin (node) collects real-time environmental data through sensors and transmits it via LoRa to a Cluster Head, which acts as a local gateway.

The Cluster Head aggregates and forwards the data to a cloud-based Network Server (Node-RED) through an Internet connection. The data is then processed and transferred via the MQTT protocol to a Dashboard for real-time monitoring and decision-making.

Although the simulation assumes the existence of a functional LoRaWAN infrastructure, local deployment may require coordination with telecommunication authorities to establish LoRa gateways.

Alternatively, a private LoRa network can be implemented for pilot testing, where cluster heads function as localized gateways to support short-range communication. This architecture provides an energy-efficient, scalable, and reliable communication framework for smart waste management in urban environments.

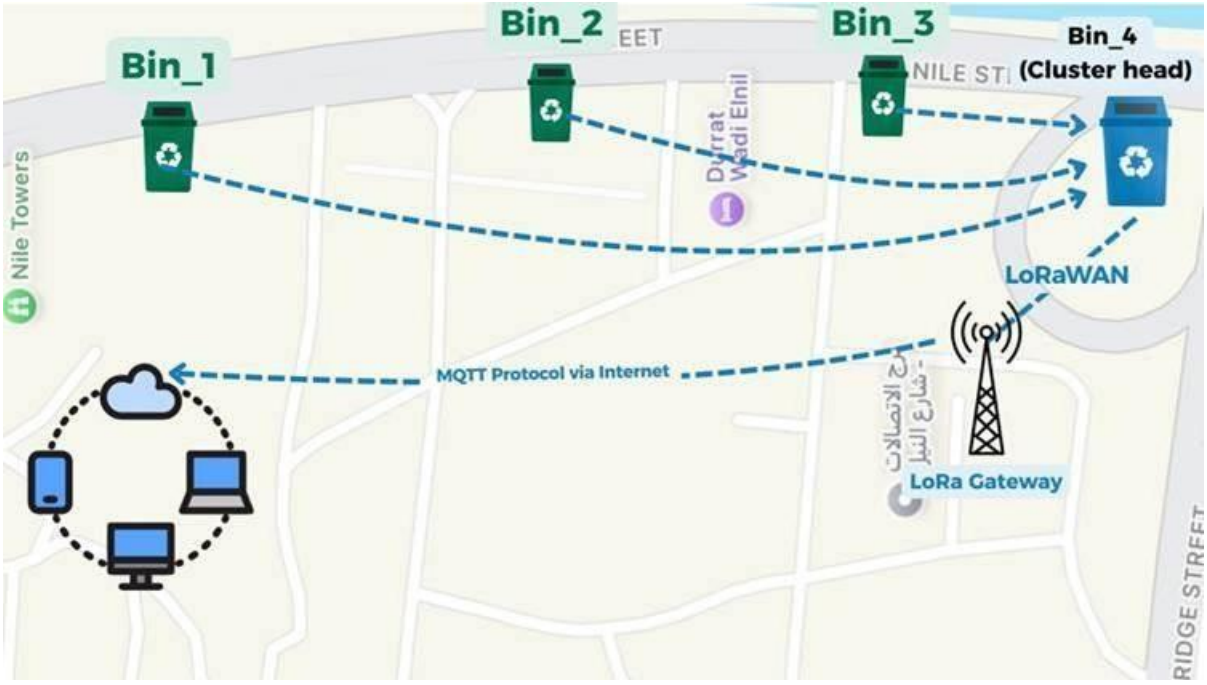


Figure 3.5: Layout of Clustered Smart Bins and Local Gateway Distribution along Nile Street.

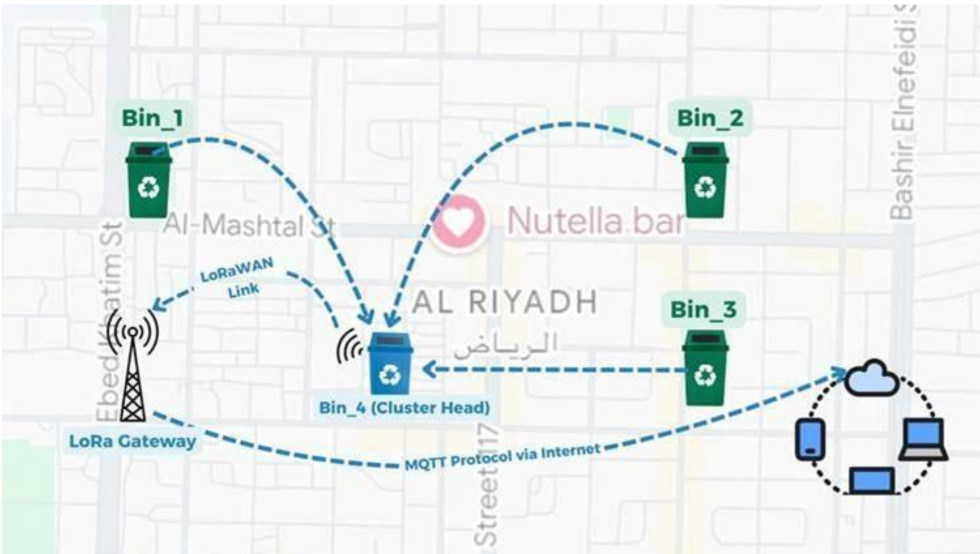


Figure 3.6: Layout of Clustered Smart Bins and Local Gateway Distribution along AL Riyadh Street.

3.5.1 Data Transmission Flow

In the proposed system, each smart bin node equipped with sensors for waste level, gas detection, and location tracking collects environmental data through the TTGO T-Beam microcontroller.

Each cluster of bins operates under a designated Cluster Head (CH), which functions as a local gateway within the LoRaWAN network architecture, the CH collects and aggregates the sensor data from all bins in JSON format via LoRa communication (approximately 300–800 meters).

The Cluster Head then transmits the aggregated data over the LoRaWAN channel to the nearest public or private LoRa gateway, which forwards the data to the cloud-based Network Server (Node-RED) for processing.

The Node-RED server acts as the Network Server, receiving the data, processing it, and forwarding it to the HiveMQ Cloud MQTT Broker, where they are subscribed and visualized on the dashboard where the waste management authority can monitor bin status, track fill levels, and receive alerts when a bin approaches its maximum capacity (e.g., 90% full).

This allows for real-time monitoring and decision-making while optimizing communication efficiency across the network. Also, this system is designed to integrate with a mobile application for real-time monitoring and notifications, but the current simulation phase employs a web-based dashboard to visualize data and system alerts.

This approach demonstrates the functionality and communication flow of the system without the need for a fully developed mobile application.

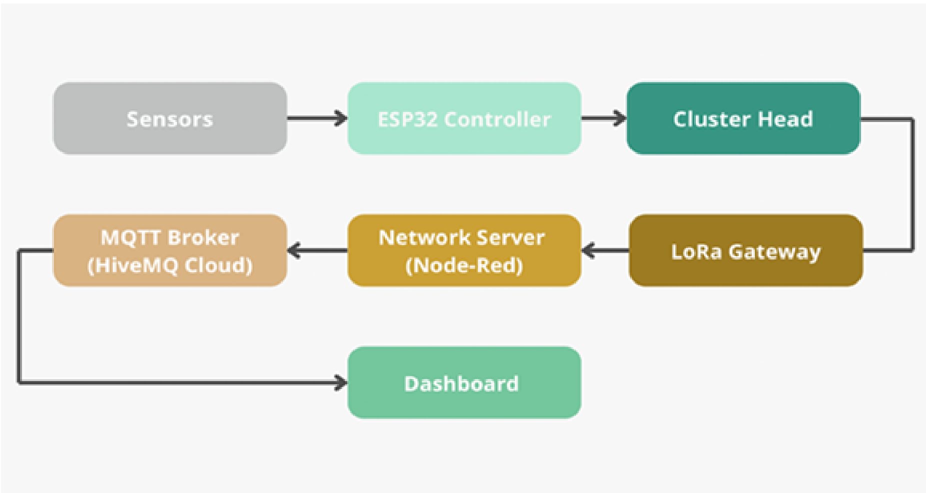


Figure 3.7: Data Transmission Flow of the Smart Waste Bin Network.

3.5.2 MQTT/HTTP Protocols

In this study, a Smart Waste Management System employs the MQTT (Message Queuing Telemetry Transport) protocol as the primary communication protocol between the IoT devices, cloud infrastructure, and web dashboard.

MQTT was chosen for its lightweight structure, low bandwidth consumption, and efficient publish/subscribe messaging model, which make it particularly suitable for IoT applications operating under constrained network conditions. [68]

Also in this system, each Cluster Head acts as an MQTT client that publishes real-time sensor data - aggregated from multiple bins- to specific topics hosted on the HiveMQ Cloud MQTT Broker.

The HiveMQ Broker serves as the central intermediary responsible for managing and routing messages between the Cluster Head, the Network Server (Node-RED), and the Dashboard.

Through the broker, messages are securely transmitted to the web-based dashboard, where authorized users can subscribe to specific topics to visualize data, monitor bin status, and receive alerts when waste levels reach predefined thresholds. The communication process relies on the publish/subscribe mechanism, which ensures minimal delay and reliable delivery even with intermittent network connectivity.

Although HTTP could be used as an alternative for data transmission, MQTT was selected due to its superior performance in IoT environments, particularly in terms of reduced latency, lower overhead, and higher energy efficiency. This makes MQTT more suitable for smart city applications where multiple devices transmit small packets of sensor data frequently and require near real-time updates.

3.5.3 Security Considerations

To ensure data integrity and privacy within the smart waste management system, several security measures are implemented at different stages of data transmission. Each TTGO T-Beam-based node (smart bin or cluster head) is assigned a unique identifier (DevEUI) that enables device authentication before transmitting data. [69]

During communication, the MQTT protocol operates through Transport Layer Security (TLS) encryption which works as secure communication channel through a standard handshake process that assures authentication and key exchange between devices, ensuring encrypted and reliable data transmission. [70]

The connection between HiveMQ Cloud broker, and the Node-RED server remains secure through Transport Layer Security (TLS) encryption and protected from unauthorized access.

Access to the MQTT broker is restricted using authenticated credentials (username and password), while the web dashboard is protected through a secure login system that prevents unauthorized users from viewing or modifying data.

Additionally, all data transactions and alerts are logged for monitoring and diagnostic purposes. Regular data backups are also performed to prevent data loss in case of system failure. These combined security layers enhance the reliability and robustness of the system, ensuring safe and continuous communication between distributed smart bins, the cloud platform, and the monitoring interface.

3.6 Data Collection and Processing

3.6.1Sensors Data Acquisition

The data acquisition process involves collecting sensor readings from multiple modules, each sensor in the system generates specific data that reflect different environmental and operational parameters. Combining sensor-node data acquisition with IoT communications and intelligent routing enables an efficient smart waste management solution that aligns with recent IoT smart-bin framework. [71]

The ultrasonic sensor HC SR04 works by detecting the distance between the bin lid and objects that are coming towards it and gives a digital signal to the microcontroller to automatically open the lid by the servo motor. An S-type load cell sensor determines the internal waste level based on the bin mass and provides an analogue differential voltage output proportional to the applied load, which is digitized by the HX711 24-bit ADC module before being processed by the ESP-32. The MQ135 gas sensor is an automatic monitoring of the number of harmful gases in the air to recognize any danger of health risk like ammonia NH_3 and carbon dioxide CO_2, it outputs analogue voltage proportional to gas concentration (ppm), which is read by the ESP32's ADC pin.

In segregation, an inductive sensor detects whether a material is a conductor of electricity or not and gives a digital signal to the ESP-32(TTGO). The AS7565X sensor is used to separate metal from plastic by measuring the rate of absorption and reflection of radiation from an object; it provides analogue reflectance data to the microcontroller. Since humidity may affect reflectance, especially when dark or wet plastics are misclassified as organic waste, a soil moisture sensor is also integrated, this sensor provides analogue readings, where high humidity values (1800) indicate organic waste, and low values represent plastic.

To provide security the 3-axis accelerometer (LIS3DH) was integrated to detect abnormal movement or tilt of the bin and provide digital data representing motion in x, y, and z directions (in g-force). To allow tracking and ensuring maintenance, The NEO-6 GPS module gives the position of the bin in geographical coordinates transmitted over the UART (serial communication) interface in text format called NMEA sentences to give digital data. **Table 1** provides a clear summary.

The collected data are held in the TTGO T-Beam memory for processing and threshold evaluation and organized in the form of a JSON to be transmitted. Parameters contained in each of these data packets are bin ID, fill level, gas concentration, GPS coordinates. This architecture is consistent with previous systems of smart bin networks based on LoRa and MQTT-based low-energy, long-range communication between distributed nodes and central dashboards. [72]

3.6.2 Threshold Settings and Alerts

Automated responses and thresholds have been specified and set up in the ESP-32 firmware. The operational logic and threshold values applied are as follows:

- Proximity / Lid control**:** When HC-SR04 proximity ≤**15** cm, a lid-open signal is sent to the servo motor to permit user disposal.

- Compression activation / Full-level alert:

The waste compaction process is carried out by DC Linear electric actuator in two stages to reduce the occupied space, according to the measurement of the S-type load cell, for a compartment volume of 0.06 m^3(0.5×0.3×0.4 m), and assuming an initial bulk density of 150 kg/m^3, the full mass is estimated at 9.0 kg. Threshold masses were defined as follows: compression for the first time at **5.4 — 6.0** kg **(**60%), compression for the second time at **7.2 —7.7** kg (80%), and a ''Bin full'' alarm at ≤**8.1** kg (90%) is generated and reported to the maintenance application. Mass is read via an HX711 amplifier and converted to kilograms after calibration; a stability requirement (3 consecutive samples) is applied before any automated action is taken.

- Gas sensor MQ135: When the MQ-135 sensor indicates a reading between **250-400** (relative unit/ppm proxy), the axial BLDC fan will activate for **2 minutes** to reduce accumulated gases and odor. For reading **> 400** a ''Toxic Gas'' alarm is triggered, constant ventilation (fan on) is sustained, and an alert message is sent to the maintenance staff immediately.

- Sterilization: When the HC SR04 sensor opens the gate **30 times**, the UV-C LED turns on for **15 seconds** and the ultrasonic sensor stops taking readings during the sterilization process.

- Material classification (NIR AS7565x): Based on reflectance and absorption ratios, when the ratio exceeds **1.2**, the material is classified as plastic, otherwise **≤ 1.2** It is classified as organic.

- Humidity check: For assisting in the correction of NIR misclassifications due to moisture, when the humidity sensor detects values > **550** (analogue reference unit) the waste is confirmed as organic, while lower readings indicate as plastic.

- Metal detection: The inductive sensor provides a digital output; when a logical **1** signal is received, the object is identified as metallic and the metal bin is opened.

- Movement / Vibration alarm (LIS3DH accelerometer): For security and maintenance tracking, when acceleration exceeds ±**3g,** a "Movement alarm" is activated and an alert message is sent to the maintenance staff.

Table 3.1: Sensor parameters, Thresholds, and Automated Responses

Automated response	**Threshold\ reference value**	**Data type**	**Measured parameter(s)**	**Sensor\ module**
Lid opens automatically via servo motor	15cm	Digital (trigger\ echo)	Distance to approaching user	HC-SR04 (Proximity)
-Activates the DC Linear compressor at 60% and 80% -Sends "bin full" alert at 90%	60%(5.4 kg), 80%(7.2 kg) Compression ON 90%(8.1kg) Full level alert	Analog (converted to digital)	Weight (kg)	S-type load cell (Fill- Level)
-Fan activates for 2 min -"Toxic gas" alert +continuous ventilation	400-250 ppm Fan ON 400 ppm Toxic gas alarm	Analog (ppm proxy)	Gas concentration\air quality	MQ-135 (gas sensor)
Direct waste to corresponding bin	(1.2) Organic (1.2) Plastic	Analog (ADC values)	Reflectance ratio	NIR AS7565x
open organic bin flap	(1800) Organic	Analog	Relative humidity\ moisture content	Soil moisture sensor
Opens metal bin flap	(Logic'1') Metalic	Digital (0\1)	Metal detection	Inductive sensor
Logs Movement\ Displacement; trigger "movement alarm" alert	3g	digital (I2C output)	Acceleration along x,y,z axes	LIS3DH (Accelerometer)
Transmits bin location to server for tracking	–	digital (NMEA data)	Geographics coordinates	NEO-6 GPS Module

UV sterilization ON for 10 seconds	Open count 30	–	–	UV-C LED

3.7 Simulation and Analytic tools

The system was designed and tested on the Wokwi simulation environment to simulate the behaviour of a real-world system and test the logic of the smart bin without physical hardware. Wokwi is a web-based simulation platform, which allows users to design and simulate Arduino-based and ESP-based systems without hardware, it can simulate an interactive interface for wiring components, provides code execution and real-time sensor data visualization, the environment supports IoT testing by allowing interactions with cloud services, e.g. MQTT and HTTP services, thus, a low cost, accessible way to prototype, debug, and test embedded systems [73].
For remote visualization and data analytics, the ESP32 was interfaced with ThingSpeak through Wi-Fi communication, Thing speak is a cloud platform and API for storing and retrieving data from hardware and performing visualization and analysis [37].

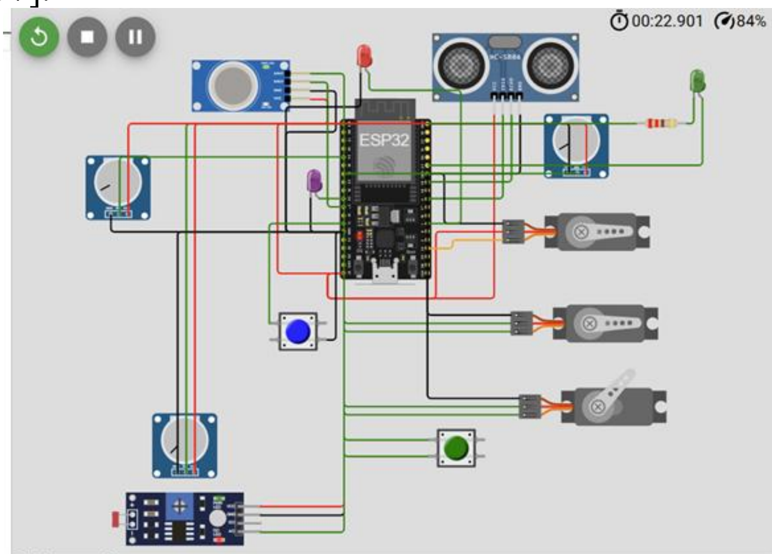


Figure 3.8: Wokwi Hardware Simulation.

3.7.1 Prototype Layout:

This part represents a prototype layout for a smart waste bin.

Table 3.2: Components description and location

Components	**Location in the bin**	**Function/Role**	**Notes**
TTGOT-Beam microcontroller	Right side inside container	Control system	Use IP65

Servo motor	Outside	Open container cover	-
HC-SR04 sensor	Outside	Detect movement to open the cover	-
Solar panel	Outside on top	Power supply	-
LiFePO4	Outside	Battery	Connect with solar panel
MPPT	Outside near battery	Voltage regulator	Use fuse
LED IP67 strip	On cover	Lights up container	-
LIS3DH Sensor	Outside	Detect free fall, motion or vibration	-
S-type load cell Sensor	Inside under small containers	Determine waste level by measuring waste weight	Use Amplifier
Inductive sensor	Detection area inside container	Detect change in magnetic field	-
Soil moisture sensor	Middle of Detection area	Measure water content	Put In point that can touch waste
NIR sensor	Detection area	Sorting plastic and organic based on reflection	-
Servo motor	Top of detection area	Waste distribution	With sorting arm
Carbon filter	Inside container left side	Remove harmful gases and Oduors	-
UV-C275	Inside container left side	sterilization	Use timer
BLDC fan	Inside container left side	Extract air inside	-
MQ-135 sensor	Inside container left side	Detect harmful gases	-
Linear actuator L44	Fixed inside cover	Plastic compression	-
Linear actuator L77	Fixed inside cover	Metal compression	-
DC motor	Near actuators	operation	-

Electrical Connections and Layout Notes

The Electrical connection in the smart bin is designed to ensure stable signal transmission. Sensors interface with the TTGO T-Beam (microcontroller), while load cell sensor needs an amplifier to the signal before transmitting it to microcontroller. The servo motor interface through PWM signal for better control. Power distribution to the components through MPPT (voltage regulator) to ensure that every component have the appropriate voltage level and prevents damages. Sensors positions must be in suitable distance to minimize interface and enhance accuracy. Bin design confirms ease of maintenance and ensuring accessibility to main components. Wiring layout must prevent tangling and electrical noise to improve overall system reliability and efficiency.

Figure 3.9: Prototype Layout of the Smart Bin.

3.7.2 Test Environment

The testing and validation of the proposed smart waste management system were carried out using a virtual simulation environment using Wokwi and Node-Red; to emulate real-world behaviour.

The Wokwi IoT simulator was selected due to its flexibility in simulating embedded systems and supporting diverse components, thus allowing real-time debugging of ESP32 firmware without requiring physical hardware. For data transmission and system networking, the TTGO T-Beam (ESP32 with LoRa network) was utilized as the microcontroller node, interfaced with simulated sensors via MQTT broker emulation using Node-Red. This setup supported real-time data transmission between sensor inputs and cloud dashboard visualization.

The test scenarios involved several operational conditions aimed at testing the functionality of the proposed smart waste bin system. The changes in the waste levels were emulated to activate the compression mechanism and full-bin alert features. The conditions of gas emission were recreated to confirm the toxic gas alert and ventilation control activation by the MQ-135 sensor. The auto lid system was experimented on the proximity detection with HC-SR04 sensor. Further, the classification sensors such as the NIR and inductive sensors were also tested to be accurate in identifying and sorting the material. Lastly, the transmission of data and communication across the system were tested by integrating the MQTT protocols and real-time observation on the Node-RED dashboard.

Since the mechanical components (linear actuator\BLCD fan) were not available to simulate the waste compaction mechanism. The actuator was triggered through digital output logic (LED) corresponding to the fill-level thresholds defined in the ESP-32 firmware. The BLCD exhaust fan and UV-C led sterilization module were integrated as output components to simulate ventilation and disinfection processes. The fan activation was controlled by the MQ-135 gas reading, while the UV-C module was configured to operate only when the bin lid closed completely, ensuring safety conditions.

Furthermore, the mechanical operation of the compaction process was explained separately by a different schematic motion diagram, which provides a conceptual view of waste compression that complements the digital simulation.

To simulate the smart waste bin behaviour, all the hardware elements were modelled in Wokwi in a virtual way. The unsupported sensors were replaced with functional equivalents to maintain logical behaviour. The LIS3DH 3-axis accelerator, which is used to sense the movement of a bin or external vibration, was modelled using variable analogue inputs simulating movement of the X, Y and Z axis (±3 g range). Any alteration of the axis more than a predetermined threshold sounded an alert to check that the system was responsive to motion disturbances. In the same manner, the inductive proximity sensor which senses metallic materials was modelled as a digital input (push button). As the input signal switched to HIGH the system began to interpret it as the detection of a conductive metallic object and so turned on the sorting mechanism of the metallic compartment.

Table 3.3: Actual Components and Their Simulation Equivalents

Virtual Representation	**Actual Component in the Project**
ESP32 Dev Board	TTGO T-Beam (ESP32)
HC-SR04 Ultrasonic	HC-SR04 Ultrasonic
MQ-2 Gas Sensor	MQ-135 Gas Sensor
LED (Purple)	UV-C LED

Servo Motor	Servo Motor
LED	Linear actuator / Compressor
LED/Servo motor	BLDC fan
Button/Analog values	LIS3DH
Analog pin input/ potentiometer	Soil Moisture Sensor
Potentiometer	S-Type Load Cell
LDR Sensor	NIR Sensor
Push Button	Inductive Metal Detector

3.7.3 Limitations

In this proposed smart waste bin system, which integrates IoT technologies such as ESP32/TTGO, LoRa communication, and solar power to enhance waste management efficiency, there are several limitations during the design and simulation process.

The absence of an active LoRaWAN network in Sudan restricted the real-world testing. Although the communication was modelled virtually, actual implementation would require regulatory approval and installation of LoRa gateways.

Furthermore, the simulation could not fully reflect real environmental conditions such as the electrical noise and interference, network delay, weather conditions, lack of real user interaction, cybersecurity considerations, or solar power variations.

The system reliance on solar energy and stored battery power means that its Performance may vary depending on sunlight availability, cloudy weather, or dust accumulation on the solar panels. Many sensors require regular calibration to maintain accuracy over time. The load cell (S-type) in particular needs frequent recalibration due to drift caused by continuous mechanical stress and temperature variation.

Such limitations serve as potential points for improvement and future development, including the incorporation of real LoRaWAN network, the implementation of advanced calibration algorithms, and extended field testing under divers environmental conditions.

3.9 Summary

This chapter provided the general methodology used in designing and simulation of the proposed IOT-based smart waste bin system, it outlined the research design, system architecture, and functional layers that combine sensing, processing, communication, and application layers.

The microcontroller (TTGO T-beam (ESP32)) was used as the main component that gathered data via various sensors, such as ultrasonic, load cell, gas, NIR, inductive, and soil moisture sensors and processed such data based on specific threshold values to enable operations to be automated, e.g. waste segregation, compression, ventilation, and sterilization. It was designed with the software architecture which provides LoRaWAN communication and MQTT protocol to provide reliable and low- powered data transmission, and the network and hardware environment were simulated using the Node-RED and Wokwi.

The prototype layout and deployment configuration was to be established to mirror the practice implementation actions with a focus on modularity, scalability and sustainability with integration of solar power.

Chapter 4

Simulation Results

4.1 Introduction

This chapter presents the results of a Network Layer Simulation (NLT) for a smart waste management and sorting system. Unlike machine learning models, this simulation relies on live data streams from sensors via MQTT. The Wokwi simulation environment is used to represent the sensors and servos, while the Node-RED environment handles message processing and data graphing. ThingSpeak is used to store and analyze time-series data.

Data from virtual sensors (such as gas sensors, waste weight sensors, sorting sensors, and lid opening sensors) is streamed as regular JSON messages sent via MQTT to Node-RED, where it is processed, monitored, and alerts are generated. A copy of the sensor data is also uploaded to the ThingSpeak platform to analyze time trends, generate live charts, and compare performance across different time periods.

This chapter aims to demonstrate the data transmission and processing format within the network, The system's behavior during normal operation, Network performance under stress and failure scenarios, Real-world operational examples (Case Studies), Comparing system performance with similar systems.

In this way, the chapter provides a comprehensive picture of network layer effectiveness, connectivity reliability, and real-time system responsiveness.

4.2.1 IoT Data Upload Mechanism via ThingSpeak

After logging in, a channel is created, and a field is defined for each type of data to be collected. The channel ID and API key are used to ensure that the data is sent to only one channel. Wokwi platform is connected to ThingSpeak using previous data, and the ThingSpeak and Wi-Fi Libraries, Wi-Fi code was also included.

```
#include <ESP32Servo.h>
#include <WiFi.h>
#include <ThingSpeak.h>

// WiFi & ThingSpeak Config

const char* ssid = "Wokwi-GUEST";
const char* password = "";

unsigned long channelID = 3177252;
const char* writeAPIKey = "QTEQE5QI9F4IEM4D";

WiFiClient client;
```

Figure 4.2.1.1: Wi-Fi and ThingSpeak libraries, channel ID and API key.

```
void connectWiFi() {
  Serial.println("Connecting to WiFi...");
  WiFi.mode(WIFI_STA);
  WiFi.begin(ssid, password);
  int tries = 0;
  while (WiFi.status() != WL_CONNECTED && tries < 20) {
    Serial.print(".");
    delay(500);
    tries++;
  }
  Serial.println(WiFi.status() == WL_CONNECTED ? "\n✓ WiFi Connected!" : "\n✗ Failed to connect!");
}
```

Figure 4.2.1.2: Wi-Fi connection.

The sensor values and system state variables are put in specific fields which are indicative of major operating factors including bin weight, compressor status, compression stages, bin-full notification, material detection signals, and the classification output.

```
void uploadToThingSpeak() {
    ThingSpeak.setField(1, ts_weight);
    ThingSpeak.setField(2, ts_compressor);
    ThingSpeak.setField(3, ts_stage);
    ThingSpeak.setField(4, ts_fullBin);

    ThingSpeak.setField(5, ts_metal);      // Metal input
    ThingSpeak.setField(6, ts_plastic);    // Plastic input
    ThingSpeak.setField(7, ts_organic);    // Organic input
    ThingSpeak.setField(8, ts_sortResult); // Sorting Output

    int response = ThingSpeak.writeFields(channelID, writeAPIKey);

    if (response == 200)
      Serial.println("✓ ThingSpeak Updated");
    else
      Serial.println("✗ Update Failed: " + String(response));
}
```

Figure 4.2.1.3: Create a link to send data to ThingSpeak using Field.

The data is written using Arduino code. During connection, the appropriate function is selected based on the sensor reading. If the sensor is digital, use digital

Read () function that returns 0 or 1 is chosen. If it is analog, use analog Read () function that returns a value 0-1023 representing the signal level selected. The field values are sent to ThingSpeak via HTTP protocol, and the transmission duration can be controlled, for example every 20\15 second, the data is uploaded to ThingSpeak.

```
currentMetal = digitalRead(BTN_METAL);
int ldrValue = analogRead(LDR_PIN);
currentOrganic = analogRead(POT_ORG);
currentPlastic = (ldrValue <= 1488) ? 1 : 0;
ts_metal = currentMetal;
ts_plastic = currentPlastic;
ts_organic = currentOrganic;
```

Figure 4.2.1.4: Reading digital and analog sensor values.

```
// ------------------ Upload to ThingSpeak ------------------
if (millis() - lastUploadTime >= uploadInterval) {
  if (WiFi.status() != WL_CONNECTED) connectWiFi();
  uploadToThingSpeak();
  lastUploadTime = millis();
}

delay(500);
}
```

Figure 4.2.1.5: transmission duration.

4.2.2 Node-Red Environment:

Node-Red is used to simulate the network layer. The simulation flow consists of many interconnected nodes each performing and processing specific task.

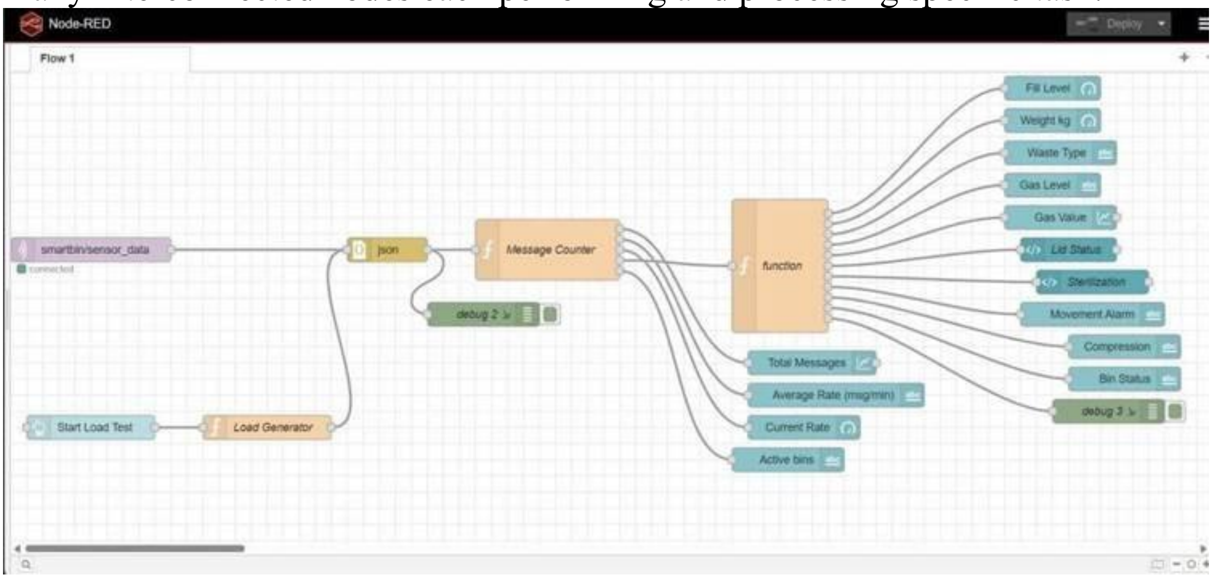


Figure 4.2.2.1: Node-Red environment.

MQTT IN is the link between node red and wokwi with MQTT broker by subscribing to common topic and therefore receiving directly all the sensors updates from ESP32.

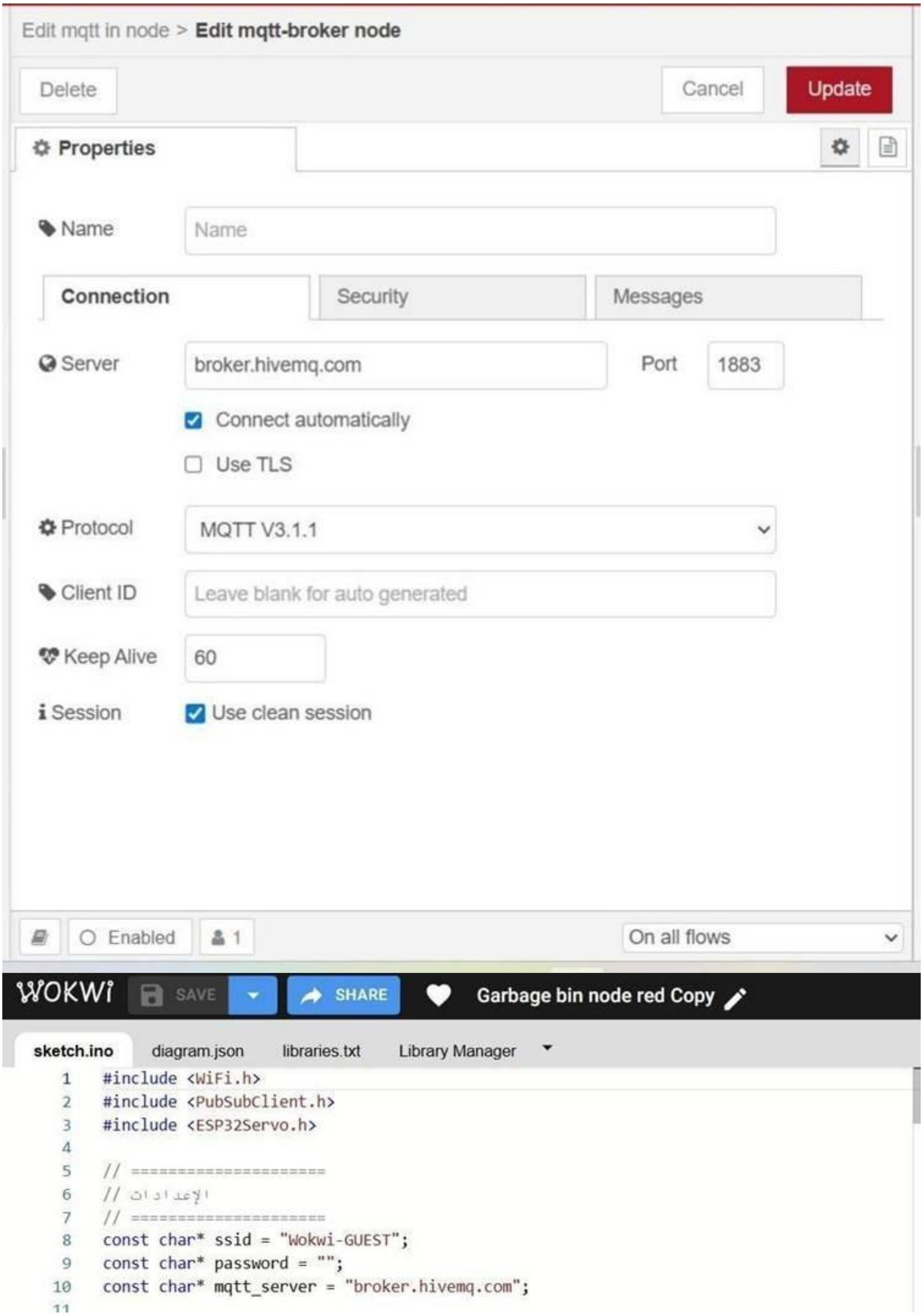
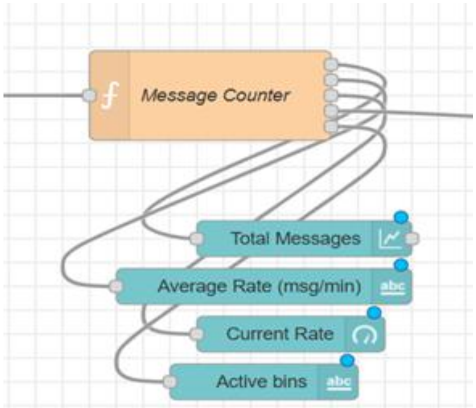


Figure 4.2.2.2: illustrates connection between wokwi and node red.

JSON node converted the incoming string payload to Java Script Object Nation. It’s made easy dealing with data in the function nodes.

Node-Red workflow has two function nodes first one is the general one that displays sensor values in dashboard and charts, second node is for messages and shows sending rates between wokwi and node-red by MQTT. Message counter node generates average messages in minutes and shows how system response to changes in sensors and values.

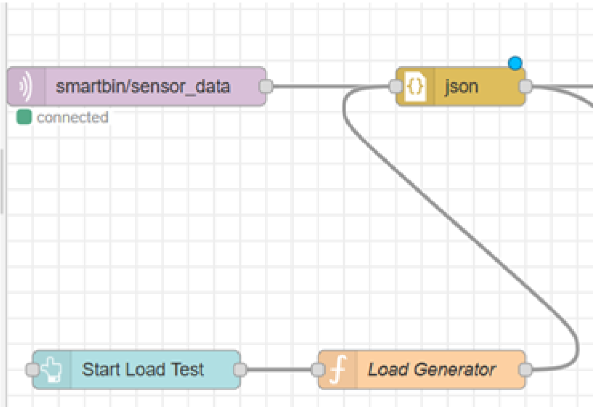



```
var messageCount = context.get('messageCount') || 0;
var startTime = context.get('startTime') || Date.now();
var lastMinuteCount = context.get('lastMinuteCount') || 0;
var lastMinuteTime = context.get('lastMinuteTime') || Date.now();
// device tracking
var devices = context.get('devices') || {};
var binId = "unknown";
//bin message
if (msg.payload && msg.payload.bin_id) {
    binId = msg.payload.bin_id;
}
//update texts number
if (!devices[binId]) {
    devices[binId] = 0;
}
devices[binId]++;
context.set("devices", devices);
//bins number
var activeBins = Object.keys(devices).length;
// update
messageCount++;
context.set("messageCount", messageCount);
// calculating elapsed time
var currentTime = Date.now();
var elapsedMinutes = (currentTime - startTime) / 60000;
// message per minute
var avgRate = 0;
if (elapsedMinutes > 0) {
    avgRate = messageCount / elapsedMinutes;
}
// last minute rate
if ((currentTime - lastMinuteTime) >= 60000) {
    lastMinuteCount = messageCount;
    lastMinuteTime = currentTime;
    context.set("lastMinuteCount", lastMinuteCount);
    context.set("lastMinuteTime", lastMinuteTime);
}
var currentRate = messageCount - lastMinuteCount;
//
return [
    { payload: messageCount },                         // Total messages
    { payload: Math.round(avgRate * 100) / 100 },      // Average rate
    { payload: currentRate },                          // Current rate
    msg,                                               // Original message
    { payload: activeBins }                            // Active Bins
];
```

4.2.2.3: Message counter node and function code.

Figure 4.2.2.3 shows message counter node in the flow and the code that generates charts inside the dashboard, the node has one input from JSON node and five outputs four relate to messages charts and the other one works as an input to main function node. Code shows how the function calculates total messages,

average rate, current rate, and active bins or sensors based on data flow from wokwi when the simulation is on and calculates it. When the simulation starts the messages, rate is low because there are no active bins or sensors only connection messages that the wokwi and node-red now connected and so on, then we change for example waste weight by the potentiometer to see how messages rate increase and active bins from zero changes to one.
This function is very important to measure system accuracy and efficiency when the system is busy and too many messages are sent per second, the response to every message and delays even the shape of changes in rates will be seen through this node and the related charts in node-red dashboard.




```
// Load Generator - High Traffic
var testData = msg.payload;

if (testData.test === true) {
    var count = testData.count || 500;
    var interval = 50; // 50ms = 20 msg/sec

    node.status({
        fill: "blue",
        shape: "ring",
        text: "Generating " + count + " messages..."
    });

    var dataTypes = ["fill_level", "weight", "waste_type", "gas_level", "gas_value", "lid_status", "sterilization", "compression", "bin_status"];
    var wasteTypes = ["Organic", "Plastic", "Metal", "Paper", "Glass"];
    var lidStatus = ["OPEN", "CLOSED"];
    var sterilizationStatus = ["ACTIVE", "COMPLETED", "OFF"];
    var binStatus = ["NORMAL", "FULL", "MAINTENANCE"];

    for (var i = 0; i < count; i++) {
        (function (index) {
            setTimeout(function () {
                var binId = "BIN_" + (Math.floor(Math.random() * 5) + 1);
                var dataType = dataTypes[Math.floor(Math.random() * dataTypes.length)];
                var value;

                switch (dataType) {
                    case "fill_level":
                        value = Math.floor(Math.random() * 100);
                        break;
                    case "weight":
                        value = (Math.random() * 10).toFixed(2);
                        break;
                    case "waste_type":
                        value = wasteTypes[Math.floor(Math.random() * wasteTypes.length)];
                        break;
                    case "gas_level":
                        value = Math.random() > 0.8 ? "HIGH" : "NORMAL";
                        break;
                    case "gas_value":
                        value = Math.floor(Math.random() * 1000);
                        break;
                    case "lid_status":
                        value = lidStatus[Math.floor(Math.random() * lidStatus.length)];
                        break;
                    case "sterilization":
                        value = sterilizationStatus[Math.floor(Math.random() * sterilizationStatus.length)];
                        break;
```

```
                case "compression":
                    value = Math.random() > 0.7 ? "ACTIVE" : "IDLE";
                    break;
                case "bin_status":
                    value = binStatus[Math.floor(Math.random() * binStatus.length)];
                    break;
                default:
                    value = "unknown";
            }

            var message = {
                payload: JSON.stringify({
                    bin_id: binId,
                    data_type: dataType,
                    value: value,
                    location: "Test Location",
                    timestamp: new Date().toISOString()
                })
            };

            node.send(message);

            if (index % 50 === 0) {
                node.status({
                    fill: "green",
                    shape: "dot",
                    text: "Sent " + index + "/" + count
                });
            }

            if (index === count - 1) {
                setTimeout(function () {
                    node.status({
                        fill: "green",
                        shape: "dot",
                        text: "Complete: " + count + " messages"
                    });
                }, 2000);
            }

        }, i * interval);
    })(i);
  }
}

return null;
```

Figure 4.2.2.4: Load Generator function and code.

Load generator function is an additional node that does not affect system principle or theory but it's for high traffic scenario and to show how system and network still work in accurate way even under pressure. The code displays how messages rate increase when start load button is activated and displays results in dashboard.

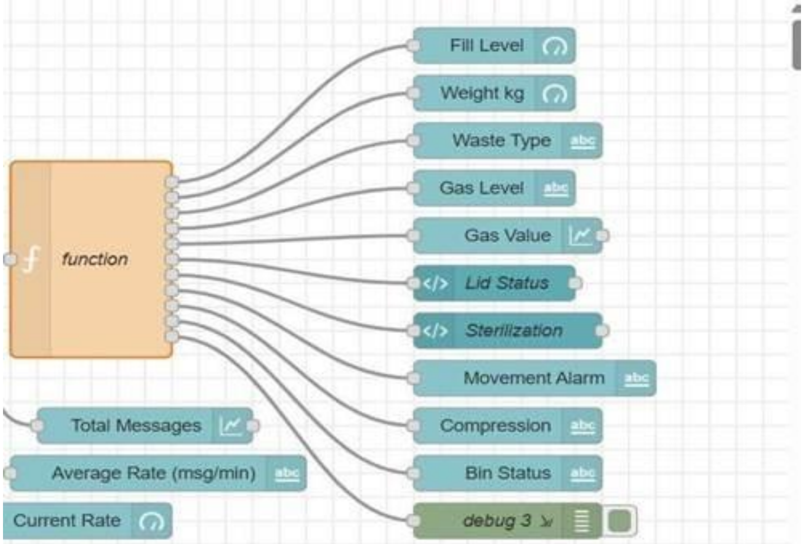


Figure 4.2.2.5: main function node.

Figure 4.2.2.5 illustrates main function node. It is where the messages categorized based on the type of data in JSON node and sent each type of the messages to the output node assigned to it using the code in the figure below:

```
        outs[6] = makeMsg("bin/sterilization", value);
        break;
    case "movement_alarm":
        outs[7] = makeMsg("bin/alarm", "movement");
        break;
    case "compression":
        outs[8] = makeMsg("bin/compression", value);
        break;
    case "bin_status":
        outs[9] = makeMsg("bin/status", value);
        break;
    case "location":
        outs[10] = makeMsg("bin/location", location || value);
        break;
    default:
        outs[10] = makeMsg("bin/raw", p);
        break;
}

return outs;
```

```
 case "fill_level":
     outs[0] = makeMsg("bin/fill_level", parseInt(value));
     break;
 case "weight":
     outs[1] = makeMsg("bin/weight", parseFloat(value));
     break;
 case "waste_type":
     outs[2] = makeMsg("bin/waste_type", value);
     break;
 case "gas_level":
     outs[3] = makeMsg("bin/gas_level", value);
     break;
 case "gas_value":
     let gasVal = Array.isArray(value) ? value[0] : value;
     outs[4] = {
         payload: parseFloat(gasVal)
         topic: "bin/gas_value",
         timestamp: new Date().toISOString()
     };
     break;
 case "lid_status":
     outs[5] = makeMsg("bin/lid_status", value);
     break;
 case "sterilization":
```

```
const outputsCount = 11;
let outs = new Array(outputsCount).fill(null);
let p = msg.payload || {};
let binId = p.bin_id;
let dataType = p.data_type;
let value = p.value;
let location = p.location;
let timestamp = p.timestamp;
function makeMsg(topic, payload) {
    return {
        payload: payload,
        topic: topic,
        binId: binId,
        location: location,
        timestamp: timestamp,
        _msgid: msg._msgid};
}

switch (dataType) {
    case "fill_level":
        outs[0] = makeMsg("bin/fill_level", parseInt(value)
        break;
```

Figure 4.2.2.6: Main function code.

There are two outputs connected to the Gauge widget dashboard, fill level node which displays the percentage of bin fulness based on weight and weight kg node, it used to monitor the weight of the bin before and after the compressing process. Waste type and Gas Level node are Text widgets dashboard displays the type of waste (plastic-Metal-organic) detected by the sorting algorithm, the level of gas and its hazard level in order, Gas value display as a graph shows the ratio of gas level relative to time.

Lid status and Sterilization displays in dashboard as (open/closed) for the lid and (In process/Complete/Off) based on the sterilization process. Movement alarm appears as warning when the bin moves.

Compression node shows the status of compression (STARTED/COMPLETED) for pressure at 60% and 80% fill level. Bin Status is text widget dashboard that shows the general condition of the bin (NORMAL -60% -80% -90% FULL). Debug node shows messages that came out of the main node after processing, useful for emphasizing that the right paths are working as they should.

4.3 Sensor Data Stream Format and Processing Outcomes

Smart bin system generates a continuous sensors data stream that transmitted to IoT platform (Node-Red) by MQTT, this data includes multiple measurements required for monitoring bin status and environmental conditions.

4.3.1 Types of Sensor Data

- Weight (%)
- Fill level(kg)

- Gas detection -toxic gas detection
- Motion detection-movement alert
- Sterilization- ON/OFF state
- Sorting waste type- (e.g. Metal)

4.3.2 Message Format (JSON Payload)

Functions and messages have a specific structure JSON format:

```
case "gas_value":
 let gasVal = Array.isArray(value) ? value[0] : value;
 outs[4] = {
  payload: parseFloat(gasVal) || 0,
  topic: "bin/gas_value",
 timestamp: new Date().toISOString()
    };
    break;
case "lid_status":
    outs[5] = makeMsg("bin/lid_status", value);
    break;
```

Figure 4.3: Gas value and Lid status JSON format.

4.3.3 MQTT Topics Structure

The smart bin system has many topics to organize data streams

Sensor/Event	Topic
Fill level	smartbin/fill_evel
Weight (KG)	smartbin/weight
Waste type	smartbin/waste_type
Gas value	smartbin/gas_value
Lid status	smartbin/lid_status
Sterilization	smartbin/sterilization
Movement alarm	smartbin/movement
Compression	smartbin/compression_status
Bin status	smartbin/bin_status

4.4Baseline Model Results

Baseline models provide a reference and starting point for evaluating performance of smart waste bin system. It starts with one Active bin (e.g. Fill level) and simple information about the system and bin, results shown in node-red dashboard. Baseline model has an average messages rate of 5 msg/min for one or two active bins in simulation.

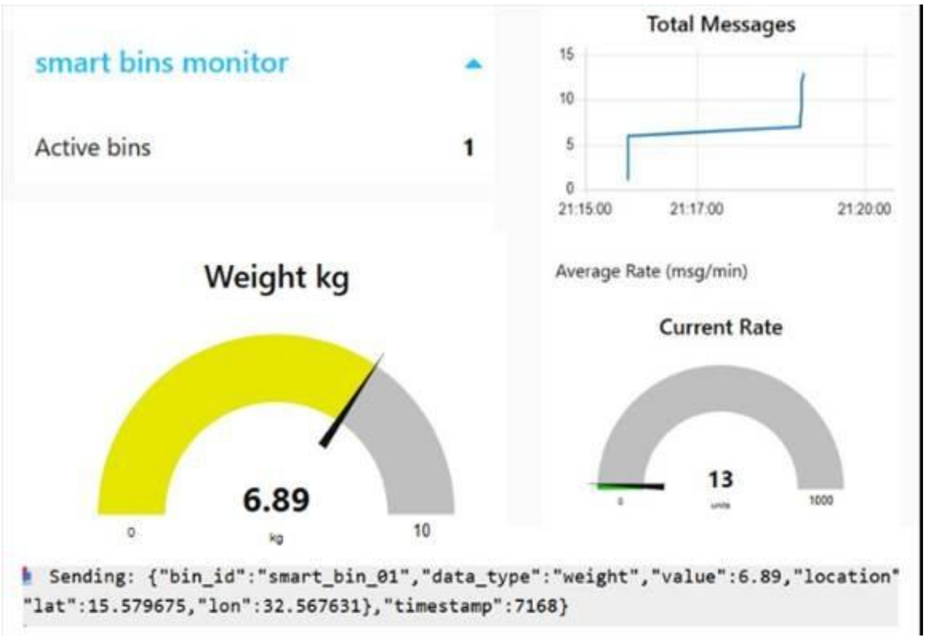


Figure 4.4.1: Baseline model result using load cell sensor to measure bin weight.

Real-Time Sorting Scenario

In Figure 4.4.2 a series of real-time graphical data are taken out of ThingSpeak cloud platform. The charts shown illustrate the sensing action and the sorting actions that the smart waste bin prototype does. There are four essential sensor indicators as described and explained below:

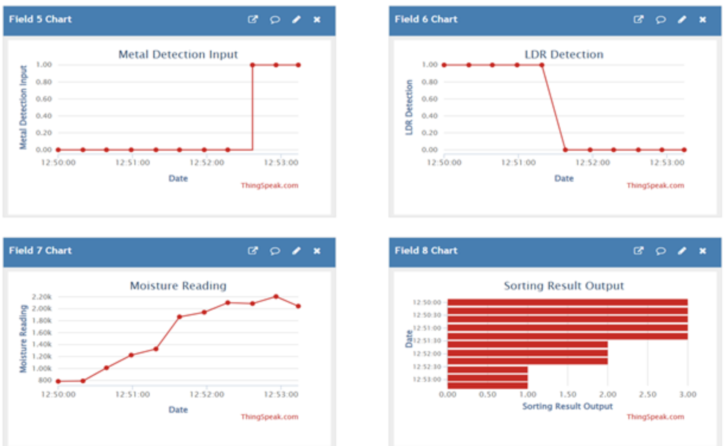


Figure 4.4.2: Multi Sensors Detection and Sorting.

Metal Detection Signal: This chart represents binary behavior of the metal sensing module. The signal was kept at zero for a long time, which meant that there was no metallic object present. When a metallic object was detected, a sudden peak was obtained to 1.0. This is indicative of the sensitivity of the metal detection system, and the sensing unit can appropriately detect the presence of metallic waste.

LDR Detection Signal: The values of the light-dependent resistor (LDR) were high at first, which means that there was reflective material in the field of measurement. When the reflective surface was removed or substituted with a non-reflective object, a rapid decrease to zero took place. The behavior proves that the optical sensing approach can distinguish between materials by their light reflection characteristics and helps to distinguish between plastic objects and other types of objects.

Moisture Reading: This graph showed a gradual upward trend with readings going up between 800 and over 2000. The increase in sensor output denotes the existence and degree of concentration moisture material, which is linked to organic waste. Therefore, the moisture sensor can detect organic material based on its detectable humidity profile.

Sorting Output Results: The last chart shows the results of the sorting algorithm classification. The decision values were represented in a bar plot where 1 corresponds to metallic waste, 2 is plastic waste and three is equivalent to organic waste.

All in all, the charts show that every identified object was placed in the corresponding category based on sensor measurements, which means that the system logic employs input signals properly and performs sorting operations successfully.

Fill Level Over Time and Compression Stages Scenario:

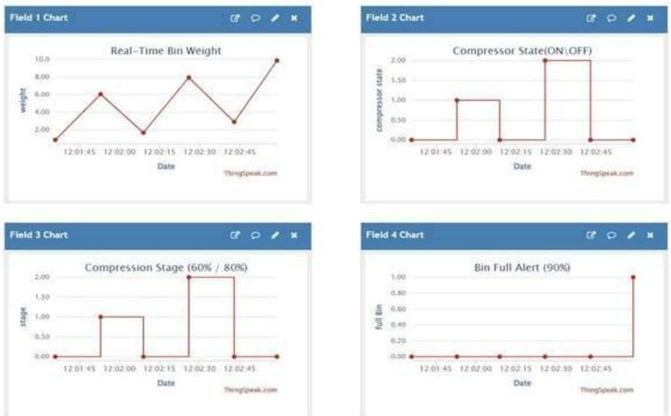


Figure 4.4.3: Bin Weight and Compression Stages.

Real-Time Bin Weight: This chart shows the real-time weight of the smart bin. The weight increases as waste is added and decreases after compression at the two stages. This data is used to estimate the fill level percentage of the bin.
Compressor State (ON/OFF): This chart indicates when the compressor was active 1 = ON, 0 = OFF From the graph, the compressor turned on twice, the fist During the 60% compression stage and the second During the 80% compression stage This confirms that the system successfully activates the compressor at the correct thresholds.
Compression Stage (60% / 80%): This chart shows which compression stage the bin completed, Stage 1 means that the waste was compressed from 60% down to 30%. Stage 2 means that the waste was compressed from 80% to 40%.
Notably, the shape and timing of the compression stage graph match the compressor state graph incurring the compressor operating during both stages.
Bin Full Alert (90%): shows that the bin sends “Bin Full” alert successfully by the fill level 90%.

Sterilization State Scenario

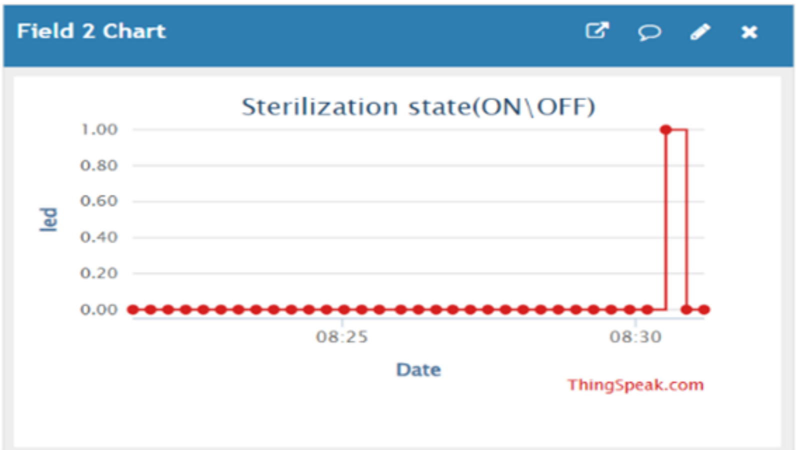


Figure 4.4.4: Sterilization State.

The diagram below illustrates the state of the sterilization system inside the smart basket. ESP32 sends a digital data message to ThingSpeak, where 1 represents the one state and 0 the off state. After 30 cycles of the lid's servo motor are completed, the ESP32 sends a signal to ThingSpeak through field 2 to change the sterilization state from OFF to ON. These results confirm that the system is responding correctly and that the data sent to the program matches the system data in the simulation environment.

4.5 Performance Evaluation

In this part we review different scenarios in different abnormal conditions to measure the stability of the system and the way it responds.

Scenario 1 (Gas value increase):

Figure 4.5.1: Gas value increase in Wokwi.

In this case we suddenly increased the gas value from 92 to 773, immediately the variation displayed in Node-Red dashboard as high gas rate in the gas value chart and alert in gas level chart.

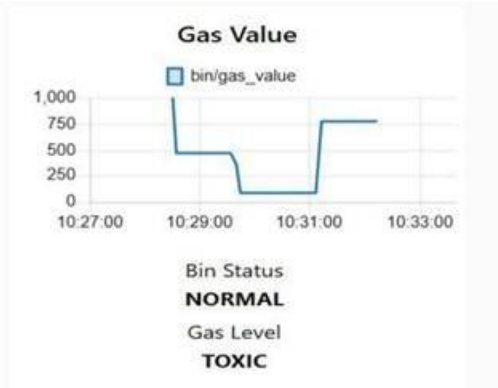


Figure 4.5.2: The variation in gas value chart and the alert in gas level in Node-Red dashboard.

Scenario 2 (Wrong Topic):

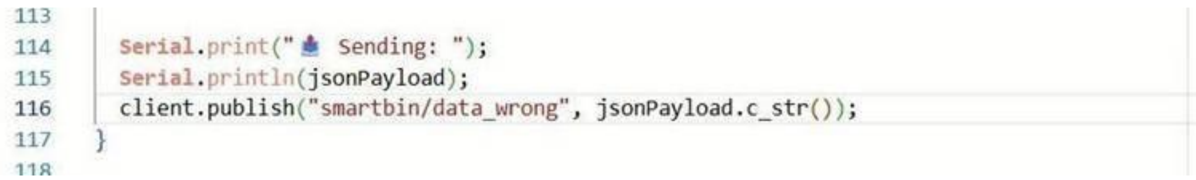


Figure 4.5.3: The topic changed in Wokwi code.

We've changed the client publish in wokwi code from smartbin/sensor data to smartbin/data wrong. No data appeared on the Node-Red dashboard. When the topic was restored, the connection was reestablished and automatically the data appeared in Node-Red dashboard.

Figure 4.5.4: illustrate the messages interrupted when topic changed and restored when it retrieved.

Scenario 3 (MQTT broker down)

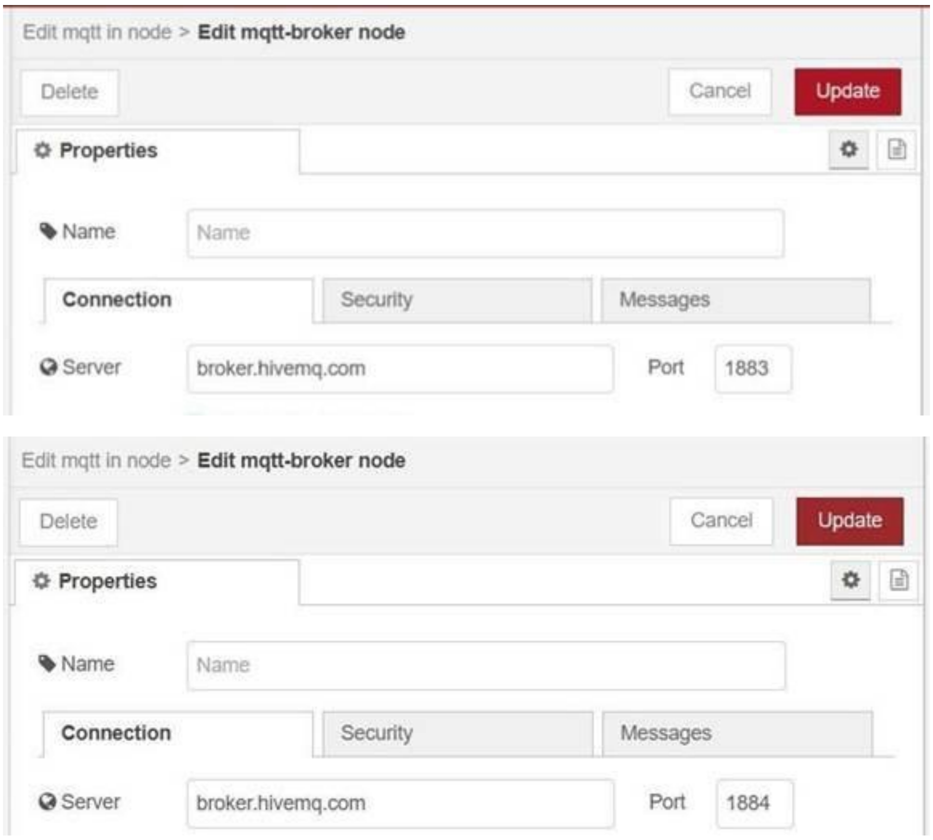


Figure 4.5.5: illustrates the change in the port.

in the MQTT node in Node-Red the port is changed from 1883 to 1884. The connection failed, the data stopped immediately and the dashboard froze.

Figure 4.5.6: illustrate no new messages arrived in total messages chart (dashboard freeze).

Scenario 4 (High Traffic)

High traffic scenario tests system's ability to perform at its best but and pressure ana high orders. Smart waste bin system simulation showed how messages sent to node-red and dashboard via MQTT in its normal status (e.g. only one or two active bins), but here the system is under more active bins and functions.

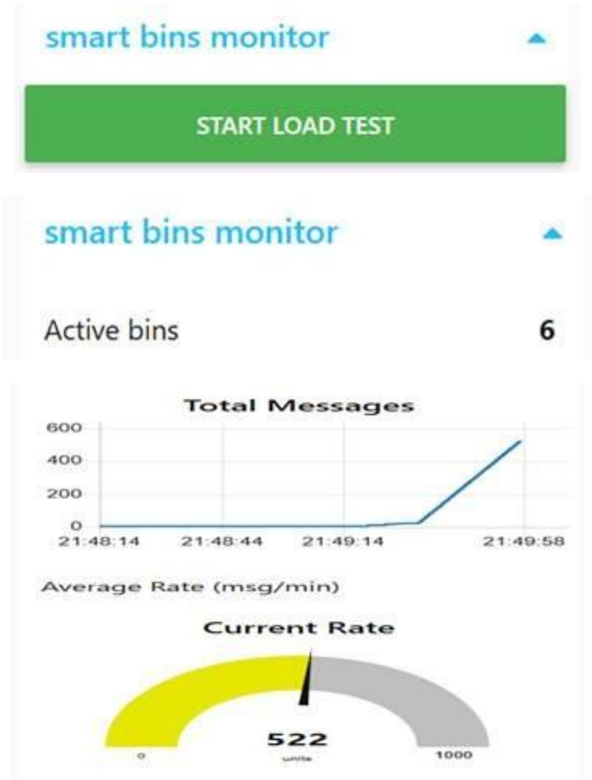


Figure 4.5.7: High Traffic Scenario (Load test/Medium).

A Load test button added to node-red nodes to perform a high traffic scenario by increasing messages rate/sec, despite the high rate of messages received (500 message in44 sec) in the network but its behavior still the same and more accurate.

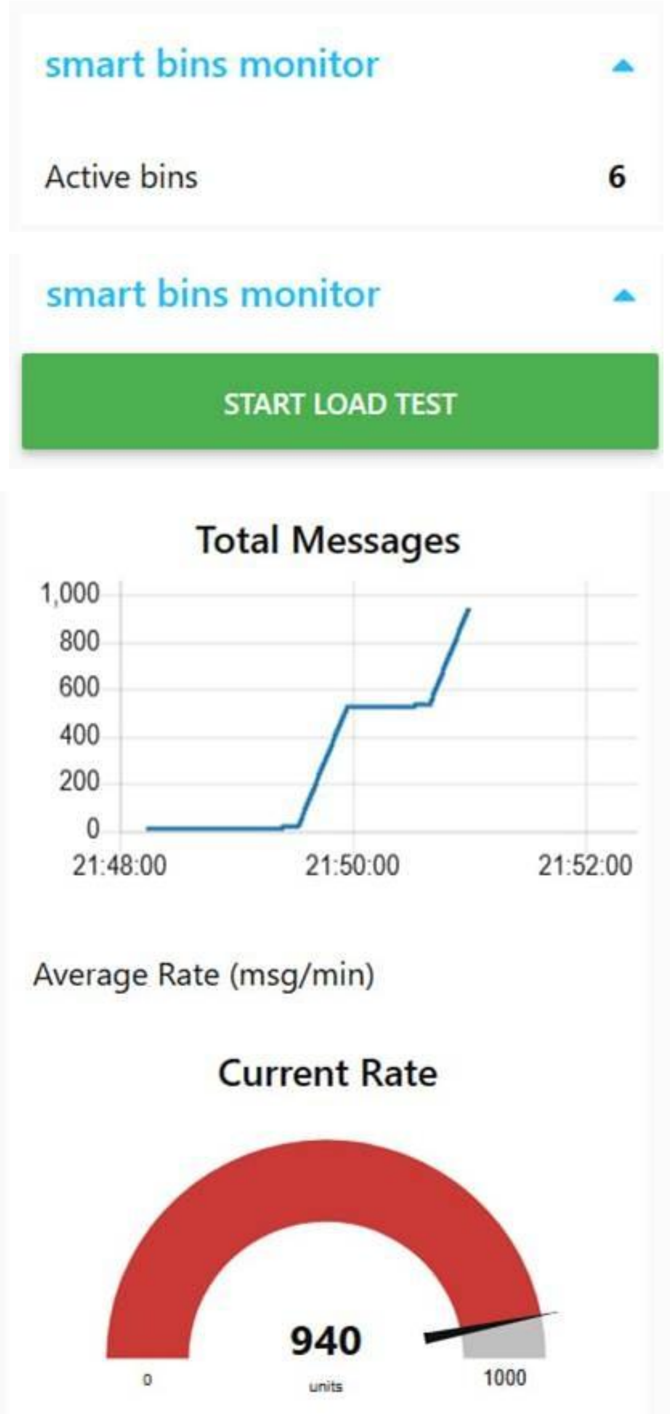


Figure 4.5.8: High Traffic Scenario (Load test/High).

Figure 4.5.8 illustrates system's performance under high traffic scenario where the load test was executed with six active bins sending data simultaneously. It simulates real-world peak conditions in which devices publish messages at high rate to MQTT broker.

The Total Messages chart displays a steady throughput even when messages volume increases, pattern demonstrates system's ability to handle high rate while continuing to process incoming data without delay. The scenario validates efficiency of smart bin monitoring architecture and proved that the system can transmit and process data under any conditions.

Scenario 5 (Latency)

Figure 4.5.9: Latency jitter.

The end-to-end latency measurements recorded on 14/03/2026 between 15:38:21 and 15:40:17demonstrated consistent and stable network performance. Latency values ranged between 604 ms and 615 ms, with an average of approximately 611.5 ms. This delay is attributed to the simulated LoRa network propagation delay introduced in the Node-RED pipeline. The calculated jitter defined as the absolute difference between consecutive latency readings ranged from 0 ms to 8 ms, with an average jitter of 2.57 ms. Such low jitter values indicate highly stable message delivery with minimal timing variation, confirming the reliability of the MQTT communication channel between the Wokwi ESP32 simulation and the Node-RED monitoring.

Scenario 6 (Confusion Matrix)

4.5.1 Confusion Matrix Table

predicated actual	**organic**	**plastic**	**metal**
organic	8	2	0
plastic	2	8	0
metal	0	0	10

1. Accuracy= $\frac{TPtotal}{Total}$ (1)

Accuracy= $\frac{26}{30}$ = 0.867

Accuracy= 86.7%

2. Organic=

TP=8, FP=2, FN=2

Precision = $\frac{8}{8+2}$ = 0.8

Recall = $\frac{8}{8+2}$ = 0.8

F1= 0.8

3. plastic

tp=8, fp=2, fn=2

Precision = $\frac{8}{8+2}$ = 0.8

Recall = $\frac{8}{8+2}$ = 0.8

F1= 0.8

4. metal

tp=10, fp=0, fn=0

Precision = $\frac{10}{10+0}$ = 1

Recall = $\frac{10}{10+0}$ = 1

F1= 1

4.5.2 Final Results Table

Class	precision	Recall	F1-Score
organic	0.80	0.80	0.80
plastic	0.80	0.80	0.80
metal	1.00	1.00	1.00

4.6 Important of Each Sensors and Model

All the bin’s components work together to create a precise system; any malfunction affects the bin’s performance, and each sensor is responsible for a specific feature of the system.

4.6.1 Important of each sensor

Ultrasonic sensor is used to measure distance, and any error in the reading leads to the cover being opened and closed at the wrong time. The gas sensor measures gas and odors, and when it rises, it activates the fan. The weight sensor measures the actual weight of the waste. The soil moisture sensor measures the amount of moisture to sort plastic and organic materials more accurately. The metal sensor is used to sort metals. NIR sensor is used to sort organic materials and plastics, and LIS3DH sensor is used to detect any vibration or movement of the bin.

4.6.2 Important of actuators

A servo motor for the lid is responsible for opening and closing it. A servo motor for sorting is responsible for directing the waste into three sections. The compressor motor uses a compression process.

4.7 Case studies / Sample prediction

A complete simulation scenario was implemented using a wokwi platform and connected to thingSpeak to display data. The ESP32 was programmed to send data every 20 seconds. A person was assumed to be disposing of waste, and the sensor values were manually changed to trigger 11 waste disposal events. After each reading, the ultrasonic, load cell, near-infrared, inductive, soil moisture and gas sensors readings, along with the status of the fan and compressor, were sent to the platform to illustrate the system's interaction with each reading, as shown in the graphs below

Scenario 1 (Ultrasonic distance detection)

The sensor detects objects at 15 cm; the system recognizes this as a waste disposal operation. The lid opens automatically, and the reading remains constant as shown in the distance graph.

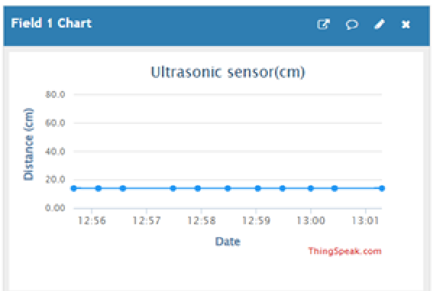


Figure 4.7.1: Ultrasonic sensor(cm) field.

Scenario 2 (Automatic waste classification)

After the waste disposal process, the waste is sorted according to the sensor readings (metallic = 1, organic = 2, plastic = 3), and the values change according to the automatic sorting process, as shown in the classification graph.

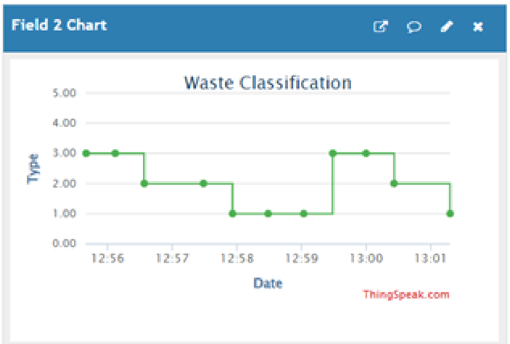


Figure 4.7.2: Waste classification field.

Scenario 3 (Waste weight changes during disposal

During the waste disposal process, the load cell sensor continuously records weight values; the weight increases when waste is added and decreases after the compaction process, as shown in the graph below.

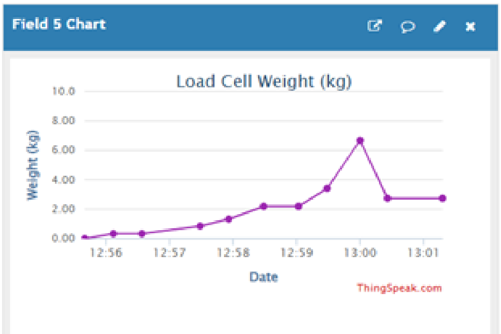


Figure 4.7.3: Load cell weight field.

Scenario 4 (Compressor activation)

After several waste disposal cycles, the weight gradually increases until it reaches a threshold value, at which point the compactor is activated. The diagram illustrates the compactor process, showing the change from 0 to 1.

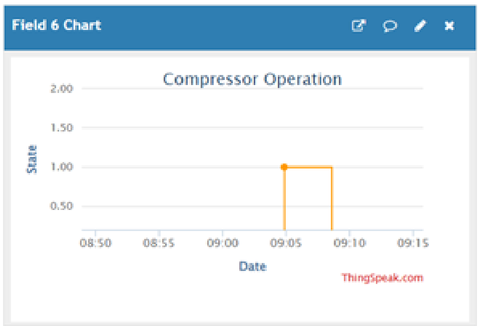


Figure 4.7.4: Compressor operation field.

Scenario 5 (Gas level and fan activation)

The gas sensor monitors the gas level inside the basket in real time. After normal readings, if the gas level rises to 400, the system sends an immediate warning message and activates the fan to reduce the gas level, as shown in the graphs below.

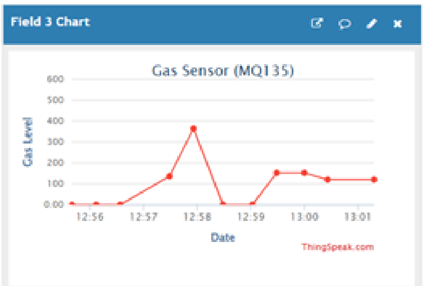


Figure 4.7.5: Gas sensor field.

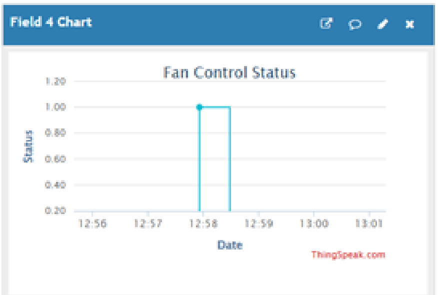


Figure 4.7.6: Fan status field.

4.8 Comparative Analysis of Existing Literature / Systems

This section provides a focused comparison between the proposed smart waste sorting system and the smart garbage monitoring system presented by Goel & Goel (2021).

The comparison highlights that the proposed smart container system offers significantly more advanced capabilities than the Goel (2021) model. While the

Goel system primarily focuses on monitoring fullness levels and environmental conditions using basic sensors and ThingSpeak connectivity, the proposed system integrates a richer array of sensors—including inductive, near-infrared, humidity, gas, and waste level sensors—to support automatic waste sorting.

One of the most significant improvements in the proposed system is its dual-motor servo-driven waste sorting mechanism. This mechanism effectively directs waste into three specific categories: 45 degrees for metals, 90 degrees for organic materials, and 135 degrees for plastics.

This mechanical sorting mechanism provides complete automation for waste separation, a significant advancement compared to the Goel system, which lacks any sorting or processing features.

Furthermore, the proposed container includes an automated compaction unit that compresses metal and plastic waste once it reaches predefined thresholds, thus improving storage efficiency and service life. A similar mechanism is not present in the Goel system (2021).

Furthermore, the proposed design incorporates a dual-servo sorting mechanism, enabling the physical separation of mineral, organic, and plastic waste, a feature absent in the Goel model. The connectivity architecture is also more robust, combining MQTT, Node-RED, and ThingSpeak, and undergoing rigorous structured network testing (latest, median failure, subject errors, and high traffic load).

Overall, the proposed system demonstrates higher network reliability, broader functionality, and a higher level of automation, making it a more comprehensive and scalable smart waste management solution compared to existing systems.

4.8 Comparison Table

Criterion	Proposed System	Goel 2021 – Smart Garbage Monitoring System
Communication Layer	MQTT + Node-RED + ThingSpeak + optional cluster routing	ESP8266 + GSM/GPS + ThingSpeak
Execution Environment	Wokwi Virtual Simulation + Node-RED Dashboard + Online MQTT Broker	Physical hardware prototype only
Sensor Types	Inductive (metal), NIR, Soil Moisture, Gas, Fill-level, Weight	Ultrasonic, Gas, Moisture, Temperature
Waste Sorting Mechanism	Yes — 2 servo motors for 3-way sorting (45° / 90° / 135°)	No sorting mechanism
Environmental Interaction	Gate control + sorting direction + gas alert response	Automatic lid opening + fill-level detection
Data Handling	Structured JSON → MQTT Topics → Node-RED + ThingSpeak cloud	Sensor readings sent to ThingSpeak
Network Robustness Tests	Broker down, wrong topic, gas spikes, high-traffic flooding	No network stress testing reported
Network Performance Analysis	Latency, packet loss, throughput simulation	No network performance evaluation
Application Focus	Smart waste sorting + IoT monitoring	Waste level monitoring only
Scalability	Topic-based MQTT architecture → multi-bin scalable	Single-bin design with limited expandability

4.9chapter Summary

Chapter 4 provides a complete evaluation of the smart waste bin's network performance, sensor interaction, sorting mechanism, and real-time behavior. The system successfully integrates simulation tools (Wokwi + Node-RED + ThingSpeak), manages diverse sensor data, and withstands multiple error conditions. Comparisons show that it is more advanced and capable than existing systems such as Goel (2021).

Chapter 5

5.1 Conclusion

This project demonstrates an intelligent design for differentiating different IoT-based zones by integrating time-of-process sensing, sorting, and network performance analysis. Instead of relying on basic sensing as in conventional systems, the proposed design uses a more sophisticated combination of sensors, such as inductive metal detection, near-infrared material sensing, moisture measurement, and weight monitoring using load cells, to more accurately differentiate between metal, plastic, and organic waste. This data powers a fully automated sorting mechanism that directs each type of waste to its designated section, while an integrated compactor helps compress the metallic and plastic materials, making storage and recycling more efficient.

The network, utilizing MQTT and Node-RED, enables high-quality data transmission via cloud-based visual data and time-of-process analysis. The network is rigorously designed through multiple compression scenarios, including media malfunction, element misalignment, data variability, and gas level spikes. As a result, the system maintains stable connectivity, offers fast sorting times, and demonstrates reliable performance after failures, exhibiting high operational efficiency even under unusual operating conditions.

Finally, the project offers a comprehensive, scalable, and innovative smart solution, departing from traditional approaches. By integrating smart sorting, environmental integration, cloud computing analytics, and network performance, it creates a more diverse and innovative technological system. Future technologies may include energy-saving features and direct learning-based waste type prediction, further enhancing the system's limited-scale intelligence capabilities.

5.2 Future Work

Though the proposed IoT-based smart waste bin system has shown good performance in monitoring, segregation, compression, and communication during the simulation stage, there are some improvements that can be considered in the future development to enhance the scalability, intelligence, and real-world applicability. Real-world deployment and on-site testing is one of the directions of future work; this involves implementing the proposed system in actual urban environments rather than simulation-only testing, by deploying physical smart bins in selected sites and evaluating system performance under real environmental circumstances such as weather changes, user behavior and activities, network disturbances, and hardware wear.

Another important improvement is the integration with a full LoRaWAN infrastructure. Although this study simulated LoRa communication, the implementation in the future can include integrating the system with a fully operational public or private LoRaWAN network. This would enable it to be deployed on a large scale, enhance its reliability, and meet smart city communication standards. In addition, the current waste sorting mechanism is based on predetermined NIR, moisture, and inductive sensor thresholds. The models could be improved by machine learning or deep learning to enhance the accuracy of classification, particularly in complex or mixed waste. This would increase flexibility and decrease misclassification.

Future system versions may also include predictive analytics for waste collection. By analyzing historical sensor data, predictive algorithms could forecast bin fill times and optimize the schedule of waste collection. This would save on unnecessary collection trips, fuel usage, and operational expenses for municipalities. Furthermore, although the system is currently based on a web-based Node-RED dashboard, the required future work may include developing a dedicated, user-friendly mobile application that will be used by the waste management authorities. The application would offer push notifications, collection truck route optimization, and real-time bin status.

Finally, future improvements may be aimed at power optimization and advanced energy management. Intelligent power control techniques, such as adaptive sleep scheduling, energy-aware data transmission, and dynamic sensor sampling rate that, can further cut power consumption and increase battery life. Additionally, enhanced security and data privacy measures, such as device-level authentication, encrypted firmware updates, and an intrusion detection system, could be integrated to protect the system against cyber-attacks in the large-scale IoT implementation.

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Appendix

Simulation Code

```
#include <WiFi.h>
#include <PubSubClient.h>
#include <ESP32Servo.h>
// WiFi & MQTT Settings
const char* ssid        = "Wokwi-GUEST";
const char* password    = "";
const char* mqtt_server = "broker.hivemq.com";

WiFiClient espClient;
PubSubClient client(espClient);

// Pin Definitions
int TRIG = 5;
int ECHO = 19;
int SERVO_LID = 15;
int SERVO_GATE = 25;
int SERVO_SORT = 27;
int BTN_METAL = 14;
int LDR_PIN = 35;
int POT_ORG = 33;
int GAS_SENSOR = 32;
int FAN_LED = 4;
int LED_PIN = 26;
int LOADCELL_PIN = 34;
int COMPRESSOR_PIN = 21;
const int buttonPin = 12;
int STERILIZATION_PIN = 13;

// Variables
bool sterilizationActive = false;
unsigned long sterilizationStartTime = 0;
const int STERILIZATION_DURATION = 10000;

// Weight calibration
const float MAX_BIN_WEIGHT = 10.0;
const float MIN_BIN_WEIGHT = 0.0;

const float TH60 = 6.0;
const float TH80 = 8.0;
const float TH90 = 9.0;

// Location
float BIN_LAT = 15.579675;
float BIN_LON = 32.567632;

Servo lidServo;
Servo gateServo;
Servo sortServo;
```

```
// State variables
int moveCount = 0;
bool stage60_done = false;
bool stage80_done = false;
int compressorState = 0;
bool alarmSent = false;
unsigned long fanStartTime = 0;
bool fanRunning = false;
unsigned long lastMsg = 0;
unsigned long lastSensorMsg = 0;

// WiFi Connection
void setup_wifi() {
  delay(10);
  Serial.begin(115200);
  WiFi.begin(ssid, password);

  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }
  Serial.println(" WiFi connected");
}

// MQTT Connection
void reconnect() {
  while (!client.connected()) {
    Serial.print(" Attempting MQTT connection...");
    String clientId = "SmartBin-";
    clientId += String(random(0xffff), HEX);

    if (client.connect(clientId.c_str())) {
      Serial.println(" MQTT connected to HiveMQ");
      client.subscribe("smartbin/commands");
    } else {
      Serial.print(" MQTT failed, rc=");
      Serial.print(client.state());
      Serial.println(" retrying in 5s");
      delay(5000);
    }
  }
}

// JSON Messaging to NodeRED
void sendToNodeRED(String dataType, String value, bool isString = false) {
  String jsonPayload = "{";
  jsonPayload += "\"bin_id\":\"smart_bin_01\",";
  jsonPayload += "\"data_type\":\"" + dataType + "\",";

  if (isString)
    jsonPayload += "\"value\":\"" + value + "\",";
  else
    jsonPayload += "\"value\":" + value + ",";

  jsonPayload += "\"location\":{\"lat\":" + String(BIN_LAT, 6) + ",\"lon\":" + String(BIN_LON, 6) +
"},";
  jsonPayload += "\"timestamp\":" + String(millis());
```

```
  jsonPayload += "}";

  Serial.print(" Sending: ");
  Serial.println(jsonPayload);
  client.publish("smartbin/sensor_data", jsonPayload.c_str());
}

// Fill Level Calculation
int calculateFillLevel(float weight) {
  float fillPercentage = ((weight - MIN_BIN_WEIGHT) / (MAX_BIN_WEIGHT -
MIN_BIN_WEIGHT)) * 100.0;

  if (fillPercentage < 0) fillPercentage = 0;
  if (fillPercentage > 100) fillPercentage = 100;

  return (int)fillPercentage;
}

// Sensors & Classification
long getDistance() {
  digitalWrite(TRIG, LOW);
  delayMicroseconds(2);
  digitalWrite(TRIG, HIGH);
  delayMicroseconds(10);
  digitalWrite(TRIG, LOW);

  long duration = pulseIn(ECHO, HIGH);
  return duration * 0.034 / 2;
}

String classifyWaste(int metal, int ldrValue, int potValue) {
  int plasticThreshold = 1488;

  if (metal == HIGH)
    return "METAL";
  else if (potValue > 1800)
    return "ORGANIC";
  else if (ldrValue <= plasticThreshold)
    return "PLASTIC";
  else
    return "UNKNOWN";
}

// Sterilization Process
void startSterilization() {
  if (sterilizationActive) return;

  digitalWrite(STERILIZATION_PIN, HIGH);
  digitalWrite(LED_PIN, HIGH);
  sterilizationActive = true;
  sterilizationStartTime = millis();

  Serial.println("========================================");
  Serial.println(" STERILIZATION STARTED");
  Serial.println(" Duration: 10 seconds");
  Serial.println("========================================");
```

```
  sendToNodeRED("sterilization", "ACTIVE", true);
}

void stopSterilization() {
  digitalWrite(STERILIZATION_PIN, LOW);
  digitalWrite(LED_PIN, LOW);
  sterilizationActive = false;

  Serial.println("========================================");
  Serial.println(" STERILIZATION COMPLETED");
  Serial.println("========================================");

  sendToNodeRED("sterilization", "COMPLETED", true);
}

// Setup
void setup() {
  Serial.begin(115200);

  pinMode(TRIG, OUTPUT);
  pinMode(ECHO, INPUT);
  pinMode(BTN_METAL, INPUT);
  pinMode(LDR_PIN, INPUT);
  pinMode(POT_ORG, INPUT);
  pinMode(GAS_SENSOR, INPUT);
  pinMode(FAN_LED, OUTPUT);
  pinMode(LED_PIN, OUTPUT);
  pinMode(COMPRESSOR_PIN, OUTPUT);
  pinMode(buttonPin, INPUT_PULLUP);
  pinMode(STERILIZATION_PIN, OUTPUT);

  digitalWrite(STERILIZATION_PIN, LOW);

  lidServo.attach(SERVO_LID);
  gateServo.attach(SERVO_GATE);
  sortServo.attach(SERVO_SORT);

  lidServo.write(0);
  gateServo.write(0);
  sortServo.write(0);

  setup_wifi();
  client.setServer(mqtt_server, 1883);

  Serial.println(" Smart Bin Started - Weight-Based Fill Level");
  Serial.println(" MQTT Server: broker.hivemq.com:1883");
  Serial.println(" Topic: smartbin/sensor_data");
  Serial.println(" Max Bin Weight: " + String(MAX_BIN_WEIGHT) + " kg");
}

// Main Loop
void loop() {

  if (!client.connected()) reconnect();
  client.loop();

  unsigned long now = millis();
```

```
// Sterilization timer check
if (sterilizationActive && (now - sterilizationStartTime >= STERILIZATION_DURATION)) {
  stopSterilization();
}

// Sensor readings
int metal     = digitalRead(BTN_METAL);
int ldrValue  = analogRead(LDR_PIN);
int potValue  = analogRead(POT_ORG);
int gas       = analogRead(GAS_SENSOR);
int reading   = digitalRead(buttonPin);

int rawWeight = analogRead(LOADCELL_PIN);
float weight  = (rawWeight / 4095.0) * MAX_BIN_WEIGHT;
int fill_level = calculateFillLevel(weight);

// Weight reporting every 3s
if (now - lastMsg > 3000) {
  lastMsg = now;

  sendToNodeRED("weight", String(weight, 2), false);
  sendToNodeRED("fill_level", String(fill_level), false);

  String binStatus = "";
  if      (fill_level < 60)        binStatus = "NORMAL";
  else if (fill_level < 80)        binStatus = "60_PERCENT";
  else if (fill_level < 90)        binStatus = "80_PERCENT";
  else                             binStatus = "FULL_90_PERCENT";

  sendToNodeRED("bin_status", binStatus, true);

  Serial.println("========================================");
  Serial.print(" Weight: "); Serial.print(weight, 2);
  Serial.print(" kg | Raw ADC: "); Serial.println(rawWeight);
  Serial.print(" Fill Level: "); Serial.print(fill_level); Serial.println("%");
  Serial.print(" Bin Status: "); Serial.println(binStatus);
  Serial.println("========================================");

  if (fill_level >= 90) {
    Serial.println(" BIN 90% FULL - NEEDS EMPTYING!");
  }
}

// Sensor reporting every 5s
if (now - lastSensorMsg > 5000) {
  lastSensorMsg = now;

  Serial.print("=== SENSORS === Metal:");
  Serial.print(metal);
  Serial.print(" | LDR:");
  Serial.print(ldrValue);
  Serial.print(" | POT:");
  Serial.print(potValue);
  Serial.print(" | GAS:");
  Serial.println(gas);
```

```
  if (gas > 400)
    sendToNodeRED("gas_level", "TOXIC", true);
  else if (gas >= 250)
    sendToNodeRED("gas_level", "MODERATE", true);
  else
    sendToNodeRED("gas_level", "NORMAL", true);

  sendToNodeRED("gas_value", String(gas), false);
}

// Movement alarm
if (reading == LOW && !alarmSent) {
  sendToNodeRED("movement_alarm", "Bin movement detected", true);
  alarmSent = true;
  Serial.println(" MOVEMENT ALARM!");
}
if (reading == HIGH) alarmSent = false;

// Ultrasonic detection
long dist = getDistance();

bool lidBusy = digitalRead(LED_PIN) == HIGH;
bool compressorBusy = digitalRead(COMPRESSOR_PIN) == HIGH;

// Sorting logic
if (dist <= 15 && !lidBusy && !compressorBusy && !sterilizationActive) {
  lidServo.write(90);
  sendToNodeRED("lid_status", "OPEN", true);
  Serial.println(" LID OPENED");

  delay(1500);

  String wasteType = classifyWaste(metal, ldrValue, potValue);

  Serial.print(" Detected Waste: ");
  Serial.println(wasteType);

  sendToNodeRED("waste_type", wasteType, true);

  gateServo.write(90);
  delay(1000);

  if      (wasteType == "METAL")    sortServo.write(45);
  else if (wasteType == "ORGANIC")  sortServo.write(90);
  else if (wasteType == "PLASTIC")  sortServo.write(135);
  else                              sortServo.write(0);

  delay(3000);
  sortServo.write(0);
  gateServo.write(0);
  lidServo.write(0);
  sendToNodeRED("lid_status", "CLOSED", true);
  Serial.println(" LID CLOSED");

  moveCount++;
  Serial.print(" Move Count: "); Serial.println(moveCount);
}
```

```
if (moveCount >= 3 && !sterilizationActive && compressorState == 0) {
  startSterilization();
  moveCount = 0;
}

// Fan control
if (gas > 400) {
  digitalWrite(FAN_LED, HIGH);
  if (!fanRunning) {
    sendToNodeRED("gas_alert", "TOXIC_GAS_DETECTED", true);
    fanRunning = true;
    Serial.println(" TOXIC GAS - FAN ON");
  }
}
else if (gas >= 250) {
  if (!fanRunning) {
    digitalWrite(FAN_LED, HIGH);
    fanStartTime = millis();
    fanRunning = true;
    sendToNodeRED("gas_level", "MODERATE", true);
  }

  if (fanRunning && millis() - fanStartTime >= 120000) {
    digitalWrite(FAN_LED, LOW);
    fanRunning = false;
    Serial.println(" GAS NORMAL - FAN OFF");
  }
}
else {
  digitalWrite(FAN_LED, LOW);
  fanRunning = false;
}

// Compression logic
if (!stage60_done && compressorState == 0 && weight >= TH60 && weight < TH80) {
  digitalWrite(COMPRESSOR_PIN, HIGH);
  compressorState = 1;
  sendToNodeRED("compression", "STARTED_60", true);
  Serial.println(" COMPRESSION STARTED - 60%");
}

if (compressorState == 1 && weight <= 4.0) {
  digitalWrite(COMPRESSOR_PIN, LOW);
  compressorState = 0;
  stage60_done = true;
  sendToNodeRED("compression", "COMPLETED_60", true);
  Serial.println(" COMPRESSION COMPLETED - 60%");
}

if (!stage80_done && compressorState == 0 && weight >= TH80 && weight < TH90) {
  digitalWrite(COMPRESSOR_PIN, HIGH);
  compressorState = 2;
  sendToNodeRED("compression", "STARTED_80", true);
  Serial.println(" COMPRESSION STARTED - 80%");
}
```

```
  if (compressorState == 2 && weight <= 5.0) {
    digitalWrite(COMPRESSOR_PIN, LOW);
    compressorState = 0;
    stage80_done = true;
    sendToNodeRED("compression", "COMPLETED_80", true);
    Serial.println(" COMPRESSION COMPLETED - 80%");
  }

  delay(500);
}
```

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