



Renewable Energy-Based Smart Waste Management System for a Circular Economy

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KEYWORDS

Waste Management (WM),
Solar Energy,
Internet of Things (IoT),
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Sustainability,
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ABSTRACT

The urbanization of cities and the growing population have led to an increase in municipal solid waste generation, which has become an environmental and public health issue in urban areas. Traditional waste collection systems are characterized by overflowing garbage bins, unnecessary pickup operations, high cost of operation, and associated environmental impact. This paper presents the design and development of the Solar-Powered Smart Waste Management System (SWMS), which uses renewable energy and IoT technology to monitor and manage waste. SWMS consists of a smart waste bin that is managed by the ARDUINO UNO microcontroller and ultrasonic, temperature, humidity, and load cell sensors that monitor waste level, environment, and weight of the waste. Communication is established by the GSM and GPS modules, and a solar panel along with a rechargeable battery serves as a power source for SWMS. The ultrasonic sensor was able to detect the changes in the level of waste, the load cell sensor detected the changes in the weight of the waste, and the temperature and humidity sensors gave environmental readings. The GSM module was able to send notifications, whereas the solar panel was able to charge the battery, and the charged battery supplied power to the prototype. Simulation was also performed on the system using Proteus software to validate the operation of the electronic control and monitoring process. It should be noted that Proteus was not able to simulate the operation of the solar panel, battery management system (BMS), buck converter, and the entire battery subsystem. Thus, the results of the study prove the operation of the prototype, but not the full quantification of the accuracy of sensors or renewable energy.

CITATION

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INTRODUCTION

Solid waste management of both rural and urban areas in Nigeria is an important issue when considering the environment, society, and economics. Among the existing challenges are inefficient waste collection techniques, lack of proper waste disposal infrastructure, lack of waste collection capacity, and increasing amount of solid waste generated due to population growth and urbanization that

may increase pressure on waste management systems (Ukala et al., 2020). Recent research continues to emphasize waste collection and monitoring, resource utilization, and lack of waste management infrastructure as critical issues in developing countries with rapid urbanization (Okubanjo et al., 2024; Atofarati et al., 2025). Such challenges also reveal the necessity to shift from solid waste disposal to resource recovery, reuse, and

recycling. The concept of circular economy offers a solution to such problems by using resource efficiency, waste reduction, recycling, and value recovery from waste flows (Guman & Wegner-Kozlova, 2020; Iacovidou et al., 2021; Suárez-Eiroa et al., 2019; Xiao et al., 2020).

Advances in the Internet of Things (IoT), sensor technology, wireless communications, embedded devices, and smart city technologies offer scope for enhancing waste monitoring and collection processes. IoT-based solutions make it possible to integrate sensors, microcontrollers, communication modules, and monitoring software for acquiring data regarding the status of waste bins and then for remote sensing and analysis (Gubbi et al., 2013; Nižetić et al., 2019; Ogbolumani & Mabaso, 2023). Recent studies have shown examples of the utilization of ultrasonic sensors, IoT communication capabilities, cloud computing, and real-time monitoring for detecting the level of waste and managing its collection (Addas et al., 2024; Henaïen et al., 2024). Likewise, waste collection through IoT-based models using real-time monitoring and routing decisions has also been explored (Hussain et al., 2024; Khan et al., 2024; Ogbolumani & Adekoya, 2025). All of these developments suggest that smart waste management is gradually evolving from the stage of sensing prototypes towards systems capable of monitoring and communication as well as collection planning (Ogbolumani & Godfrey, 2024).

Current literature reviews have also indicated that good waste management is becoming more related to Industry 4.0 and artificial intelligence technologies. For example, Kannan et al. (2024) reviewed the implementation of the mentioned technologies in waste management and developed a model that connects smart people, smart cities, smart enterprises, and smart factories. Olawade et al. (2024) recognized real-time monitoring, route optimization, dynamic scheduling, and prediction technologies as emerging ones in smart waste management. Recent scientific papers have been dedicated to the issue of IoT implementation problems and sustainability aspects in developing countries' waste management systems (Dehshiri et al., 2025). Lakhout (2025) discussed the growing use of IoT and artificial intelligence technologies in the process of waste collection, sorting, recycling, and resource recovery. The above studies prove the growing development of smart waste management, but they also suggest that system design should consider the particularities of technological integration and the target environment.

The employment of renewable energy for powering IoT-enabled waste management systems has been another area of interest regarding reducing the dependence on existing electric supply and operating in areas where there is a limited possibility of accessing the power grid (Zubairu, 2026). Previous research has considered the employment of solar energy, battery power, sensors for waste level

detection, and wireless communication for smart waste bin prototypes (Mohd Yusof et al., 2018; Kumaravel & Ilankumaran, 2022; Kabir et al., 2020). Modern research continues to explore the use of intelligent waste management systems combining sensing, communication, automation, and other technologies (Henaïen et al., 2024; Atofarati et al., 2025). However, the functional features and subsystem combination of different systems vary greatly. While some researchers focus on waste-level detection and communication only, others emphasize waste collection optimization, the use of artificial intelligence, or even more complex approaches in municipal waste management (Addas et al., 2024; Hussain et al., 2024; Lakhout, 2025; Ajibola & Ogbolumani, 2024).

Thus, there is an identified research gap at the prototype stage regarding the combination of various monitoring and support functionalities in a single solar-assisted intelligent waste management system. Specifically, there is no consistent consideration of the combination of waste-level sensing, waste weight sensing, environmental condition sensing, GSM communication, GPS localization, and solar energy power supply in the prototype under discussion. At the same time, modern scientific studies consider system-level integration and sustainability issues; however, most of the presented solutions are oriented toward various specific functionalities such as route optimization, cloud-based monitoring, artificial intelligence, and decision support systems for municipalities (Kannan et al., 2024; Dehshiri et al., 2025; Lakhout, 2025). This means that there is an opportunity to research a relatively compact prototype with the integration of the mentioned elements.

This research takes advantage of this opportunity through the design and implementation of a Solar-Powered Smart Waste Management System (SWMS). This proposed system uses waste level sensors, waste weight sensors, and environmental sensors, along with communication, positioning, and solar-powered electrical subsystems. An Arduino Uno microcontroller will be used for the acquisition of sensor data and control. The ultrasonic sensor will be used to detect the waste level, while the load cell will be used for waste weight detection. Sensors for temperature and humidity will be included in order to monitor the environmental status inside the waste-bin environment. The GSM and GPS modules are included for communication and positioning purposes, respectively. The electrical subsystem comprises the solar panel, rechargeable battery, BMS, and related power conversion components.

The primary purpose of this study is to design and develop an Internet-of-Things-based smart waste management system powered by solar energy. The detailed objectives include: (i) design a smart waste bin that can monitor the level and weight of waste; (ii) install sensors to monitor the

temperature and humidity of the environment; (iii) install the GSM module and GPS module for communication and localization, respectively; (iv) design the electrical power subsystem of the proposed prototype based on solar energy; and (v) evaluate the functional operation of the developed system with a prototype and simulation environment.

Literature Review

Solid Waste Management with the help of Internet of Things (IoT) Technologies has been receiving significant attention due to the possibility of providing instant information regarding the state of waste bins and a more efficient solid waste collection process. IoT-enabled waste management systems can combine sensors, embedded control systems, communication technologies, and monitoring systems to enable remote monitoring of waste bins. This technology has the potential to make the information available for waste management officers and make the waste collection process more flexible (Gubbi et al., 2013; Nižetić et al., 2019; Pardini et al., 2020).

An IoT-based bin-level monitoring system has been designed by Ramson et al. (2021) for solid waste management. In this system, sensors installed in the waste bins were used to determine the level of non-filling in the bins and send the data for remote monitoring. They conducted experimental analysis of the system using different fill levels and also studied the communication distance, system lifetime, and implementation cost. The results showed the effectiveness of using a self-sustaining IoT-based approach for bin-level monitoring. Nevertheless, waste-level detection was the main feature, not both the measurement of waste weight and environmental conditions (Ramson et al., 2021).

An IoT-based smart-bin system for keeping a clean environment through automated waste monitoring has been proposed by Murugaanandam et al. (2018). It is the use of using embedded sensing and communication technologies for waste-bin condition monitoring and provides information through the connected monitoring system. The paper shows an example of how the IoT technology could be used to automate the waste-bin monitoring process. However, the discussed system is not mainly based on the integration of energy supply with waste and environmental measurements (Murugaanandam et al., 2018).

Pardini et al. (2020) proposed an intelligent waste management system using IoT technology where sensors were employed for continuous monitoring of the filling level of compartments in waste bins. This information was then transmitted via an IoT-based communication and processing system to facilitate waste collection management. This research involved a physical prototype and a real-life experiment for testing the proposed system.

This research highlights the incorporation of sensing, communication, data processing, and monitoring for waste management applications. However, the primary focus of this research was on real-time waste level monitoring and waste collection management instead of incorporating waste level, waste weight, environment, and solar energy into a single prototype (Pardini et al., 2020).

Mohd Yusof et al. (2018) introduced a smart bin that has a real-time monitoring system consisting of renewable energy, sensing, wireless communication, and notification capabilities. In their report, the system consists of the following elements: Arduino controller, ultrasonic and passive infrared (PIR) sensors, ESP8266 Wi-Fi communication, GSM/GPRS, and a solar power system. In the proposed system, a smart bin using solar power and a communication mechanism have been employed for remote monitoring and notification. This research paper is pertinent to the current research because of the combination of solar power, sensing, and wireless communication within a smart waste management system. Nevertheless, the design of the reported system varies from the current study in terms of waste level, weight, and environment sensing functions.

Kumaravel and Ilankumaran (2022) examined an IoT-based intelligent system that tracks the power of batteries and the levels of waste for a solar waste bin utilizing GSM technology. The intelligent system involved the use of photovoltaic power, battery power management, waste level monitoring, and GSM communication. This research presents an example of the potential of using solar power and battery storage as the driving force for a smart waste bin. While this research focuses mainly on the battery power and waste level tracking, it lays the foundation for adding other monitoring functions such as weight and environment measurements to the solar waste-management system prototype.

Kabir et al. (2020) presented an IoT-based solar energy-powered smart waste management system with real-time monitoring for the smart city. The proposed system included the use of solar energy, wireless sensor networking, Arduino Mega, ultrasonic and PIR sensors, GSM technology, and a LoRa communication module. The purpose of the system was to provide remote monitoring of solar-powered smart bins and assist waste collection operations. This system illustrates the possibility of using a renewable energy source along with waste level monitoring, wireless technology, and remote monitoring. However, the proposed system was based more on the monitoring of waste bins and their collection (Kabir et al., 2020).

Further research has looked at the use of smart technologies and circular economy concepts, which create a wider context for an intelligent waste-management system. For example, Nižetić et al. (2019) provided a review on the use of smart technologies in

relation to energy efficiency, sustainable resource usage, and waste management. In this case, the authors highlighted the connection between technologies and the resource-management process. Another study conducted by Guman and Wegner-Kozlova (2020) was related to waste management according to the principles of the circular economy and stressed resource recovery and sustainable waste-management practices. The work by Iacovidou et al. (2021) investigated challenges of the

circular economy through the systems thinking approach. The authors showed that technological interventions should be viewed in the wider context of resource and waste management.

These different SWMS reviewed vary in terms of the sensing, communications, energy, and storage methods, and validation processes utilized. The selected studies have been compared in Table 1.

Table 1: Comparative Analysis of Selected Smart Waste Management Systems

Research	Sensor/Monitoring	Communication	Power Supply	Energy Storage/Autonomy	Test/Validation
Ramson et al. (2021)	Bin unfilled/waste level	Wireless communication and central monitoring	Self-powered	Self-powered monitoring; lifetime assessment of the system	Tests on fill level, transmission distance, and system lifetime/cost
Murugaanandam et al. (2018)	Smart-bin sensor and waste condition monitoring	Ethernet and web-based monitoring	Not mentioned to be solar powered	Not mentioned	Prototype demonstration
Pardini et al. (2020)	Filling level of bin compartment	IoT communication and middleware	Not mentioned as being solar powered	Not mentioned as being important	Physical prototype and experimental use case
Mohd Yusof et al. (2018)	Ultrasonic and PIR sensors; waste-bin monitoring	ESP8266 Wi-Fi, GSM/GPRS and SMS	Solar power	Solar power subsystem	Prototype/system demonstration
Kumaravel and Ilankumaran (2022)	Waste level and power monitoring	GSM	Photovoltaic solar power	Battery and power conversion system	Prototype/system assessment
Kabir et al. (2020)	Ultrasonic and PIR sensors; waste level monitoring	LoRa, GSM and wireless sensor networking	Solar power	Solar-based power system	System/prototype demonstration
Present study	Ultrasonic waste level sensor, load cell, temperature/humidity sensor	GSM and GPS-based functionality	Solar power and rechargeable battery	3S battery, BMS and power conversion subsystem	Prototyping and Proteus simulation

Note. BMS refers to battery management system; GSM is short for Global System for Mobile Communications; GPS stands for Global Positioning System; IoT is Internet of Things; PIR is passive infrared; Wi-Fi means wireless fidelity.

As seen from Table 1, the compared systems use different technologies of sensing, communication, and energy. In particular, Ramson et al. (2021) paid attention to IoT-based waste level monitoring and performed an experiment to test the distance of communication and lifetime of the system. Meanwhile, Pardini et al. (2020) developed real-time waste level monitoring by means of a prototype and a real-life case study. Some other studies considered the implementation of renewable energy in smart waste bins. Mohd Yusof et al. (2018) used solar energy in combination with ultrasonic and PIR sensing, Wi-Fi, GSM/GPRS, and notifications, while Kumaravel and Ilankumaran (2022) paid attention to solar energy, battery management, waste

level monitoring, and GSM communication. Kabir et al. (2020) further demonstrated the integration of solar energy, ultrasonic and PIR sensing, GSM, and LoRa. It can be observed from the reviewed literature that it is possible to incorporate several monitoring functions within one prototype of solar-powered smart waste management. Specifically, the integration of waste-level detection function, waste-weight measurement, temperature and humidity measurement, GSM communication, GPS-related functions, and a solar-powered battery will allow obtaining additional information about the condition of operation of a waste bin. At the same time, such integration will allow obtaining

an idea about the functional interaction of the sensing, communication, and power functions of a prototype.

The current study develops a Solar Powered Smart Waste Management System (SWMS) incorporating all of these functions in one prototype. The prototype will use an ARDUINO UNO microcontroller for data acquisition and control, an ultrasonic sensor for waste level detection, a load cell for waste weight detection, and temperature and humidity sensors for environmental condition detection. The system will have GSM and GPS modules used for communication and related functions. Finally, the electrical power for the prototype will be provided by a solar panel, a rechargeable battery, a battery management system, and a power conversion system. The proposed system will be tested in the form of a physical prototype and simulated in Proteus.

In general, it can be said that the IoT, wireless communication, and renewable energy technologies can be used in order to enhance the monitoring of solid waste management systems. Nonetheless, the existing research works use different combinations of those technologies and monitoring capabilities. This current research extends these methods through the integration of waste level, waste weight, environmental, communication, and solar-powered technologies in one prototype. The development process includes testing and simulation of the electronic

system. The methodology and system design are presented in the next section.

MATERIALS AND METHODS

System Overview

It can be observed that the proposed Renewable Energy-Based SWMS is based on the use of solar energy, which is coupled with the IoT to build an intelligent and sustainable waste management system. This SWMS is designed to monitor and transfer data related to the amount of waste, as well as temperature and humidity in real time.

This combination will make it energy-efficient and will allow it to reduce the cost of energy infrastructure as well as improve its environmental sustainability. The main parts of the different systems will include the power supply system, the sensing and control system, and the communication system.

System Design and Block Diagram

The constituent components of the smart waste bin system and their interactions are represented through the block diagram in Figure 1. It gives a visual representation of the system architecture that facilitates its design and comprehension. All the components play an essential role in the functionality of the waste management system.

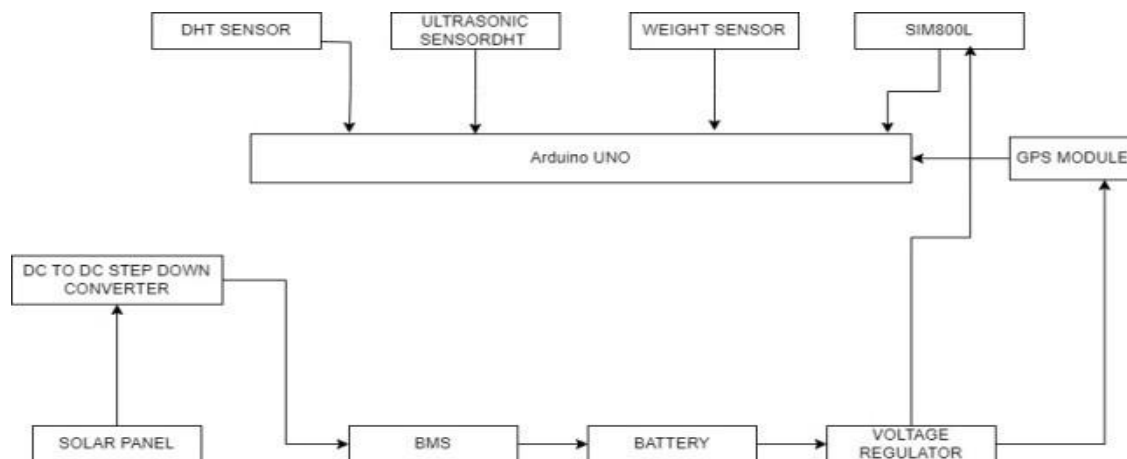


Figure 1: Block diagram of architecture of waste bin powered by solar energy

There are eleven units included in the system block diagram:

1. **Microcontroller unit (Arduino UNO):** The microcontroller unit called Arduino UNO is an essential component that acts as the processing unit for the smart waste bin system. The microcontroller collects data from the ultrasonic and DHT sensors, analyzes the data, and executes control algorithms to control the functionality of the trash bin.
2. **DHT sensor unit:** The temperature and humidity sensors belong to the DHT sensor unit. This unit helps measure the surrounding environment of the trash

bin. Information about these environmental factors is crucial in decreasing the rate of microbial development, preventing odors, and improving the process of breaking down waste.

3. **Ultrasonic sensor unit:** With the help of the ultrasonic sensor unit, effective trash collection becomes possible because it helps measure the volume of waste inside the trash bin. Real-time measurement of waste accumulation is done using the ultrasonic sensor unit based on the distance between the sensor and the waste level.

4. **SIM800L Unit:** The SIM800L unit is an example of a cellular communication feature that enables the smart waste bin system to communicate wirelessly over the cellular network with remote servers or other units. This is achieved by incorporating the use of a SIM card and a GSM module to establish a wireless link to the cellular network.
5. **GPS Module:** The GPS module has great accuracy, and the smart garbage bin system is able to locate the exact position of the module and transmit it to the outside for communication in real time. The GPS module is used to determine the coordinates of the garbage bin through satellite signals. This can later be integrated into the waste management platforms, or it can be transmitted to other servers. This feature enables waste management organizations to optimize their operations through locating and monitoring the exact position of the garbage bin.
6. **Voltage regulator unit:** In order to ensure reliable performance of the electronic components, the voltage regulator unit ensures that the voltage supplied to the smart trash bin system remains constant. In this case, it converts input voltages that come from renewable energy sources such as solar panels or battery power into the required output voltages for the Arduino UNO microcontroller unit, the sensors, and other communication modules.
7. **BMS unit:** For safe and effective functioning of the battery unit, the battery management system (BMS) unit monitors and manages the activities of the battery unit. Cell voltage balancing, control of the charging and discharging process, and protection against short circuit, overcharge, and overdischarge are some of its activities. To enhance battery performance, conserve energy, and prevent damage to the batteries, advanced algorithms and safety features are used by the BMS unit.
8. **Solar panel:** Solar panels capture renewable energy from the sunlight, offering a sustainable and clean source of energy for the smart waste bin system. The solar panels consist of photovoltaic cells that convert the solar energy into electricity either for immediate use or storage in the battery unit. The solar panel unit minimizes reliance on grid electricity or fossil fuels, enhances energy independence and resiliency, and reduces carbon footprints and their negative impacts on the environment.
9. **DC to DC step-down converter:** The requirement for the smart waste bin is addressed through the use of the DC-to-DC step-down converter. The process allows for compatibility of the low voltage systems with electronic components, which have the ability to operate on lower voltages through the effective conversion of the high input voltage to a low output voltage. Through the control of the voltage output, noise filtration, and the provision of reliable power to sensitive electronics, step-down converters maximize the performance and energy efficiency of the system.
10. **Battery unit:** If there is insufficient sunlight or during nighttime, the battery unit supplies energy to the smart waste bin system using energy derived from renewable energy sources. The battery unit usually consists of rechargeable batteries like lead-acid or lithium-ion batteries, due to their environmental-friendliness, longevity, and energy density.
11. **Load cell:** A weight sensing component is used as a crucial element of the smart waste bin, which monitors the recyclable part. Owing to its high accuracy and sensitivity, a load cell is selected as the weight sensing component. In order to effectively weigh the material collected, the weight sensing component is strategically placed at the bottom of the recyclable part. Calibration of the weight sensing component is conducted rigorously before installation to allow for the creation of the baseline and ensure accurate weighing of the material. In Figure 2, the component weighs the recyclables continuously once it is installed. Data is collected and processed using the microprocessor to filter out any noise or fluctuations.

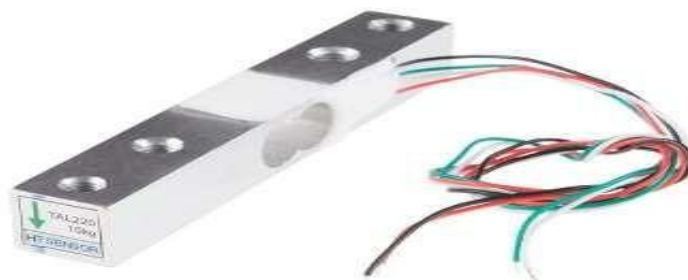
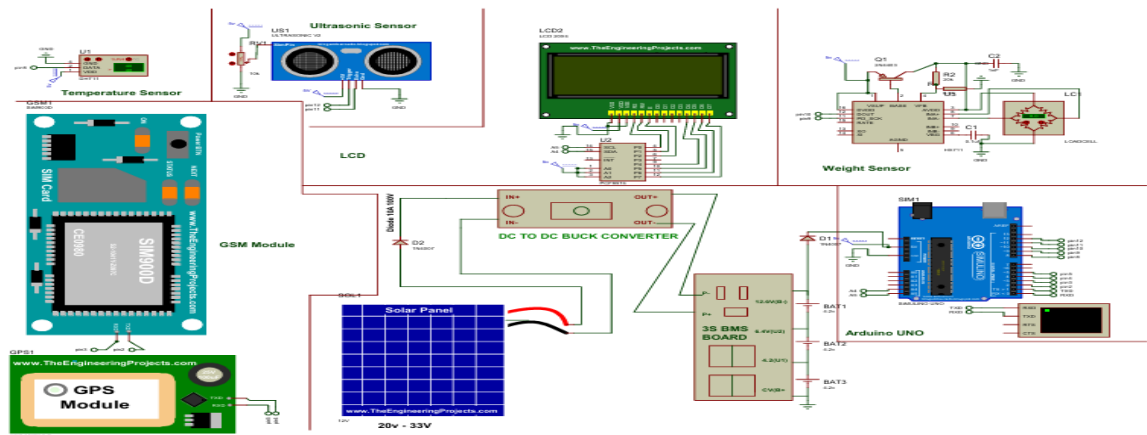


Figure 2: Straight-bar load cell used for waste-weight measurement
Source: SparkFun Electronics (2015).

Circuit Diagram Description

In Figure 3, a part of the circuit was designed to measure the weight of the deposited material accurately. The load cell sensor was thoroughly tested before its installation to form a baseline and ensure that it measures the weight of the loads accurately. The load cell sensor monitors the weight of the recyclable loads continuously as they are being loaded into the bin. The signals will be converted to digital format, where the microcontroller filters out the electrical noise to enhance

the precision of measurement. The exact weight values to trigger an alarm were determined based on the capacity of the bin. In case the measured weight exceeds the set value, the alarm system triggers an action on the GSM module to notify the control center/waste collection center. This process will ensure that the waste bins are collected in time.



Renewable energy based for smart waste bin for circular economy

Figure 3: Circuit diagram

Calculation

Solar Panel Size

We considered the following factors to determine the solar panel size:

- 1. Power Consumption of Components
- 2. Operating Hours
- 3. Efficiency Losses
- 4. Sunlight Availability
- 5. Battery Capacity
- 6. Safety Margin

Solar Panel Size (W) =
$$\frac{\text{Total Daily Energy Consumption (Wh)}}{\text{Average Sunlight Hours per Day} \times \text{Efficiency}} \tag{1}$$

We used eqn. (1) to calculate the solar panel size of the bin. Total Daily Energy Consumption (Wh) = Sum of power consumption of all components multiplied by their operating hours per day. (2)

We used Eqn. (2) to determine the total daily energy consumption in the waste bin
Efficiency Factor = Factor accounting for efficiency losses in the system (usually between 0.7 and 0.9).
Using efficiency = 0.9, the power consumption of the following is:

Table 2: Power needs for each component of the system

Component	Voltage(V)	Current(A)	Power(W)
Gsm Module	4.1	2	8.2
Gps	5	0.1	0.5
Ultrasonic Sensor	5	0.03	0.15
DHT11	5.5	0.025	0.1375
Weight Sensor	5.5	0.003	0.0165
Arduino Uno	5.5	0.5	2.75
Voltage Sensor	5	Negligible	-----

$$P_T = 11.754W$$

$$\text{SIM800L unit} = P_1(W) = 8.2W$$

$$\text{GPS} = P_2(W) = 0.5W$$

$$\text{Ultrasonic Sensor Unit} = P_3(W) = 0.15W$$

$$\text{DHT Sensor Unit} = P_4(W) = 0.1375W$$

$$\text{Weight Sensor Unit} = P_5(W) = 0.0165W$$

$$\text{The Microcontroller unit (Arduino UNO)} = P_6(W) = 2.75W$$

$$P_T = P_1(W) + P_2(W) + P_3(W) + P_4(W) + P_5(W) + P_6(W) = 8.2 + 0.5 + 0.15 + 0.1375 + 0.01655 + 2.75 = 11.754 \quad (3)$$

System Daily Energy Requirement

Total power required for the system is 11.754 W. Let us take the operating hours per day of the system to be T hours.

Therefore, daily energy consumption of the system will be:

Energy consumed daily = Power × Operating Hours

$$E_{\text{daily}} = 11.754 \times T \text{ Wh/day} \quad (4)$$

Hence, the total daily energy requirement of the system will be 11.754T Wh/day.

The 15W solar panel has more rated power compared to the estimated load of 11.754W. The applicability of the 15W solar panel to sustain continuous operations is dependent upon the daily energy usage, number of sunlight hours in a day, and energy losses within the system.

Size of Solar Panel

Where, T = Operating time of system per day (h/day).

Daily Energy required is,

$$E_d = 11.754T \text{ Wh/day}$$

The solar panel power required will be,

$$P_{\text{panel}} = E_d / (H \times \eta) \quad (5)$$

Where E_d = Daily energy requirement (Wh/day),

H = Equivalent peak sun hours (h/day),

η = Overall system efficiency.

The Solar resource data for Nigeria was extracted from the Global Solar Atlas, which gives long-term solar irradiation and photovoltaic power potential data, including GHI (Global Horizontal Irradiation) for the different regions of Nigeria (World Bank, 2023). The size of the solar panel required will be,

$$A = P_{\text{panel}} / (G \times \eta_p) \quad (6)$$

where A = Solar panel area required (m^2),

G = Solar irradiance (W/m^2),

η_p = Solar panel efficiency.

Battery Capacity: Li-Ion Cell:

Li-Ion Cell:

Low voltage threshold is 2.5v

Full charge voltage threshold is 4.2v

Normal voltage is 3.7v (most common)

n_c : number of cells

n_{CI} : number of cells to meet current requirement

n_{CV} : number of cells to meet voltage requirement

n_T : total number of cells needed to meet requirement

p_T : total power requirement

Load: Using a low voltage threshold of 2.5v and 3600mAh cells

Number of cells to meet voltage requirement

Table 3: Calculation of the number of 3600 mAh batteries needed for system components

Component	Voltage(V)	Low Voltage Threshold, V_L (V)	$n_{CV} = V/V_L$	$\sim n_{CV}$
Gsm Module	4.1	2.5	1.6	2
Gps	5	2.5	2.0	2
Ultrasonic Sensor	5	2.5	2.0	2
DHT11	5.5	2.5	2.2	3
Weight Sensor	5.5	2.5	2.2	3
Arduino Uno	5.5	2.5	2.2	3
Voltage Sensor	5	2.5	2.0	3

Load: Using 3600mAh cells

Number of cells to meet current requirement

Table 4: Calculation of battery cells of 3600-mAh capacity based on current needs of components

Component	Current (mA)	Low Current Threshold, I_L (mA)	$n_{CI} = I/I_L$	$\sim n_{CI}$
GSM Module	2000 (peak)	3600	0.556	1
GPS	100	3600	0.028	1
Ultrasonic Sensor	30	3600	0.008	1
DHT11	25	3600	0.007	1
Weight Sensor	3	3600	0.0008	1
Arduino Uno	500	3600	0.139	1
Voltage Sensor	Negligible	3600	-----	-----

$n_T = \text{highest } n_{CV} \times \text{highest } n_{CI}$ (7)
eqn. (7) is used to calculate the total number of cells needed to meet the requirement.

highest $n_{CV} = 3$

highest $n_{CI} = 1$

$n_T = 3 \times 1 = 3$

Therefore, three cells would provide the needed load requirement at least.

Power Requirement

Total power requirement = 11.754W

Battery Energy Capacity:

$E = 11.1 \times 3.6 = 39.96 \text{ Wh}$ (8)

Therefore, the nominal energy capacity is 39.96 Wh. This is based on approximately 3.40 hours of use of the battery when there is a load of 11.754 W.

The nominal voltage of 3.7 V is chosen due to the fact that the battery capacity has been measured using the nominal voltage and not the fully charged voltage of 4.2 V.

Solar cell power also has to meet this requirement.

Chosen solar cell power is 15W (greater than 11.754W, load requirement again, therefore met)

Battery Autonomy

Usable energy from the battery will be calculated taking into account the allowable depth of discharge (DoD), efficiency of the battery, and converter efficiency:

Usable energy from the battery = $39.96 \times \text{DoD} \times \text{battery efficiency} \times \text{converter efficiency (Wh)}$ (9)

Then,

Battery autonomy (days) = $\frac{\text{Usable energy from the battery}}{\text{Daily energy consumption}}$ (10)

where Daily energy consumption = 11.754 T Wh/day.

Power Distribution

In the proposed design, three 3.7-V, 3600 mAh Li-ion batteries are used in series connection. Thus,

Battery voltage = $3 \times 3.7 = 11.1 \text{ V}$

Battery capacity = 3600 mAh = 3.6 Ah

Battery nominal energy = $11.1 \times 3.6 = 39.96 \text{ Wh}$

Source:

Cells: connected in series.

Max. total cell voltage = $4.2 + 4.2 + 4.2$
= 12.6V (max.) (11)

Min. total cell voltage = $2.5 + 2.5 + 2.5$
= 7.5v (min) (12)

Highest load voltage is 5.5v

7.5v would also suffice for the 4.1 to 5.5 V devices.

So:

Buck converter 1 for 5v devices: all except the GSM module

Buck converter 2 for 4.1v: GSM module

Design Overview



Figure 4: Design Overview

The project begins with a secure exterior design, incorporating both functionality and visual appeal. The multi-section modular design of the garbage bin and its wheels for mobility make it portable and environment-

adaptable, as shown in Figure 4. The bin is easy to use and appropriate for both indoor and outdoor use thanks to its design.



Figure 5: Sustainability with Solar Power

Renewable energy is used in Figure 5 by incorporating a solar panel in the lid, which houses the electronic components and ensures economical and

environmentally friendly operation. The emphasis on technology and sustainability is also clearly captured in the perfect fit of the panel.



Figure 6: Overview of the Internal Configuration

Figure 6 gives an insight into the interior design, which consists of Li-ion batteries connected in series to obtain the required voltage and capacity. The components are the microcontroller board that functions as the computer's processor, as well as a number of connecting wires, voltage regulators, and others such as capacitors for stabilizing electrical output. The wiring is intricate, but the design inside the unit is functional and compact.
Max. total cell voltage = 4.2 + 4.2 + 4.2

= 12.6 V (max.)
Min. total cell voltage = 2.5 + 2.5 + 2.5
= 7.5v (min)
Highest load voltage is 5.5v
7.5v would also suffice for the 4.1 to 5.5 V devices.
So:
Buck converter 1 for 5v devices: all except GSM module
Buck converter 2 for 4.1v: GSM module



Figure 7: Final Housing and Accessibility Design

The durability and accessibility of the power unit casing are shown in Figure 7. It has a manual toggle switch for ease of use, enabling the system to be switched on or off with ease and reducing the risk of tangling or electrical shorting with the neatness of wiring, and a secure cable harness ensures neat wiring and reduces the risk of tangling and electrical shorting.

Testing and Validation

Functionality testing was carried out on the prototype to ensure that the sensing, control, communication, and power subsystems were working correctly. The ultrasonic sensor was tested for detecting the level of waste, the load cell for weight detection, and the communication device for communication. The prototype was also tested under

different conditions of operation to ensure that it responded correctly to the set threshold conditions. Quantitative testing and measurement of error percentage were, however, not done.

RESULTS AND DISCUSSION

The implementation and evaluation of the smart waste management system using IoT and solar energy is presented in this section. The findings are based on the methodological framework and focus on the main functions of the system, integration of the hardware, and performance of the software. The experimental and simulated results illustrate how the system operates and how it integrates.

System Performance

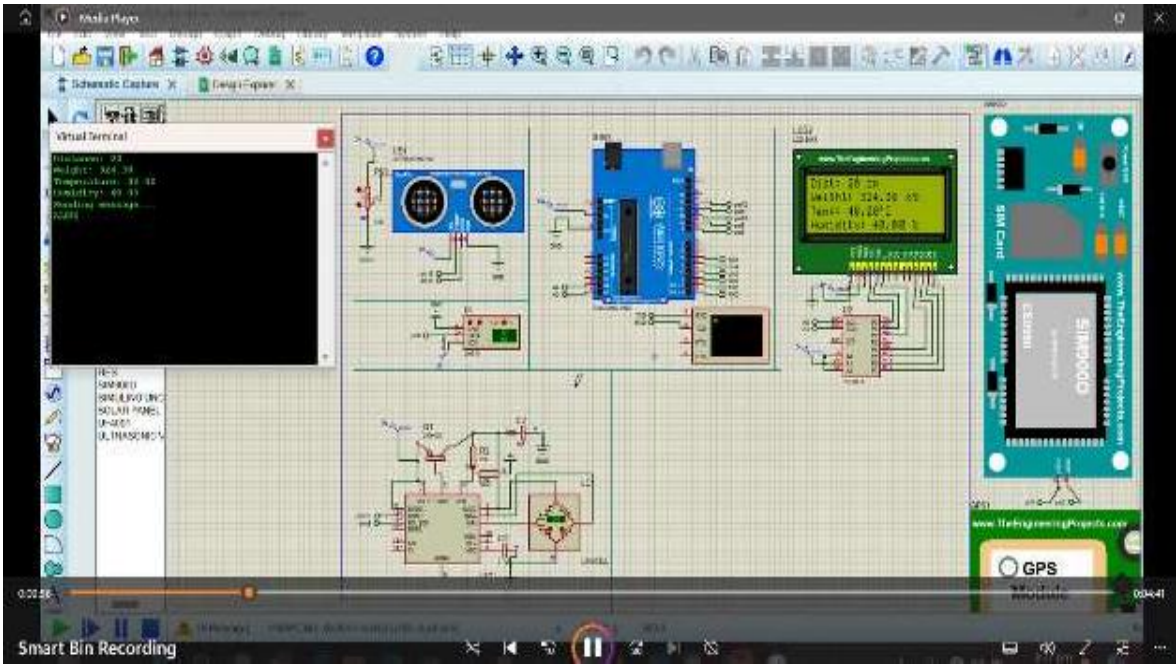


Figure 8: System performance

In order to simulate the performance of the system and to test it, the system is shown in Figure 8. Proteus simulation was employed for the functional verification of selected sensory, control, and communication units operating under the regulation of a 5 V supply voltage. Functional integration of the sensory, communication, and power sub-systems was then illustrated by using a physical prototype. The emphasis of the testing procedure was laid on functional testing without taking into consideration accuracy or efficiency.

Hardware Performance

Functional evaluation of the hardware was done to ensure that all the major components such as the sensors, controller, communications, and display work properly. The ultrasonic sensor was employed for waste level detection, while the load cell and HX711 modules were used for weight measurement. DHT11 was responsible for temperature and humidity measurements, while the LCD was used to show the collected data.

It was noted that the GSM module sends alerting messages during the operation of the prototype. It was found from the performance evaluation of the hardware that all the connected hardware components worked properly during the tests. However, quantitative testing for the accuracy of sensors, GPS, battery, etc., was not done in the current research.

Software Performance

Arduino UNO microcontroller was used to implement the control program in the Arduino IDE, and then the firmware was uploaded to the microcontroller. Data acquisition, sensor calibration, and communication protocols between all modules were controlled by software.

The serial communication channels of the GSM and GPS modules were initiated, the I²C interface for the LCD was initialized, and the DHT11 and load cell sensors were initialized. The data from the sensors were continuously collected, calculated, and presented. Alerts were activated if the threshold values were exceeded, due to conditional logic in the code.

In addition, this program included system identification during start-up, which would give necessary information regarding the project on the LCD screen, check if all components were initialised properly, and ensure smooth operation during testing.

Software implementation showed that the sensor data could be processed, and there was communication between the GSM and GPS modules. From the findings, it can be recommended to adopt the use of Arduino as the microcontroller for embedded-based waste management systems.

Simulation Results and Analysis

The circuit was simulated using the software Proteus in order to verify the interaction of the selected circuit

elements before its physical implementation. The simulation involved a regulated 5-V DC power source instead of the solar panel and battery configuration employed in the prototype system. In addition, the Battery Management System (BMS) and buck converter were excluded from the simulation process.

Therefore, the simulation in Proteus is a verification of the circuit level under the regulated 5-V DC power source and does not provide the full validation of the solar energy subsystem, BMS, and buck converter levels.

SIM900D was used instead of SIM800L module due to the unavailability of the latter in the simulation. Therefore, the behaviour of the simulated GSM module cannot be regarded as an actual validation of the SIM800L hardware in the prototype system.

Simulation results show how the selected sensing, control, display, and communication components interact with each other in the simulated setup.

Discussion

Integration of the hardware and software parts showed that the functionality of the proposed smart waste management system works fine. All modules (sensing, control, communication, and display) worked fine with the observed test conditions. The GSM module was also found to work fine by transmitting the alert messages when the specified conditions are triggered.

Proteus simulation verified the functioning of the selected components in terms of circuitry using a regulated 5-volt DC power source. But the solar panel, battery management system, and buck converter that have been employed in the physical prototype could not be simulated. Moreover, SIM900D module has been used in place of SIM800L module in the simulation. Thus, the simulation results provide only functional verification of the circuit but not the full-fledged validation of the renewable energy subsystem and physical GSM module.

From the observations made above, it can be seen that there is much potential of integrating the renewable energy source, sensor-based detection, automatic control, and GSM communication in the smart waste management system. But the tests related to accuracy of sensors and GPS, battery endurance, delivery rate of GSM, energy efficiency, and long-term reliability have not been conducted in this study.

Limitations of the Study

There are some limitations to the study. Field testing was limited, and there was no comprehensive test of battery endurance. The Proteus simulation was run under controlled 5V DC power and did not include the solar panel, BMS, and buck converter. The SIM900D module was used as a substitute for SIM800L in the Proteus simulation. Comprehensive analysis of sensor uncertainties and long-term solar charging capabilities were not tested either.

CONCLUSION

A design, development, and functional evaluation of the Renewable Energy-Based Smart Waste Management System using solar energy, sensor monitoring, automation control, and IoT communication was carried out in this research. The results obtained from the design and development of the prototype included the implementation of waste level, weight, temperature, and humidity monitoring together with GSM-based communication alerts.

The ultrasonic sensor, load cell, DHT11 sensor, GSM module, and display interface were used as interrelated components in the prototype tests carried out. The control system that was based on the Arduino, managed sensor data acquisition, threshold-based control, and communication between all the connected components. Solar energy integration in the physical prototype was an indication of the implementation of renewable energy in the waste management system.

Functional tests and the Proteus simulation were done for the evaluation of the system. In the simulation, a regulated 5-volt DC supply was used, and it did not contain the whole solar-energy subsystem, BMS, or buck converter. In addition, the quantitative sensor accuracy, GPS positioning accuracy, battery endurance, GSM performance, energy efficiency, and reliability tests were not carried out.

The proposed system offers a platform to integrate renewable energy generation, automation, and Internet of Things for smart waste management. Future research efforts will be devoted to the application of such systems, quantitative analysis of their performance, long-term testing of the batteries, multi-bin communication, cloud-based monitoring, and machine learning algorithms for waste generation/prediction.

RECOMMENDATIONS

Future research will have to concentrate on testing the designed system under controlled conditions in the field with regard to accuracy of the sensors, accuracy of GPS positioning, performance of GSM communication, endurance of batteries, consumption of energy, and reliability of the system in various environmental and operational conditions. Additional developments might include the use of more advanced sensors and low-power electronics, along with new ways of managing the consumption of energy and hybrid renewable energy sources that would help operate the system under various weather conditions.

The system can also be upgraded by introducing cloud computing and mobile devices for the management of waste bins and multi-bin communication systems for large-scale operations. Machine learning algorithms can also be applied for analysis of the waste generation data

and prediction of the level of waste and planning of its collection.

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