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Smart Battery Storage Integration in An IoT-Based Solar-Powered Waste Management System

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Abstract - The global waste crisis is worsening, with more than 33% of the world's 2.01 billion Tonnes of annual solid waste being poorly managed, which could reach 3.40 billion Tonnes by 2050. Low-income countries are projected to triple their waste production by this time, adding further burdens to traditional waste management systems, which are often very inefficient and environmentally damaging. Hence, this research integrates smart battery storage into an IoT-based solar-powered waste management system to improve efficiency and sustainability. A model system was developed and simulated using the Proteus circuit design, which integrates IoT sensors, solar panels, and smart battery storage. The key components of the project include ultrasonic sensors for bin fill-level monitoring, GPS modules for bin location, weight sensors for precise waste measurement, GSM modules for real-time alerts, and DHT11 sensors for battery condition tracking. The system demonstrated reliable performance, achieving real-time bin and battery status monitoring. Alerts were triggered under presumed conditions, such as near-full bin capacity. The smart battery system was designed to ensure continuous operation by managing solar energy efficiently for power, reducing downtime and energy waste. Performance testing and validations were done to reduce operations inefficiencies, improve resource allocation, and advance decision-making. These results are very important for advancing sustainable waste management practices, providing a framework for scalable IoT-based applications in urban waste management and beyond.

Keywords: *Smart Waste Management, Solar Power, Sustainability, Smart Battery Storage, Real-Time Monitoring, Internet of Things (IoT), Prototype Development.*

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ISSN 2709-4529

LIST OF ABBREVIATIONS

- **GPS**: Global Positioning System
- **GSM**: Global System for Mobile Communications
- **ToF**: Time-of-Flight
- **Li-Po**: Lithium-Polymer
- **DHT** Sensor: Digital Humidity and Temperature Sensor
- **BMS**: Battery Management System
- **DC**: Direct Current
- **GPRS**: General Packet Radio Service
- **SMS**: Short Message Service
- **SIM**: Subscriber Identity Module
- **LTE-TDD**: Long-Term Evolution - Time Division Duplex
- **LTE-FDD**: Long-Term Evolution - Frequency Division Duplex
- **HSPA+:** High-Speed Packet Access Plus
- **EDGE**: Enhanced Data rates for GSM Evolution
- **UART**: Universal Asynchronous Receiver-Transmitter
- **USB**: Universal Serial Bus
- **I2C**: Inter-Integrated Circuit
- **GPIO**: General Purpose Input/output
- **GNSS**: Global Navigation Satellite System
- **IoT**: Internet of Things

JDFEWS 5 (2): 17 - 42, 2024
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I. Introduction

Rapid urbanization and industrialization of modern societies have resulted in the rise of an increasingly complex problem: waste management. Many existing approaches toward managing solid waste prove inefficient, usually resulting in environmental pollution and a high operation cost. IoT technologies coupled with renewable energy provide a promising approach to handling such problems. These problems bring about this topic of interest: designing and implementing a smart battery storage system integrated into an IoT-based solar-powered waste management system.

Currently, at least 33% of about 2.01 billion tons of solid waste produced worldwide yearly is not managed environmentally sustainable. By 2050, 3.40 billion tons of waste will be produced worldwide. The waste generated by a person daily worldwide ranges from 0.11 to 4.54 kilos, with an average of 0.74 kilograms. By 2050, it is predicted that the total quantity of waste produced in low-income countries will have more than tripled. [1]. Proper waste management should be given top attention to protect public health and minimize environmental contamination. Waste management and awareness are new ideas in developing nations. Appropriate waste management is required to guarantee sustainable growth and a healthy environment. However, inadequate infrastructure and unsustainable methods have worsened waste management in underdeveloped countries, contaminating the environment [2]. Significant health hazards, such as skin infections and chronic illnesses, result from open dumping and waste pickup at open dumpsites. The issue worsens in slums due to the high human density. It suggests linked environmental/health concerns and improper waste management[3].

The sustainable and proper management of produced solid wastes by various nations worldwide has been a significant problem (4). However, it is more noticeable in developing countries like Nigeria than in industrialized ones. Many developing countries have failed to adequately manage their generated solid waste because they are preoccupied with the rapid speed of industrial and economic growth [5].

Lagos is Nigeria's second most populous state and central urban area after Kano, as well as the country's most economically significant state. The state creates around 12,000 metric tons of waste daily (0.72 kg/person) [6]. To address budget constraints, the Lagos State Government established the Lagos State Waste Management Authority (LAWMA) to oversee waste management policy, including implementation, monitoring, advocacy, and enforcement [7]. As part of its responsibilities, the agency hired a private service provider (PSP) to properly handle the invoice for waste services. LAWMA collects income centrally and remits the agreed-upon 60% of waste levies to individual PSP accounts based on the expected waste collected [6].

In recent years, innovative and environmentally friendly options for waste management techniques have emerged across various industries thanks to the convergence of renewable energy sources and Internet of Things (IoT) technologies [8]. Solar energy can reduce carbon emissions and reliance on non-renewable energy sources; solar power has attracted interest in waste management [7], [9], [10]. However, relying on solar energy for waste management systems can be challenging due to its inconsistent nature. To fully harness the benefits of solar energy in smart waste management systems, there is a need to find a reliable way to store it. This will ensure a consistent power supply for IoT-based waste management systems, allowing them to operate smoothly and maximize the use of renewable energy.[11]. Integrating smart battery storage is vital for storing excess solar energy generated during peak sunlight hours and releasing it when there's little or no sunlight. Batteries allow regulated energy usage across various sectors, including transportation, manufacturing, and power. Optimizing battery life cycle performance to improve battery longevity is a continuous problem for all industries [12]. Incorporating intelligent battery storage systems with solar-powered waste management systems is an exciting prospect. This convergence contributes to more innovative, greener urban environments by addressing the critical need for better waste and energy management. Sustainable power sources such as solar, wind, and hydro-energy are the lights of the future because traditional sources such as fossil, coal, and oil reserves are limited and running out due to rising demand [13]. This study aims to contribute to

JDFEWS 5 (2): 17 - 42, 2024
ISSN 2709-4529

the current IoT interface architecture in waste management systems that run on solar power, taking cognizance of the following aspects:

- Real-time Energy Monitoring.
- Dynamic Energy Switching.
- Predictive Analytics for Optimization.

The design, simulation, and development of smart battery storage integration in Internet of Things-based solar-powered waste management systems are carried out. This study intends to add to the expanding body of knowledge that seeks to address the energy issues in waste management while promoting environmental sustainability by utilizing insights from previous research and industry advances.

Furthermore, integrating IoT and solar-powered smart battery storage in waste management is a big leap toward solving global environmental and operational challenges. Inefficient collection schedules, high operation costs, and reliance on non-renewable energy sources characterize traditional waste management systems. This study's design offers a sustainable alternative through real-time monitoring and energy switching that will change contemporary waste management practices. One major significance of this study is its contribution to environmental sustainability. By harnessing solar energy as a primary power source, the system reduces the traditional dependence on fossil fuels, thereby minimizing carbon emissions. The smart battery storage enables energy storage during periods of low sunlight, thus ensuring the system's continuous operation. This design initiative aligns with the global goals to mitigate climate change and promote [14] adoption.

This paper also demonstrates a practical application of IoT in waste management system. The system optimizes waste collection schedules with real-time data collection and analysis, reducing unnecessary trips and conserving resources. This enhances operational efficiency, lowers costs, and reduces environmental impact. Predictive analytics further enable proactive resource allocation, extending system life and reducing maintenance needs. It is also a scalable and flexible study since architecture could be applied to other urban systems, such as water management or traffic monitoring. Thus, this shows the potential of facing any brilliant city challenge. Equipped with renewable energy and top-notch technologies, the study represents the benchmark for sustainable infrastructure development. Thus, this work points to the inefficiency in waste management and serves long-term environmental goals, reducing operational costs and fostering sustainable IoT-based solutions for urban ecosystems.

II. Related Works

This section highlights the work related to designing and implementing a smart battery storage system integrated into an IoT-based solar-powered waste management system. Having the knowledge that the poor waste management system threatens the environment. The increasing volume of waste generated by urban areas is difficult to manage by traditional waste management systems, which frequently rely on manual labour and inefficient management methods. So, scholars and experts have recommended incorporating the Internet of Things (IoT) into waste management systems to improve waste management.

2.1 IoT Smart Waste Management

IoT is an emerging area that is changing smart cities' solid waste management practices. The scenes of pilled waste and ineffective collection routes are all gone now. These state-of-the-art technologies, integrated with sensor networks, offer real-time data regarding temperature, tilt angles, and fill levels inside the waste can. [15]. This information is then transmitted wirelessly to a central hub, where it is analyzed to determine optimal collection schedules and routes, leading to a form of waste management for cities that are far more efficient, cleaner, and greener. This is because researchers are now looking into various Internet of Things-based waste management techniques. A system using weight and ultrasonic sensors to measure the fill level of the bins and detect overflow instances uploads the data

JDFEWS 5 (2): 17 - 42, 2024
ISSN 2709-4529

collected to a server for web-based monitoring, thus enabling waste management organizations to deal with waste overflow before it happens [16].

Another method used is the gas sensors and ultrasonic sensors [17]. The system will detect dangerous gasses that are released from waste and bin filling levels. Waste management bodies can monitor the waste bin status using real-time data, allowing them to respond to different waste situations on time. More advanced systems use many sensor nodes to monitor bin fill levels and the location of home and public bins [18]. Waste collection agencies reduce time wasted traveling from one place to another, thus reducing fuel consumption by routing optimization using rich data. Furthermore, extra efficiency advantages can also be made possible by using predictive insights and dynamic route adjustments with the help of this rich data using machine learning algorithms. Finally, some systems advance with server-less structures and edge computing [19].

Innovative technologies bring opportunities to a better future for the earth and cities by promoting efficiency, supporting environmental sustainability, and guaranteeing cleaner environments. Researchers are exploring other ways to use IoT in waste management. One example is a home waste management system that uses machine learning, specifically K-Nearest Neighbors (KNN), to sort and compost biodegradable waste [20]. A system that predicts waste bin fill levels based on university class distribution has been developed at the university level. This system uses graph theory and machine learning (ML) with logistic regression (LR) to predict waste buildup. It also uses route optimization for efficient waste collection, has a low-cost circuit design, and LoRa integration. Also, the system uses pressure sensors to measure how full waste bins are. When a bin is almost full, an alert is sent. This helps ensure waste is collected on time, keeping the environment clean. Online apps and text messages are used to send these alerts on specific bin conditions [21]. These methods prove IoT technology can help create cleaner environments, collect waste more efficiently, and protect the environment.

2.2 Smart Battery Storage in Smart Waste Management

Solar-powered Internet of Things (IoT) waste management systems are the foundation of a more sustainable and data-driven method of waste collection. These systems use solar energy to power sensors used in the bins and continuously monitor fill levels, temperature, and even tilt angles. Real-time data is sent through an IoT network to a monitoring system for analysis and route optimization [22]. This technology has several advantages, broadening waste management possibilities. One of the main advantages is using a more environmentally friendly energy source. By using solar energy, this solution minimizes dependence on traditional electricity sources, resulting in a greener approach. This also reduces greenhouse gas emissions related to electricity generation by traditional means and promotes energy independence for waste collection systems [23].

Consequently, Solar power and the Internet of Things (IoT) can improve waste collection. By tracking how full bins are, companies can plan their routes more efficiently, avoiding unnecessary trips and saving money. The data can also help in understanding how waste is generated and where to place bins strategically. A study even showed a 20% reduction in fuel use for city collection vehicles by using real-time bin data to plan routes.[24].

Several studies emphasize the importance of efficient energy. The authors in the cited work [25] proposed a solar-powered method of waste management but highlighted that power consumption needs to be optimized through sensor selection and communication protocol. Ref [26] wrote on the unstable nature of solar energy and suggested using duty cycling for sensors and low-power communication technologies like LoRaWAN. Ref [27] researched the use of rechargeable batteries as a backup, highlighting battery degradation as an issue and the need for effective battery management techniques. The studies highlight the importance of optimizing power consumption for the sustainable use of these systems.

Moreover, solar-powered IoT waste management systems promote data-driven planning. The collected data provides an outlook on waste generation patterns, including differences based on seasonality or population density [28]. This information can be used to plan waste management infrastructure and resource allocation. For example, areas that consistently generate high amounts of waste, planning additional processing facilities, or using targeted waste

JDFEWS 5 (2): 17 - 42, 2024
ISSN 2709-4529

reduction campaigns. Research was done, and data was used to identify areas with high food waste generation. This information was used to start composting initiatives in those areas, reducing waste sent to landfills [29].

The present research has been on using solar or battery power in waste management systems, paying little attention to the Internet of Things (IoT) and its essential part in smart battery storage. This oversight limits the amount of data the system can gather, resulting in incomplete and inconsistent datasets that decrease the system's efficiency. One problem discussed is the inability to check the battery's health or control it remotely without using the Internet of Things (IoT). This shows how important it is to study this and ensure IoT is part of solar or battery-powered waste management systems, hence this study. Using IoT helps us use energy better, making waste management more efficient and eco-friendlier. It does this by improving data collection and letting us monitor and fix batteries from a distance.

III. Methodology

This section provides a systematic approach to designing, developing, and implementing a smart solar-powered waste management system. This process included the definition of system requirements, the selection of appropriate hardware and software components, and the creation of detailed system architecture. Much emphasis was put on integrating IoT technologies, sensors, and smart battery storage for real-time monitoring and efficient energy use. Each stage involves prototyping and simulation to properly deploy the field for functionality and reliability. The methodology consists of various test methods and validation to assess system performance, making it robust and adaptable for sustainable waste management practices.

3.1 Design Process

Developing an innovative waste management system requires system concept, component selection, architectural design, prototyping, testing, integration, deployment, and constant enhancement. Figure 1 below outlines a structured process for developing a smart waste management system. From conceptualization through deployment and improvement, each stage is significant in ensuring the system's success. The system's specifications and objectives are first established, focusing on effective waste monitoring, location tracking, efficient communication, and sustainability. These factors pick components with dependability, compatibility, and energy efficiency given top priority. These components include microcontrollers, GPS/GSM modules, and ultrasonic sensors.

JDFEWS 5 (2): 17 - 42, 2024
ISSN 2709-4529

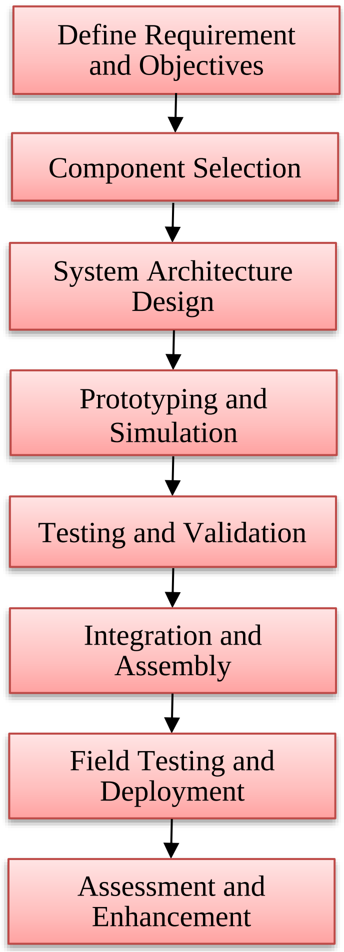

Fig. 1. Design process chart

Next, an efficient system architecture is determined, detailing component interconnections, data flow, and functional needs. Hardware and software components are constructed for optimum performance and integration. Circuit diagrams and virtual prototypes are made to verify the design, spot possible problems, and improve the system.
Then, testing is done at both the component and system levels to ensure peak system performance. Power management, communication stability, and sensor accuracy are tested. Next, the system is assembled using sensors, microcontrollers, communication modules, and parts for power management.

Field testing simulates real-world implementation and provides user input and system performance data. The optimization process is guided by data analysis and user input, improving user interaction, efficiency, and dependability. To maintain system effectiveness and adjust to changing demands, constant review and improvement are necessary to simulate real-world implementation that efficiently handles environmental issues, maximizes waste collection, and offers valuable data for well-informed decision-making.

3.2 System Architecture

In Figure 2, the considered smart waste management system comprises five (5) layers, each having a role to play in ensuring sustainability and effective operation. The system's core is the sensor interface layer, which consists of a

Journal of Digital Food, Energy & Water Systems [JD-FEWS]

JDFEWS 5 (2): 17 - 42, 2024
ISSN 2709-4529

microprocessor to which several sensors are connected, such as ultrasonic, weight, temperature, and humidity sensors. The microcontroller receives data from these sensors, allowing it to track the bin's status (weight of the waste bin, the amount of waste within it, and the conditions of the battery unit). The microcontroller is fitted with a GPS/GSM module, which makes up the Communication Layer that updates the central server with the status and position of the bin. The user interface layer handles user interaction, and the system features a mobile application that displays information about the bin's status and battery conditions.

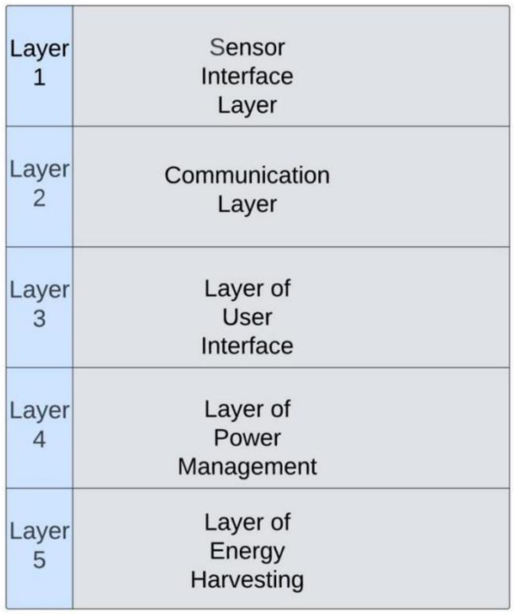

Fig. 2. System architecture diagram

The power management layer maintains reliable operation, and a power module is responsible for managing the distribution of power to the various components of the system. This includes a battery charger controller, which is in charge of the charging process to ensure a stable power supply, which works hand-in-hand with the energy harvesting layer, which boosts sustainability and autonomy; the system incorporates a solar panel that harnesses solar energy to supplement or recharge the battery. This renewable energy source reduces dependence on external power and enhances the system's environmental friendliness.

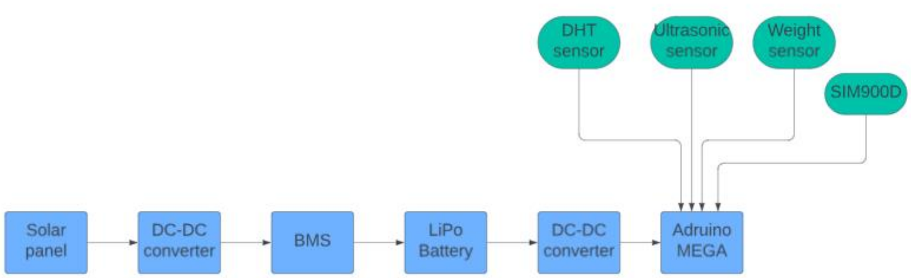

Fig. 3. Block diagram of system architecture

Figure 3 above shows the energy and data flow in the smart waste management system, where solar energy captured via a solar panel feeds directly into a DC-DC converter, regulating it in voltage for storage in a Li-Po battery via

Journal of Digital Food, Energy & Water Systems [JD-FEWS]

JDFEWS 5 (2): 17 - 42, 2024
ISSN 2709-4529

Battery Management System control. However, using another DC-DC converter, this stored energy powers the system with stabilized voltage for the use of the Arduino MEGA microcontroller.

The Arduino MEGA acts as the system's central processing unit, interfacing with sensors such as the DHT sensor for temperature and humidity, the ultrasonic sensor for bin fill level, and the weight sensor for waste weight. It also communicates via a SIM900D GSM module for data transmission to a remote server. This architecture ensures sustainable energy use, precise data collection, and seamless communication, thus enabling efficient operations about waste management. See Figure 4 (Proteus system schematic) for more information on the circuitry connections of the hardware prototype components.

3.3 Hardware Components Selection

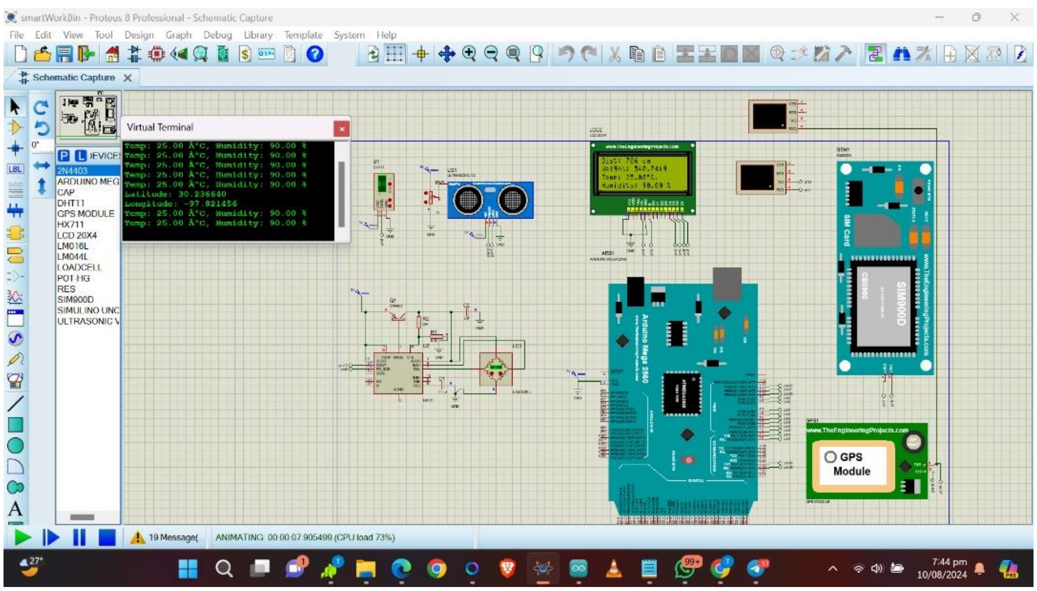

Fig. 4. Proteus system schematic

3.3.1 Microcontroller (Arduino-nano)

The microcontroller, a tiny computing device integrated into a chip, lowly operates the waste management system's peripherals. The microcontroller of choice for both final board design and prototyping is the Arduino-nano. The microcontroller interfaces with the ultrasonic sensor, weight sensor, voltage sensor, temperature sensor, charge controller, and Li-Po battery. Figure 5 below shows the image of the microcontroller used in the project development.

JDFEWS 5 (2): 17 - 42, 2024
ISSN 2709-4529

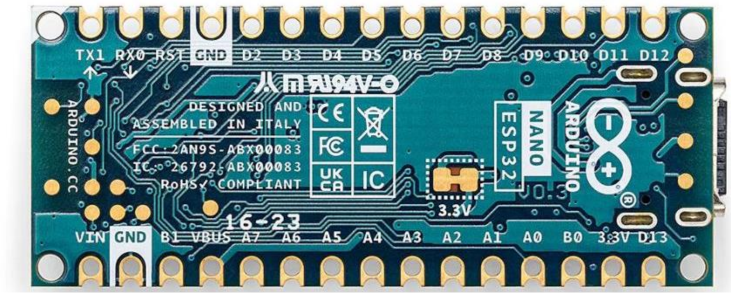

Fig. 5. Arduino-nano microcontroller

3.3.2 Ultrasonic Sensor (HC-SR04)

Ultrasonic sensors use sound waves to measure distances, making them essential for monitoring waste levels. They also enable bin-fill data to be gathered, which is necessary to optimize resource allocation and waste management. An ultrasonic sensor measures the time-of-flight (ToF) of an acoustic wave. Figure 6 below shows the image of the HC-SR04 ultrasonic sensor used in the project development.

Fig. 6. HC-SR04 Ultrasonic sensors

Time-of-Flight Equation of the Ultrasonic Sensor

The fundamental equation governing the operation of an ultrasonic sensor is:

$$\text{Distance (d)} = \frac{\text{Speed of sound (c)} \times \text{Time-of-flight (t)}}{2} \quad (1)$$

Where:

- d represents the distance to the object.
- c represents the speed of sound in the medium (typically air), and
- t represents the time elapsed for the ultrasonic pulse to travel to the object and return.

3.3.3 Weight Sensor (HX711)

Weight sensors make accurate measurement and waste management processes possible. They offer real-time data on waste weight, which is essential for a user reward system based on waste weight. The fundamental concepts of strain gauge technology, especially load cell mechanics, regulate the weight sensor's operation. A weight sensor monitors the force applied to a load and transforms it into an electrical signal that is processed to calculate the weight. Figure 7 below depicts a typical image of an HX711 weight sensor with a load cell used in this project design.

JDFEWS 5 (2): 17 - 42, 2024
ISSN 2709-4529

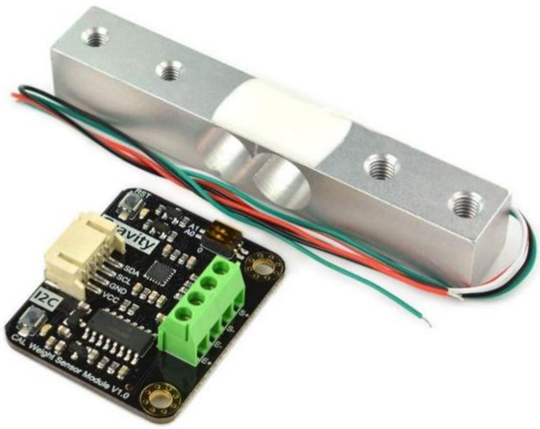

Fig. 7. Weight sensor (HX711) with Load Cell

The governing equation for the operation of a weight sensor can be expressed as follows:

$$V_{out} = S \times F_{applied} \quad (2)$$

Where:

V_{out} is the output voltage of the weight sensor (in volts).
S is the sensitivity of the sensor, also known as the calibration factor (in volts per unit force), and
$F_{applied}$ is the applied force or weight (in newtons or grams, depending on the calibration).

Conversion of Force to Weight: In real-world applications, the acceleration caused by gravity, or g (or 9.81 m/s^ on Earth), is frequently considered when converting the applied force, or F, to weight. Thus, the following relation may be used to find the weight if the output voltage matches a force:

$$W = \frac{V_{out}}{S} = F_{applied} = m \,.\, g \quad (3)$$

In this case, mass is denoted by m and gravitational acceleration by g.

3.3.4 Voltage Sensor

Voltage sensors monitor electrical potential variations to provide a steady power supply to the system. They improve system dependability and enable timely interventions via real-time voltage change detection. Fig. 8 below shows a typical image of a voltage sensor used in this project development.

Fig. 8. Voltage Sensor

JDFEWS 5 (2): 17 - 42, 2024
ISSN 2709-4529

3.3.5 DHT Sensor Unit

The DHT sensors unit integrates temperature and humidity sensors to monitor environmental conditions within the waste bin's battery unit. These sensors play a crucial role in ensuring that the operational environment remains within safe and optimal limits, thereby enhancing the longevity and performance of the battery system. Figure 9 below shows a typical example of a DTH11 sensor used in this project development.

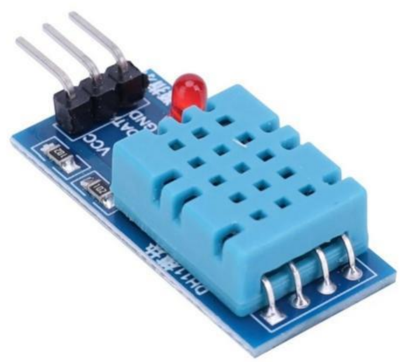

Fig. 9. DTH11 Sensor

Temperature Sensor: The DHT unit's temperature sensor measures the ambient temperature inside the waste bin battery enclosure.

Humidity Sensor: The DHT unit's humidity sensor measures the relative humidity inside the waste bin battery enclosure.

3.3.6 SIM900D

SIM900D in Figure 10 is a small and reasonably priced GSM/GPRS module that allows devices to communicate over cellular networks through features like SMS, voice calls, and GPRS data transmission. Because of its low power consumption, small size, and ease of integration, the SIM900D is used in IoT projects, remote monitoring systems, and mobile-based applications. It works especially well in smart systems, providing cellular communication capabilities that let the system send and receive commands remotely. The SIM900D creates a wireless link to the cellular network by combining a SIM card and a GSM module. This allows real-time communication with external servers, management platforms, or mobile applications.

JDFEWS 5 (2): 17 - 42, 2024
ISSN 2709-4529

Fig. 10. SIM900D Diagram

3.3.7 SIM7600H

The SIM7600H is an LTE Cat 4 module that supports LTE-TDD/LTE-FDD/HSPA+/GSM/GPRS/EDGE networks and provides fast wireless connection. This is shown in Figure 11. It has a 50 Mbps upload speed and a 150 Mbps maximum download speed. This allows easy migration and flexible product design due to the SIM7600H's compact LCC1 size and compatibility with previous module generations. The module combines high-accuracy GNSS location technologies with several satellites. Its support for several network protocols and compatibility with different operating systems make it adaptable and user-friendly. It also has a wide array of interfaces, which include UART, USB, I2C, and GPIO.

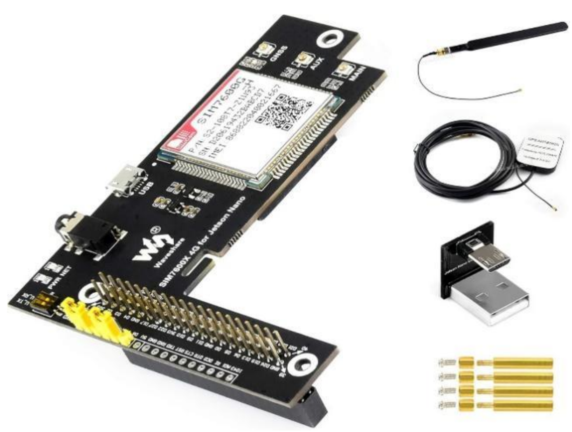

Fig. 11. SIM7600H Diagram

JDFEWS 5 (2): 17 - 42, 2024
ISSN 2709-4529

3.4 Battery Management System

A battery management system (BMS) manages the charge and discharge of a battery to keep it in safe operating condition. In general, it monitors and keeps the battery in good health. The system integrates circuitry for charge protection, discharge protection, temperature protection, and battery health monitoring, having the following features:

i. Over-voltage Protection
ii. Over-current Protection
iii. Under-voltage Protection
iv. Charge Balancing

Over-Voltage Protection

This voltage protection feature under charge protection protects from overcharging, acquiring a voltage level greater than the manufacturer's rated voltage upper limit. With this feature, the circuit ensures the battery can charge each cell to a nominal voltage and cuts off or stops charging the battery before it reaches its maximum specified voltage to prevent overcharge.

Over-current protection

The BMS also protects the battery against loads that draw excessive amounts of current, such as capping or setting a boundary to the maximum current supply.

Under-Voltage Protection

The BMS also protects the battery from usage beyond its rated under-voltage specification, beyond which the battery would be damaged. It cuts off discharge when the voltage drops to this level. For a single cell, the under-voltage rating is about 2.5V.

Charge Balancing

This is also a feature under charge protection for the battery. The BMS also ensures that approximately the same voltage level is reached across all the cells, preventing a case of one cell having a higher or lower voltage than another.

3.5 DC to DC Converter

The DC-to-DC step-down converter adjusts the solar panel or battery unit's voltage levels to meet the needs of the smart waste bin system. It ensures compatibility with electrical components operating at lower voltage levels by effectively converting greater input to lower output voltages. The step-down converter maximizes energy economy and system performance by controlling voltage output, filtering noise, and supplying steady power to delicate devices. The DC-to-DC step-down converter increases overall system dependability and prolongs battery life in renewable energy-based applications by improving energy conversion and use.

3.6 LI-PO Battery

Lithium polymer (LiPo) batteries are the main energy storage option with their great energy density and dependability. They are perfect for smart battery storage applications because of their extended cycle life and rechargeability. To determine the size of the battery, several factors need to be considered; see calculations in section 3.7 below.
The LiPo battery is integrated with a BMS to ensure the solar charging system works safely and efficiently. This is the model that controls the charging balancing/control for overcharging and undercharging control. The BMS works

JDFEWS 5 (2): 17 - 42, 2024
ISSN 2709-4529

in synergy with the solar controller and DC-DC converters for regulating power flow from the solar panel to the battery and connected devices.

3.7 Calculations

Calculations on the Amount of Energy Consumed per Cycle

The Arduino Nano operates for 10 seconds to connect to Wi-Fi and transmit data, then sleeps for 10 minutes. The power consumption for the sensors is constant while the Arduino Nano is active. Given:

- Arduino nano: 130mA
- Ultrasonic Sensor: 6.3mA
- Weight Sensor: 16.7mA
- Temperature Sensor: 20mA
- Voltage Sensor: 15.5mA

Total current draw when active, Pt

$$Pt = 130mA + 6.3mA + 16.7mA + 20mA + 15.5mA = 188.5mA.$$

The active time per cycle, T is 10 seconds every 10 minutes, and the deep sleep time is negligible. The energy consumed per cycle is;

$$Pt \times \mathrm{T} = 188.5mA \times 10s = 1885mAs$$

Therefore, the energy consumed in an hour is;

$$Pt \times \mathrm{T} \times 6 = 6 \times 1885mAs = 11310mAs$$

In battery charge capacity it consumes;

$$\frac{11310}{3600}mAh = 3.141667mAh$$

In a year it consumes (16hours run time);

$$3.141667 \times 16 \times 365 = 18347.33528mAh$$

Therefore, the battery needs to store at least $18347.33528mAh$ all year.

Calculation of Solar Panel Size

When calculating the solar panel size for the system, the following factors were considered to determine the solar panel size:

- **i.** Power Consumption of Components
- **ii.** Operating Hours
- **iii.** Efficiency Losses
- **iv.** Sunlight Availability
- **v.** Battery Capacity
- **vi.** Safety Margin

$$\text{Solar Panel Size (W)} = \frac{\text{Total Daily Energy Consumption (Wh)}}{\text{Average Sunlight Hours per Day}\times\text{Efficiency}} \quad (4)$$

Total Daily Energy Consumption (Wh) = Sum of power consumption of all components multiplied by their operating hours per day.
Efficiency Factor = Factor accounting for efficiency losses in the system (usually between 0.7 and 0.9).
So, Efficiency = 0.9 (selected)
the power consumption of the following is:

1. The Microcontroller unit (ESP 32) = P_1(W)
2. Ultrasonic Sensor Unit = P_2(W)
3. Weight Sensor Unit = P_3(W)

JDFEWS 5 (2): 17 - 42, 2024
ISSN 2709-4529

4. DHT Sensor Unit= P_4(W)
5. SIM800L unit = P_5(W)

$$P_T = P_1(W) + P_2(W) + P_3(W) + P_4(W) + P_5(W) \quad (5)$$

Let the operating hour be **T**

Average sunlight hour per day in Lagos = 5hr

Total Daily Energy Consumption = $P_T \times T$

$$\text{Solar Panel Size(W)} = \frac{P_T \times T}{5 \times 0.9} = \frac{(P_T \times T)}{4.5} = \frac{2}{9}(P_T \times T)\ \text{(W)} \quad (6)$$

Then, the conversion of the solar panel size in watt to meter square:

$$\text{Solar Panel Size(m}^2\text{)} = \frac{Solar\ Panel\ Power\ (W)}{SOlar\ Irradiance\left(\frac{W}{m^2}\right) \times Solar\ Panel\ Efficiency} \quad (7)$$

The efficiency of solar panels is about 15%

Solar Irradiance in Lagos is 184.17 (w/m^2)

$$\text{Solar Panel Size(m}^2\text{)} = \frac{\frac{2}{9}(P_T \times T)}{184.17 \times 0.15} = \frac{\frac{2}{9}(P_T \times T)}{27.6255} = 8.04(P_T \times T) \times 10^{-3}(m^2) \quad (8)$$

IV. Results

This section presents the designed and developed smart waste management system, emphasizing field performance. Designed performance evaluation of the functionality covers mainly the energy efficiency, accuracy, and reliability of system operations. The findings confirm that the system can improve waste collection and resource optimization through data-driven decision-making. This section outlines the development process after implementing and discussing smart battery storage integration in IoT-based solar-powered waste management systems, expanding on the implementation decisions and the project's outcomes. It delves into the integrated system's essential features and functionalities.

4.1 Performance

The designed smart waste management system showed strong performance in each key component. IoT sensors have been used for real-time monitoring, effectively measuring the bin's fill level, weight, and environmental parameters like temperature and humidity. Similarly, integrating GPS and GSM modules ensured accurate location tracking and efficient data transfer to a central control system. The solar-powered energy setup, complemented by a smart Li-Po battery storage system, provided a consistent power supply, reducing reliance on grid energy. Dynamic energy switching mechanisms effectively optimize power usage, preventing overcharging and undercharging of the battery. Field testing confirmed the system's ability to sustain operations under varying environmental conditions, ensuring uninterrupted functionality. Overall, it greatly improved the efficiency of waste collection and resource use while providing a scalable, sustainable response to waste management concerns. The waste management system's performance is based on the functionality and efficiency of the components performing their tasks individually and as a whole.

Journal of Digital Food, Energy & Water Systems [JD-FEWS]

JDFEWS 5 (2): 17 - 42, 2024
ISSN 2709-4529

4.1.1 Hardware Performance

The SIM7600H module replaced the SIM900D module during the prototype development stage. The requirement for more excellent compatibility and speed led to this choice. The SIM7600H provides noticeably faster 4G connectivity than the SIM900D, a reliable 3G module. This allows for more effective data transfer and real-time communication. Furthermore, the SIM7600H ensures secure connectivity by being compatible with various network standards. The system dynamically switches away from solar energy, stopping the battery charging when it is complete and allowing a transition from solar to battery power. This feature maximizes the solar system's efficiency and helps prolong the battery's lifespan.

The battery system minimized energy drain by ensuring consistent power delivery to all sensors and modules through regulation of energy demand and entry into low-power modes during idleness. The waste bin system functions correctly over extended periods and was supported by recharging and proper maintenance, which were made possible by monitoring battery health and charge state. The Ultrasonic Sensor (HC-SR04), connected with the microprocessor to send the data collected for real-time monitoring, identified the waste bin's fill levels. The Load Cell (HX711) accurately measured the waste's weight, resulting in accurate weight measurements that were collected and displayed successfully. The DHT11 Sensor efficiently monitored the temperature and humidity levels within the waste bin battery unit to ensure that battery conditions could be monitored and sent to the system for analysis.

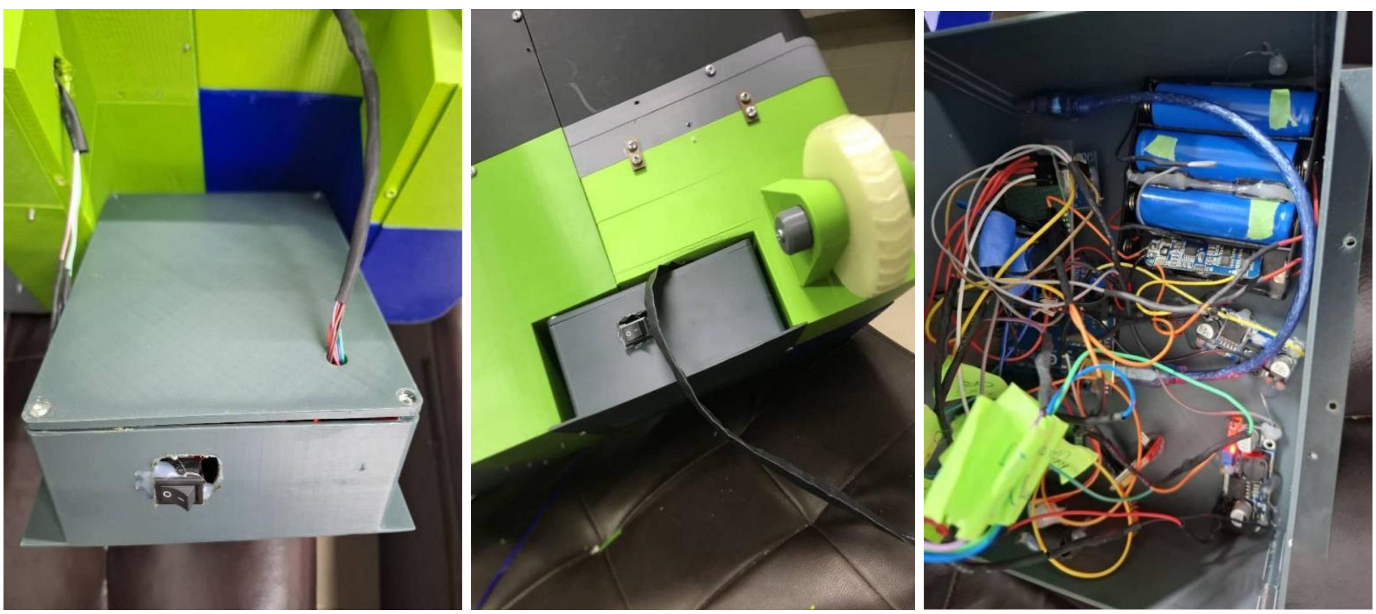

Fig.12. Images showing the circuit inside the developed system (inward and outward view).

Figure 12 above clearly shows the images of the inward view, exposing the inner circuits and components of the system, and the outward view, showing the fully packaged design of the developed system. This unit was placed at the bottom of the designed smart IoT-based solar-powered waste bin.

The GPS Module (TinyGPS++) tracked the waste bin's location, and the alarm system sent alerts at the desired conditions. When specific conditions were met, such as the bin filling up to capacity or specific bin conditions were met, the GSM Module sent out SMS notifications.

Also, Figure 13 below depicts the fully packaged design integrated into an IoT-based solar-powered waste management system with a solar panel on top of the waste bin. Even though the Li-Po battery is the main source of

Journal of Digital Food, Energy & Water Systems [JD-FEWS]

JDFEWS 5 (2): 17 - 42, 2024
ISSN 2709-4529

energy storage in the system, the integration of solar energy into it plays a vital role in making the smart waste management system work sustainably and efficiently. In other words, the Li-Po battery acts like an energy storage facility, while the solar panels are its primary energy source, making this solution highly reliable, renewable, and cost-effective; rather than changing the batteries at intervals, the solar panel allows for longer system usage.

Fig. 13: Image of the designed smart battery storage system integrated into an IoT-based solar-powered waste.

4.1.2 Software Performance

The system's software parts, such as the custom functions and Arduino libraries, worked together with the hardware's, allowing the system to operate and communicate as intended. The Arduino libraries achieved reliable functioning and data transfer, promoting proper integration and communication between the microcontroller and hardware components. The component functions were done by using custom functions, such as using the ultrasonic sensor to measure distance, processing GPS module position data, and sending SMS notifications when sensor readings met specified conditions. Due to these functionalities, the system could monitor and make decisions in real-time. Figure 14 shows the system's real-time monitoring capabilities using bin sensors' data.

JDFEWS 5 (2): 17 - 42, 2024
ISSN 2709-4529

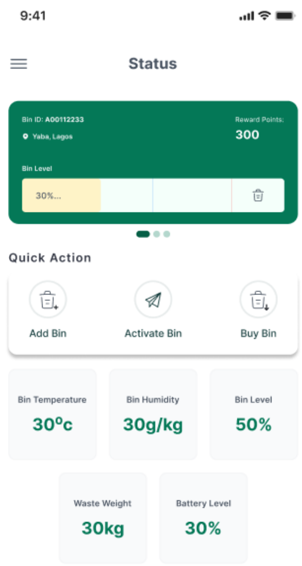

Fig. 14: Mobile app: Monitoring page

4.1.3 System Functionality

The waste bin's fill level was measured using the ultrasonic sensor, and the fill level was displayed on the system database. The load cell weighed the waste, and the database stored the results. Monitoring the battery unit conditions was done by measuring temperature and humidity with the DHT11 sensor. The GPS module provided the location of the bin. The system continually monitored distance, weight, temperature, and humidity to ensure that any predetermined conditions resulted in an SMS alert.

4.1.4 Alert System

The system is designed to send an alert SMS when critical conditions are detected. Alerts are triggered if:

- The waste bin is nearly full (distance < 20 cm).
- The waste weight exceeds 500 g.
- The temperature rises above 50°C.
- The humidity level exceeds 90%.

The alert SMS includes the current distance, weight, temperature, humidity, and GPS location (if valid). This ensures that stakeholders are promptly informed of critical conditions requiring immediate attention.

JDFEWS 5 (2): 17 - 42, 2024
ISSN 2709-4529

Table 1: Waste bin conditions and fill level indication

Condition No.	Threshold	Indication	SMS Sent	Description	Action Required
1	Distance < 20 cm	Nearly Full Bin	Yes	Indicates that the waste bin is nearly full and requires immediate attention to avoid overflow.	Schedule waste collection immediately.
2	Weight > 500 g	Exceeds Weight Limit	Yes	Indicates that the waste bin's weight exceeds the safety limit, risking damage to the system.	Collect and empty the waste bin.
3	Temperature > 50°C	High Temperature Alert	Yes	Indicates an abnormal temperature rise, which could signal fire risk or environmental issues.	Inspect and mitigate overheating.
4	Humidity > 90%	High Humidity Alert	Yes	Indicates excessive humidity levels, which could affect waste decomposition or system hardware.	Investigate and address humidity issue.
5	Valid GPS Location	Location Tracking Active	Yes (included in alerts)	Provides real-time GPS location for the waste bin, ensuring precise location tracking.	Use for planning efficient collection.

Table 1 above highlights the system's ability to promptly detect and respond to critical conditions, ensuring effective waste management. Each SMS includes real-time location, distance, weight, temperature, and humidity data to provide actionable insights.

V. Conclusion

The smart waste management system integrated hardware and software to ensure precise monitoring and efficient data transfer, and the findings showed that it performed reliably across all components. The ultrasonic sensor, load cell, DHT11 sensor, GPS module, and GSM module provided real-time information on the bin's location, weight, fill levels, and environmental conditions. The power management features of the smart battery system further guarantee reliable performance over long periods, cutting downtime and maximizing energy use. The system proved reliable for enhancing waste-collecting procedures via resource efficiency and data-driven decision-making.

This research has successfully integrated IoT and solar energy into the smart waste management system and addressed the key objectives such as real-time monitoring and dynamic energy management and optimization. Real-time monitoring is enabled through the precise tracking of energy metrics and bin status, with seamless source switching enabling the dynamic energy management system for uninterrupted operations and optimization through predictive analytics to bring in improved energy allocation and reduce operational inefficiencies. Therefore, the sustainability and scalability of the system make it promising for addressing modern urban challenges. This may be expanded in further works for use in other smart city systems, implementing machine learning for improved predictive abilities.

JDFEWS 5 (2): 17 - 42, 2024
ISSN 2709-4529

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JDFEWS 5 (2): 17 - 42, 2024
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APPENDIX

MICROPROCESSOR CODE

```
#include <LiquidCrystal.h>
#include <DHT.h>
#include <TinyGPS++.h>
#include <SoftwareSerial.h>
#include <HX711.h>

// Pin Definitions
#define TRIG_PIN 12
#define ECHO_PIN 11
#define DHT_PIN 8
#define LOADCELL_DOUT_PIN 10
#define LOADCELL_SCK_PIN 9
#define GSM_TX 0
#define GSM_RX 1
#define GPS_RX 18
#define GPS_TX 19
// LCD Pins
LiquidCrystal lcd(2, 3, 4, 5, 6, 7);
// DHT11 Setup
#define DHTTYPE DHT11
DHT dht(DHT_PIN, DHTTYPE);
// HX711 Setup
HX711 scale;
```

JDFEWS 5 (2): 17 - 42, 2024
ISSN 2709-4529

```
// GPS Setup
TinyGPSPlus gps;
HardwareSerial &gpsSerial = Serial1; // Using Serial1 for GPS
// GSM Setup
SoftwareSerial gsmSerial(GSM_RX, GSM_TX);
void setup()
{
   // Initialize Serial Monitor
   Serial.begin(9600);
   // Initialize LCD
   lcd.begin(20, 4);
   lcd.print("WELCOME");
   delay(300);
   lcd.clear();
   // Initialize DHT11
   dht.begin();
   // Initialize HX711
   scale.begin(LOADCELL_DOUT_PIN, LOADCELL_SCK_PIN);
   // Initialize GPS
   gpsSerial.begin(9600);
   // Initialize GSM
   gsmSerial.begin(9600);
   delay(10);
}
void loop()
{
   // Read and display ultrasonic distance
   long distance = measureDistance();
   lcd.setCursor(0, 0);
   lcd.print("Dist: ");
   lcd.print(distance);
   lcd.print(" cm");
   delay(50);
   // Read and display weight from HX711
   float weight = scale.get_units(10) / 1000; // Convert to kg
   lcd.setCursor(0, 1);
   lcd.print("Weight: ");
   lcd.print(weight);
   lcd.print("kg");
   delay(50);
   // Read and display temperature and humidity from DHT11
   float temperature = dht.readTemperature();
   float humidity = dht.readHumidity();
   if (isnan(temperature) || isnan(humidity))
   {
      Serial.println("Failed to read from DHT sensor!");
   }
   else
   {
      Serial.print("Temp: ");
      Serial.print(temperature);
      Serial.print(" °C, ");
      Serial.print("Humidity: ");
      Serial.print(humidity);
      Serial.println(" %");
      lcd.setCursor(0, 2);
      lcd.print("Temp: ");
```

```
      lcd.print(temperature);
      lcd.write(223); // Print the degree symbol (°)
      lcd.print("C, ");
      lcd.setCursor(0, 3);
      lcd.print("Humidity: ");
      lcd.print(humidity);
      lcd.print(" %");
      delay(50);
    }
    // Process GPS data
    while (gpsSerial.available() > 0)
    {
      gps.encode(gpsSerial.read());
    }
    if (gps.location.isUpdated())
    {
      float latitude = gps.location.lat();
      float longitude = gps.location.lng();
      Serial.print("Latitude: ");
      Serial.println(latitude, 6);
      Serial.print("Longitude: ");
      Serial.println(longitude, 6);
    }
    // Check conditions and send alert if needed
    if (distance < 10 || weight > 5000 || temperature > 40 || humidity > 80)
    {
      sendAlert(distance, weight, temperature, humidity);
    }
    delay(100); // Wait for 2 seconds before next loop
  }
  long measureDistance()
  {
    digitalWrite(TRIG_PIN, LOW);
    delayMicroseconds(2);
    digitalWrite(TRIG_PIN, HIGH);
    delayMicroseconds(10);
    digitalWrite(TRIG_PIN, LOW);
    long duration = pulseIn(ECHO_PIN, HIGH);
    long distance = duration * 0.034 / 2;
    return distance;
  }
  void sendAlert(long distance, float weight, float temperature, float humidity)
  {
    // Prepare the alert message
    String message = "ALERT! Bin Full or Critical Condition.\n";
    message += "Dist: " + String(distance) + " cm\n";
    message += "Weight: " + String(weight) + " g\n";
    message += "Temp: " + String(temperature) + " *C\n";
    message += "Humidity: " + String(humidity) + " %\n";
    if (gps.location.isValid())
    {
      message += "Location: https://maps.google.com/?q=";
      message += String(gps.location.lat(), 6) + "," + String(gps.location.lng(), 6);
    }
  {
    // Send the message via GSM module
    gsmSerial.println("AT+CMGF=1"); // Set GSM module to text mode
```

JDFEWS 5 (2): 17 - 42, 2024
ISSN 2709-4529

```
  delay(100);
  gsmSerial.println("AT+CMGS=\"+2349039227520\""); // Replace with your phone number
  delay(100);
  gsmSerial.print(message);
  delay(100);
  gsmSerial.write(26); // End SMS command
  delay(100);
}
```