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Design and Implementation of an IoT-Based Smart Bin for Real-Time Fill Level Monitoring

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ABSTRACT

In today's world, as populations and cities grow, the generation of waste increases accordingly. Traditional waste management systems face several problems, like poor human monitoring, untimely collection, inadequate disposal of hazardous material, and high costs. This project focused on the design and implementation of an IoT-based smart bin, a prototype that was developed to provide automated waste disposal while also offering real-time monitoring capabilities. The project involved the Espressif32 (ESP32) microcontroller, which was used for its fast-processing speed and integrated Wi-Fi stack. The hardware of the system included two HC-SR04 ultrasonic sensors that provided signals for the ESP32 to operate with. Upon detecting a user, the first ultrasonic sensor facilitated automated waste disposal by sending signals to the ESP32 for the opening and closing of the bin's lid using the servo motor. The second ultrasonic sensor monitored the waste fill level of the bin, and when the bin was filled up, an email notification was sent to the user. The prototype offered multi-layered feedback that included remote monitoring and immediate local alerts through LEDs and a buzzer. The prototype, which is powered by lithium-ion batteries, offered a reliable, technologically advanced result for improving urban sanitary infrastructure.

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INTRODUCTION

Effective waste management is a vital element of environmental sustainability, as it inevitably accompanies urbanisation, community development, and population growth worldwide. In recent years, urbanisation, population, and industrialisation have expanded at a phenomenal rate, and due to this, the amount of waste being generated has also increased (Orimogunje et al., 2022; Dodo & Ashigwuike, 2023). The World Bank estimates proved that 2.24 billion tonnes of waste are created yearly worldwide, with an average of 0.79 kilograms of waste from each person daily (Agnew et al., 2023; Agha et al., 2025).

Current waste management systems rely mainly on human interaction to monitor waste bin fill levels, which is not only time-consuming but also inefficient. Waste collection bins with smart capabilities are now increasingly important because manual waste management has proven inefficient in generating a more sanitary environment. Recently, the population growth and the enormous increase in human activities, consumption patterns, and production have increased the generation of waste materials (Dauz et al., 2024; Bello & Dodo, 2025). Solid waste management is a need for reaching a developed nation status, and the relationship between an efficient waste management system, a healthy environment, and quality of life is vital. In many cities throughout the world, waste bins located in open areas are filled beyond capacity, indicating ineffectiveness.

The insufficient real-time monitoring of waste fill levels has contributed to the exposure of potentially unsafe waste materials, which could be uneconomical and detrimental to the surroundings (Roy et al., 2022; Msheliza & Dodo, 2025). When

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a lot of waste bins are overfilled, it causes the waste collection trucks to run out of space before the collection route is completed. If this happens, another truck has to be sent out to collect the remaining waste, which leads to higher operational costs. Also, the overflow of waste bins creates an unsafe and unhygienic atmosphere that is harmful to economic activity and human health.

There are different studies in the literature with a focus on waste bin monitoring. For instance, Guo (2024) conducted a study on a smart bin system using IoT technology with Global System for Mobile Communications (GSM) that made use of a mobile app for remote monitoring to improve efficiency. In another study by Agnew et al. (2023), overfilled waste bins were detected during waste collection using computer vision. Onyagu et al. (2024) designed a smart bin system that employed ultrasonic sensors to monitor fill levels and gas sensors to measure air quality in real time. Oyewo (2025) developed a smart waste bin that made use of a solar power source and provided automatic lid control. The system could also monitor the level of waste in the bin using IoT technologies.

Ishaq et al. (2023) improved biomedical waste handling by integrating IoT sensor technology into smart waste bins across hospitals. Also, Pulparambil et al. (2024) aimed to design and implement an IoT automated bin in hospitals that integrated sensors to enable real-time monitoring of waste level, weight, and storage time. Image processing and machine learning were used to accurately detect and classify the fill level of solid wastes (Hannan et al., 2013). Okethweu et al. (2024) designed a smart waste bin that provided automated waste disposal and monitoring with minimal human intervention. Meanwhile, White et al. (2020) created an automated waste bin that was able to classify and sort waste materials at the edge, increasing the efficiency of smart bins and reducing recycling contamination.

Most of the existing studies focused on remote-based solutions, solar-powered waste management, and computer vision waste monitoring. Therefore, the present study aimed to design and implement a prototype Internet of Things (IoT)-based smart bin for real-time fill-level monitoring. To achieve this, a circuit design was developed to establish a reliable hardware foundation for the system. When this was achieved, all the components were integrated with the ESP32 microcontroller, and the ESP32 was programmed for the system to execute automated lid control, immediate local alert, and remote monitoring. Finally, the system was tested to ensure its reliability and efficiency in improving waste management. This study is highly relevant because conventional waste management has become inefficient and unreliable. The prototype demonstrates how waste collection efficiencies can be improved as the system identifies when the bin reaches its predefined threshold, which will enable waste collectors visit only, when necessary, thereby reducing operational costs.

MATERIALS AND METHODS

This study addresses the lack of an automated waste bin system that uses IoT technology to monitor the amount of waste in the bin while also improving the waste collection process. The system integrated an Espressif32 (ESP32) microcontroller, ultrasonic sensors, Light Emitting Diodes (LEDs), and a buzzer to indicate when the bin was full. This prototype helped demonstrate how the need for manual checks can be reduced and how waste collection can be improved. The materials used were an ESP32 microcontroller, ultrasonic sensors, a servo motor MG90S, an active buzzer, green LED, yellow LED, Red LED, lithium-ion batteries, a buck converter, a Battery Management System (BMS), and a plastic waste bin.

Design of the ESP32 microcontroller

Operating Voltage is gotten by:

Logic voltage = $3.3V$

Input voltage= $5V$

The ESP32 development board contains an onboard voltage regulator that converts the 5 V input to a 3.3 V logic level.

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The voltage constraint is given by $V_{\log ic} = 3.3V$

ESP32 GPIO pins are not 5 V tolerant, hence $V_{GPIO(MAX)} = 3.3V$ was applied.

This means that any external signal exceeding 3.3 V had to be scaled down before connection. The current consumption of the ESP32 could be seen as:

Idle current: $80 - 100 mA$

Peak current $I_{ESP32(MAX)}$: $600\,mA = 0.6\,A$

Power consumption is expressed in equation (1)

$$P = V \times I \quad (1)$$

Idle Power (P_{idle}) $= 5 \times 0.1 = 0.5W$

Peak Power (P_{peak}) $= 5 \times 0.6 = 3.0W$

Therefore, the ESP32 requires up to 3 W during maximum operation.

Design of HC-SRO4 Ultrasonic Sensors

Operating voltage = $5V$. This is because the HC-SR04 consists of an ultrasonic transmitter, an ultrasonic receiver, and an internal signal conditioning circuit. The ultrasonic transmitter requires sufficient voltage to generate acoustic waves in air. Operating below this voltage reduces transmitted acoustic energy, leading to unreliable distance measurements.

Operating current = $15\,mA = 0.015\,A$

The HC-SRO4 alternates between the idle state (listening) and active state (transmitting ultrasonic pulses).

Using equation (1) to compute the power consumption;

$$P = V \times I = 5 \times 0.015 = 0.0075$$

This indicates that each ultrasonic sensor consumes approximately 75 mW during operation.

Design of Servo motor

The nominal regulated voltage for the ESP32 that controls the motor is 5 V. Therefore, 5 V was chosen as the basis because the buck converter is a regulated DC source, which eliminates the voltage fluctuations found in raw battery packs. The servo motor power was calculated using equation (2). Where I_{stall} = $700\,mA = 0.7\,A$

$$P_{stall} = V \times I_{stall} \quad (2)$$

$$P_{stall} = 5 \times 0.7 = 3.5W$$

Power consumption of the servo motor when moving = $100 - 250\,mA$

Operating power range:

P_{idle} = $5V \times 0.01A = 0.05W$

Moving (Average): P_{move} = $5V \times 0.25A = 1.25W$

The buck converter provides 2 A, which means if the servo motor consumes 700 mA when stalled, the ESP32 has a peak current consumption of 600 mA, and the total (1.3 A) remains below the 2A limit, preventing a system burnout.

Design of Active Buzzer

The active buzzer has sound-producing electronics in it. It requires a small DC voltage to function. The buzzer's internal circuit requires at least 3 V to start working. If the buzzer is given a lower voltage than this, it does not sound properly. Also, the buzzer is not designed for high voltages because it can cause overheating or get damaged.

The safe operating range is $3V - 5V$.

Current Consumption $(20 - 40\,mA)$

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The internal resistance of a buzzer is $100 - 150\ \Omega$

Current at the minimum voltage was determined using Ohm's law expressed in equation (3), taking the voltage as 3 V.

$$I = \frac{V}{R} \quad (3)$$

$$I = \frac{3}{150}$$

$I = 0.02\,A = 20mA$ (which is the minimum current needed for sound)

At maximum voltage (5 V), the current becomes;

$$I = \frac{5}{125}$$

$I = 0.04\,A = 40mA$ (which is the maximum current when powered at 5 V).

Using equation (1), the power under this condition is:

$$P = 5 \times 0.04 = 0.20\,W$$

Design of LEDs (Green, Yellow, Red)

The wavelength of a green LED is approximately 565nm, while its electron-volt was computed using equation (4).

$$E = \frac{h \times c}{\lambda} \quad (4)$$

Planck's constant (h) = 6.626 x 10^{-34} J.s

Speed of light (c) = 3 x 10^{8} m/s

Wavelength (λ) = 565 x 10^{-9} m

$$E = \frac{(6.626 \times 10^{-34}) \times (3 \times 10^{8})}{565 \times 10^{-9}} =$$

$$3.52 \times 10^{-19}\ J$$

Converting to Electron-Volt (eV)

$$1eV = 1.6 \times 10^{-19}\ J$$

Therefore,

$$E = \frac{3.52 \times 10^{-19}}{1.6 \times 10^{-19}} = 2.2\,eV$$

$$2.2\,eV = (1\,electron\ charge) \times V$$

$$V = \frac{2.2\,eV}{1e} = 2.2V$$

The yellow LED has a wavelength of 590 nm. Equation (4) was used to compute the electron volt.

$$E = \frac{(6.626 \times 10^{-34}) \times (3 \times 10^{8})}{590 \times 10^{-9}} = 3.37 \times 10^{-19}\ J$$

$$E(eV) = \frac{3.37 \times 10^{-19}}{1.6 \times 10^{-19}} = 2.1eV$$

$$V = 2.1V$$

Red LED has a wavelength of approximately 633 nm. Equation (4) was used to compute the electron volt.

Wavelength (λ) = 633 x 10^{-9} m

$$E = \frac{(6.626 \times 10^{-34}) \times (3 \times 10^{8})}{633 \times 10^{-9}} = 3.14 \times 10^{-19}\ J$$

$$E(eV) = \frac{3.14 \times 10^{-19}}{1.6 \times 10^{=19}} = 1.96\,eV$$

V is 1.96 V, which is approximately 2.0 V.

The LED brightness depends on how much current flows. For small indicator LEDs, 10 mA is visible but also safe, and 20 mA is bright but still safe. Having a current higher than this range $(10 - 20\,mA)$ will create excessive heat and damage the LEDs.

Hence, the safe working current range is $10 - 20\,mA$.

Design of Lithium-ion Batteries

Each battery has a 3.7 V nominal voltage. Most Lithium-ion batteries use a Lithium Cobalt Oxide ($LiCoO_2$) cathode and a Graphite (C_6) anode.

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Anode potential = $0.1V$

Cathode potential = $3.8V$

Therefore, the cell voltage was computed using equation (5)

$$E_{cell} = E_{cathode} - E_{anode} \quad (5)$$

$$E_{cell} = 3.8V - 0.1V = 3.7V$$

The Lithium-ion batteries are both in series = $V_1 + V_2 = 3.7V + 3.7V = 7.4V$

The batteries have a capacity of 3500 mAh (3.5 Ah) and are rated at 1C. The maximum current was calculated using equation (6).

$$I_{max} = Capacity \times C - rating \quad (6)$$

$$I_{max} = 3.5\,Ah \times 1C = 3.5\,A$$

The flowchart of the study is shown in Figure 1, while the implemented circuit is shown in Figure 2.

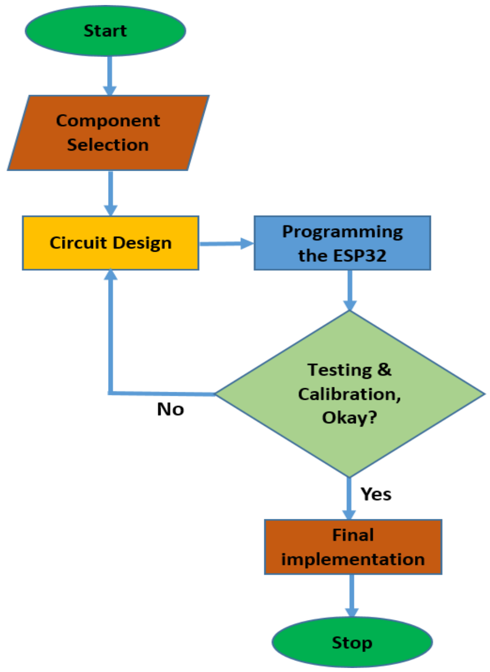

Figure 1: Flowchart of the System

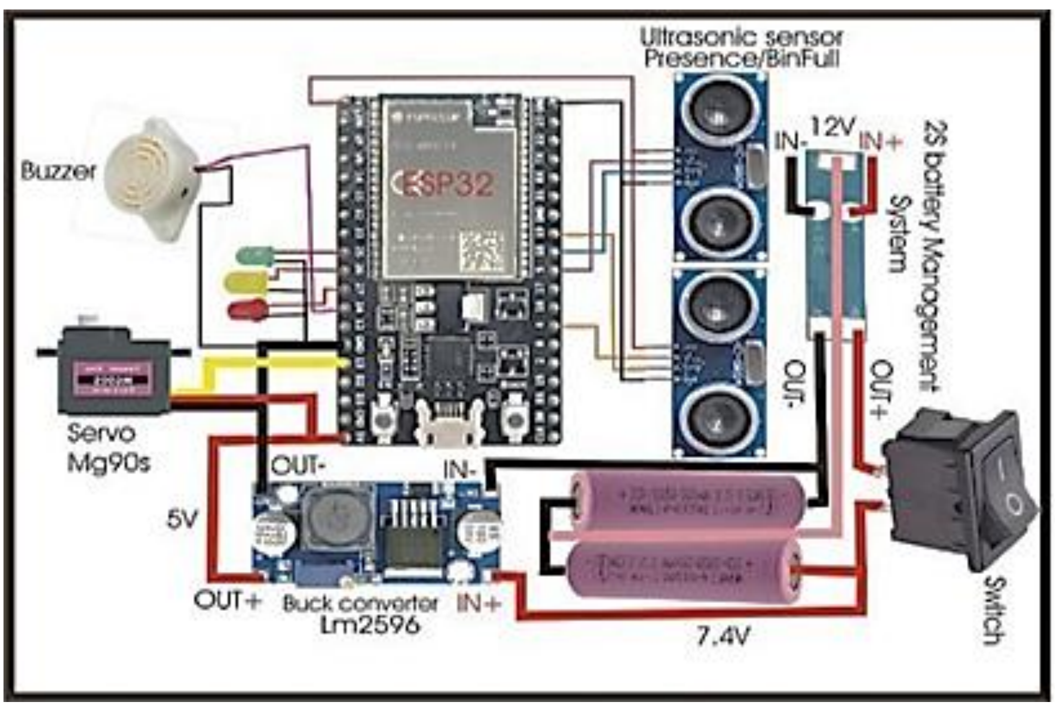

Figure 2: Circuit Diagram

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RESULTS AND DISCUSSION

The results of this research indicated that the use of an IoT smart bin greatly enhances the efficiency of waste management when compared to typical human monitoring. This prototype provided automated waste disposal and accurate monitoring of the waste fill level by combining the ESP32 microcontroller with two ultrasonic sensors. The system offered multi-layered feedback by combining both immediate local alerts (using LEDs and a buzzer) with remote notifications for the bin's fill status to be viewed simultaneously, which is a substantial improvement over traditional, manual monitoring.

Before connecting the whole system together, each component was first integrated with the ESP32 microcontroller and subjected to various tests. This was done to make sure that all the components were working properly and could perform their expected functions without errors. The MG90S servo motor was tested to see how well it could open and close the bin's lid. During the test, the motor smoothly rotated from 0° to 90° to open the lid and returned to 0° when the system was idle. This showed that the motor responded correctly to commands from the ESP32 and could reliably control the lid movement. The ultrasonic sensor placed inside the bin was tested by measuring the distance of the waste from the sensor. This helped set the distance threshold used to know when the bin is getting full.

The second ultrasonic sensor, which is placed outside the bin, was tested to detect when an individual comes close. This testing was done using an object, and it was able to detect it within 30 cm and then sent a signal that allowed the bin to open automatically. Also, local visual and audio components (LEDs and buzzer) were tested to ensure proper triggering at defined thresholds, while the ESP32's Wi-Fi module was validated by properly transmitting an automatic email notification when the full threshold was met.

After testing, the HC-SR04 ultrasonic sensors provided signals for the ESP32 to operate with. The first ultrasonic sensor was mounted internally at the top of the bin's lid to monitor the waste fill level by calculating the amount of time it takes for transmitted high-frequency sound waves to hit the waste and return. This illustrated that the duration of the signal's return is inversely proportional to the waste fill level. A reduced time interval signified a higher fill level while a prolonged interval signified a lower fill level of waste in the bin.

Figure 3 indicates the smart bin operated in such a way that when it was 0-39% filled, the green LED was lit to indicate empty status, when it was 40-59% full, the yellow LED was lit, when it was 60-100% full, the red LED was lit and the buzzer was triggered to provide an immediate audio alert. The second ultrasonic sensor was evaluated for proximity detection. It recognised human presence at a distance of less than 30 cm. Figure 3 also demonstrates that the system provided automatic lid control by activating the servo motor when the ultrasonic sensor detected a user, which rotated effectively from 0-90° to open the lid and reverted to 0° during idle periods. It was shown in Figure 4 that when the bin reached the full threshold (60-100%), the ESP32 used its integrated Wi-Fi to send the user an automated email message through the Blynk IoT platform.

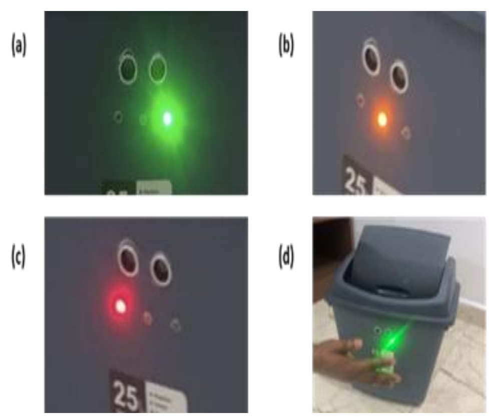

Figure 3: (a) Green LED indicating 0-39% filled, (b) Yellow LED indicating 40-59% filled, (c) Red LED indicating 60-100% filled, (d) Automatic lid control

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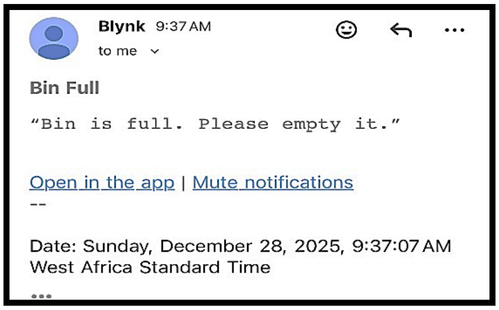

Figure 4: Email notification when the bin is filled up

Figure 5 indicates the scatter plot that represents the relationship between the waste fill-level in real-time. It is observed from the graph that as time increases, the level of waste disposed of in the bin increases.

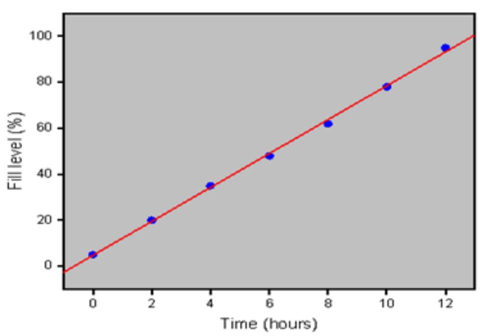

Figure 5: Graph of fill level against Time

When compared to similar studies, this research presents several advantages. The prototype made use of an ultrasonic sensor that was integrated inside the waste bin, which accurately monitored the waste fill level in real time, while Jerbi et al. (2025) made use of machine learning for predictive analytics to assess the bin's capacity, which does not account for unexpected irregular waste disposal. Also, Agnew et al. (2023) used computer vision to monitor waste fill-levels, and computer vision may struggle with environmental factors like glare or shadows. In contrast to the Pulparambil et al. (2024) system, which did not provide automatic lid control, the ESP32 activated the servo motor when the ultrasonic sensor detected a user in order to enable automated waste disposal, which would promote hygiene and user convenience. Unlike Oyewo (2025), who made use of solar powered model, which may fail during cloudy weather or require high maintenance, this prototype made use of two lithium-ion batteries in series, which can operate in both indoor and outdoor environments and also provided a high-capacity (3500 mAh) power source suitable for long-term deployment. Overall, the present study confirmed that a tech-driven approach to sanitation can reduce fuel consumption for waste collection trucks by preventing unnecessary trips to empty bins and avoiding the unhygienic overflow of waste in public spaces.

CONCLUSION

A prototype IoT smart bin for real-time fill-level monitoring was implemented. The smart bin was capable of automated waste disposal, immediate local alerts, and remote notification when the bin was full. As a result, the overflow of waste is prevented, which helps maintain a cleaner and healthier environment. It provides automated waste disposal, which promotes user convenience and reduces physical contact.

The use of both immediate local alerts and remote monitoring mechanisms reduces manual monitoring as the bin's status can be viewed physically (using LEDs and a buzzer) and remotely (through email notification). The system was powered by rechargeable lithium-ion batteries, which activated the components only when necessary, resulting in a more sustainable solution. Overall, the study showed how IoT technology may be used to improve waste management procedures by eliminating manual monitoring, reducing overflowing bins, and improving hygiene. The successful implementation of this prototype demonstrates its suitability for use in residential, institutional, and public settings.

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