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Design of an IoT-Based Smart Waste Management System for the Detection of Hazardous Gases

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Abstract

Effective waste management has become a major safety concern, due to an increase in waste generation and the emission of hazardous gases into the environment. This research was conducted to design and develop a prototype of an IoT-based smart system to enhance waste management in real time. The model utilized multiple sensors—MQ4, MQ7, MQ135, and MQ-137—and an ESP32 microcontroller with a Wi-Fi module to detect and monitor the concentrations of ammonia, carbon (ii) oxide, carbon (iv) oxide, hydrogen sulfide, and methane, in the vicinity of dumpsites and landfills. Remarkably, the ESP32 microprocessor handled the raw data the sensor sent to it, and then made suitable decisions using the algorithms. Additionally, the system used the LCD display and buzzer alerts for immediate public safety, while the processed information is transmitted by the IoT cloud unit for real-time monitoring. The experimental results showed the system achieved 90% effectiveness in detecting high gas concentrations and triggering appropriate alerts, reliably delivering information via SMS and email. Specifically, this research's findings revealed that an IoT-based hazardous gas detection system can be developed for effective waste management practice, thereby improving public safety, human welfare, and environmental sustainability.

Keywords: ESP32 controller, IoT, public health, real time clock, sensors

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Introduction

Poor waste management is a significant challenge in developing and under-developed countries, as it is linked to a wide range of health issues and socioeconomic challenges. Improper waste management activities have resulted in environmental degradation and hindered infrastructural development. Emissions from poorly treated waste are loaded with lethal gases and substances such as pathogens, VOCs, carbon oxides (COx), methane (CH_4), toxic metals, ammonia (NH_3), aromatic hydrocarbons, and hydrogen sulfide (H_2S) (Dandotiya et al., 2020; Uguru *et al*., 2025). Additionally, poorly managed waste creates avenues for infrastructural (mostly roads and drainages) decay, leading to the accumulation of water and sewage in the environment, which encourages the breeding of disease vectors in the region. Toxic gases linked to poor waste management practices are a major cause of respiratory infections, while their leachates have been linked to cholera epidemics (Omang *et al*., 2021; Siddiqua *et al.,* 2022).

Scholars have developed various automated waste management structures with different modes of operation such as: sensor-based control approach, Internet of Things "IoT", and Global Positioning System enabled monitoring method. Saviour and Mensah (2023) developed a system that uses the MQ-4 sensor to monitor biogas concentration in a dumpsite, but they recommended that further designs be carried out using more sensors. Ramson *et al.* (2020) designed smart waste management units that use wireless access point units, which are adaptable for smart cities. Furthermore, Karthikeyan *et al*. (2017) designed an automated garbage collecting structure that uses the ZigBee network and the Message Queue Telemetry Transport protocol. The working conditions of the system were transmitted through the Telegram application. Also, Vishnu *et al.* (2021) designed an IoT-based WSM that uses end sensor nodes and a Graphical User Interface to monitor the wastebasket situation. Primarily, the system uses the volume occupied by solid waste as a major parameter to alert the authorities about the need for evacuation.

Remarkably, most of the existing smart waste management systems are designed based on mass or volume, where the system is triggered when a specific weight or volume threshold is attained. Specifically, there is a dearth of information on designs that focus on the early detection of harmful gases emitted from dumpsites and landfills. This makes environmental pollution due to the accumulation of toxic gases inevitable, as some lightweight wastes and small-sized wastes have the potential to emit large volumes of colorless and odorless toxic gases. Therefore, this study is aimed at designing a waste management smart system, which combines hazardous gas monitoring with the waste management system. Additionally, the IoT unit will enhance the reliability of real-time gas concentration monitoring and management. The smart device will enable real-time communication of waste collection and disposal practices, leading to the improvement of digital waste management system and public health protection.

2.0 Materials and Methods

To achieve this study's aim, the system was primarily designed by harmonizing hardware components, software devices, and programming languages. The schematic diagram of the system is presented in Figure 1.

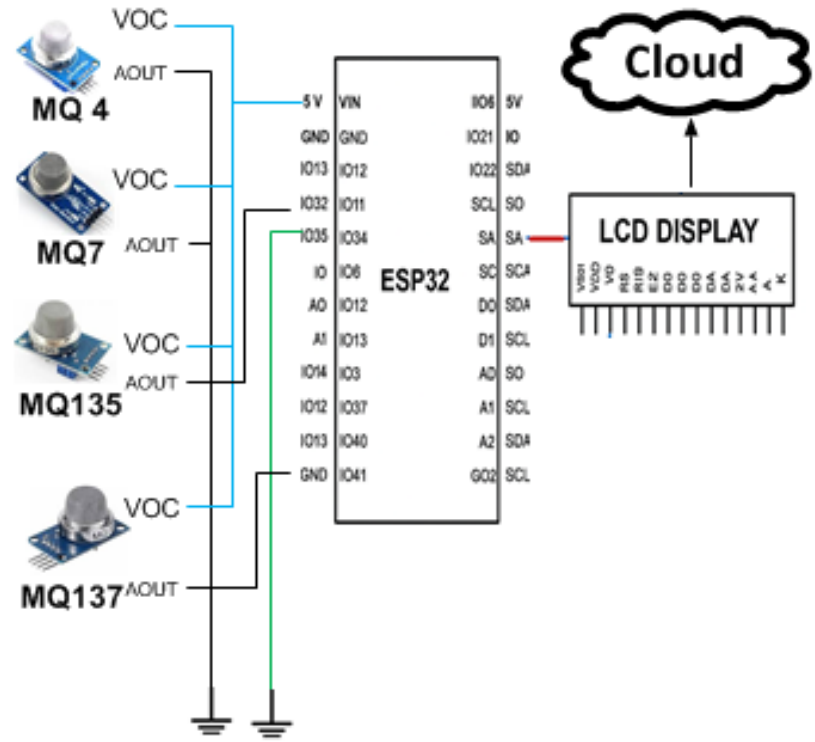


Figure 1: The IoT gas detection system schematic diagram

The system components

The components used to design and develop the system, and their respective specifications are presented in Table 1.

Table 1: system components List

System component	Functions	Specifications
ESP32	Microcontroller	Clock speed: approximately 240 MHz; dual-core processor; operating voltage: 2.2 V; 520 KB SRAM; 16 MB flash memory; 32-bit microcontroller.
MQ-135 gas sensor	It helps in monitoring CO_2, NH_3, and benzene level	Operating temperature ~ -10 to 45^{o}C, operating humidity ~ max 95% RH, operating voltage ~ 5±0.1V DC, compatible with ESP32,detection range ~1000 ppm
MQ-4 gas sensor	Detects methane level	Operates at a temperature range of -10 and 52^{o}C, heater resistance (HR) within the range of 31 and 33 Ω, operates at 5V,detection range of 200 to 1000 ppm
MQ-7 gas sensor	It helps in controlling CO level	HR ranged from 29 to 33 Ω, operating temperature ~ -20 to 55^{o}C, humidity ~ ≤95%, detection range of 10 and 10,000 ppm.
MQ-136 gas sensor	It detects H_2S presence	HR ranged from 29–31 Ω, power consumption of ≤ 900 mW, operating temperature of −10 to 50°C, and RH of ≤ 95%.
Wi-Fi (ESP32) module	Sends information	Operating voltage ~ 3.3V, Wi-Fi ~ 802.11 b/g/n (2.4 GHz), 520 KB SRAM, 32-bit Dual-core, and built-in Bluetooth.
LCD Display	Displays the system operation	16x2 LCD, operating voltage ~ 4.7V, 8-bit
Battery	Provides power	12V, 50Ah, rechargeable
Buzzer	Provides alerts	88 decibel maximum, operating voltage ~3 to 24V

The system software and workflow

The Arduino IDE (version 2.x) and MATLAB were used for system design. Additionally, C++ was chosen as the programming language. Each sensor reads the individual concentration level, matches it with the recommended safe limit, and sends signals to the microprocessor. Then the microprocessor interprets the signals and transforms the information into digital form, which will be displayed on the LCD. If the concentration of the toxic gas in the area exceeds the safe limit, it will activate the sound unit and send messages (email/SMS) through the cloud platform, using the built-in Wi-Fi capabilities. The thresholds of the various gases are presented in Table 2. Furthermore, the sensors' outputs will be connected to the microprocessor ADC pins, and the system is designed to be powered by a 12V (DC) battery. The calibration was done in an open environment to obtain a reference point for the sensor. Additionally, real-time data logging and performance monitoring of the system were performed by using the ThingSpeak.

Table 2: Recommended safe limits

Gas	Sensor involved	Safe limit
Ammonia	MQ-135	≤ 25 ppm
Benzene	MQ-135	≤ 1 ppm
Carbon (ii) oxide	MQ-7	≤ 40 ppm
Carbon (iv) oxide	MQ-135	≤ 1000 ppm
Hydrogen sulfide	MQ-137	≤ 10 ppm
Methane	MQ-4	≤ 1000 ppm

Testing

The gases used for the prototype evaluation were of high grade and purchased from a certified chemical shop. Also, the tests were conducted in a fume cupboard to avoid health risks, as these gases are hazardous. The model was tested 20 times, using various gas concentrations to validate responsiveness, and the performance was calculated by using Equation 1 (Odoh *et al.*, 2023). A sample of the messages sent is shown in Figure 2.

$$P = \frac{T_0}{T_o + F_o} \times 100 \quad 1$$

Where: T_o and F_o are true and false outcomes, respectively.

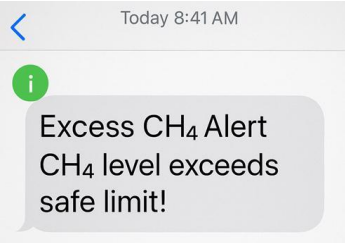


Figure 2: SMS showing excess CH_4 limit

3.0 Results and Discussion

The results of the tests conducted on the prototype are presented in Figures 3 to 8. It was noted that prototype IoT system exhibited the following performances percentage: CO (85%), CH_4 (95%), H_2S (90%), Benzene (85%), and overall (100%), achieving an average of 90% efficiency. This is similar to the findings of Arka *et al*. (2025) and Odoh *et al*. (2023) on developed smart systems. The outcomes portray that the system demonstrated prompt detection, interpretation, and real-time transmission, which will enhance safety thresholds in waste management. The significant true positive outcomes, recorded during the performance evaluation of the system, can be linked to the excellent functionality and partnership of the

system's hardware, software, and algorithms employed for the overall prototype development (Malembeka *et al.*, 2025). The false positives recorded during the tests, which are a limitation, can be attributed to sensor drift and anthropogenic activities such as high temperature, humidity, and particulate matter (Sharma *et al.*, 2025). Remarkably, the developed IoT waste management system was able to provide consistent, receptive, and precise detection of hazardous gases, which will be useful within the municipal waste management structures and dumpsites.

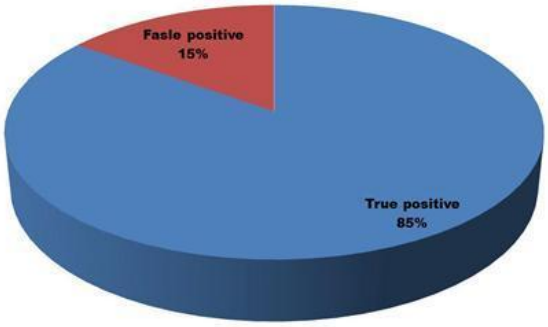


Figure 3: The CO outcome

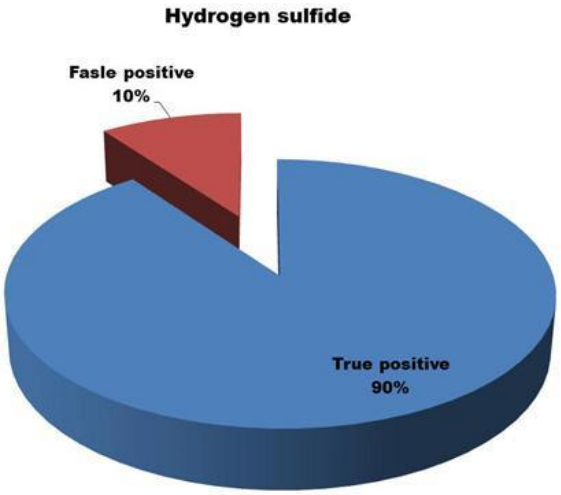


Figure 4: The H_2S outcome

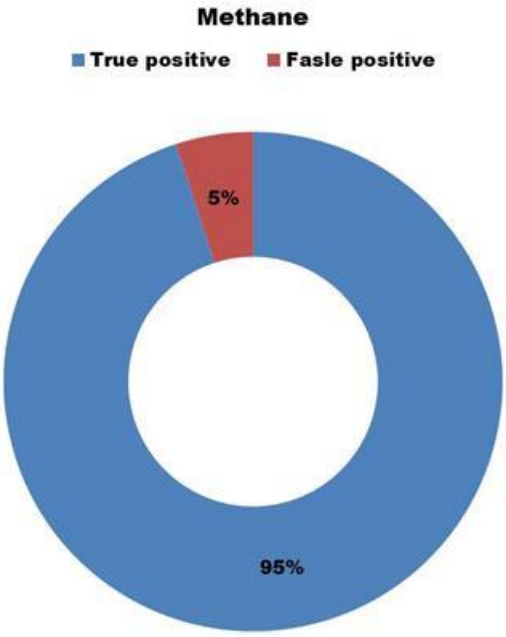


Figure 5: The Methane outcome

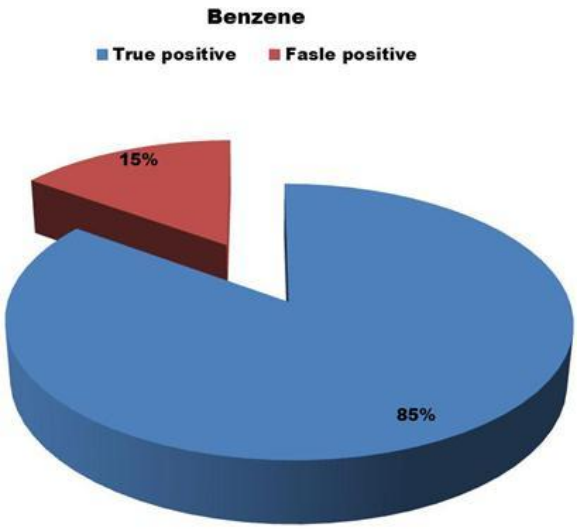


Figure 6: The benzene outcome

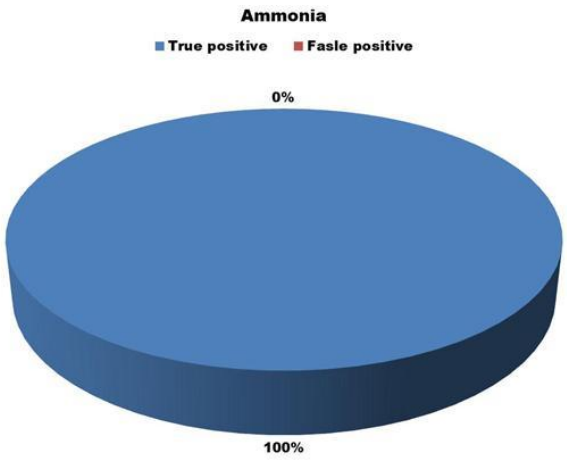


Figure 7: The ammonia outcome

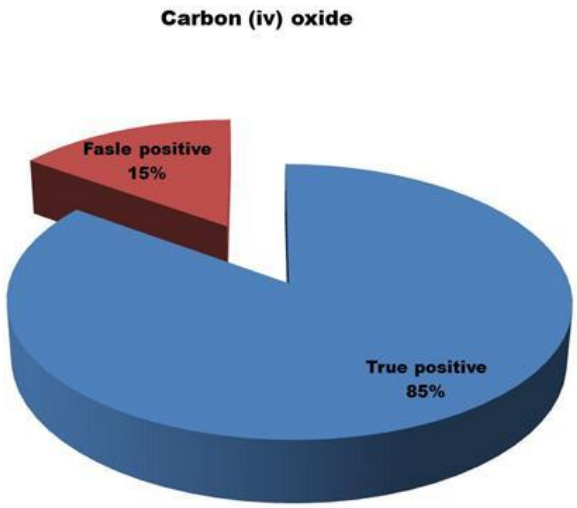


Figure 8: The CO_2 outcome

4.0 Conclusion

Environmental protection is essential for human capital development. This study was carried out to design and develop a prototype IoT-based smart waste management system, which can detect the concentrations of toxic gases emitted, by the waste and alert the public once the safety limit has been exceeded. Specifically, this system integrates cloud monitoring platform, which facilitates preemptive waste management and ecological safety. The major components of this system include sensors (MQ4, MQ7, MQ135, and MQ-137), an ESP32 microcontroller, an LCD display, a battery, and a buzzer. Remarkably, the IoT model was developed to monitor the concentrations of NH_3, CO, CO_2, H_2S, and CH_4 gases in the environment, primarily regions in proximity to waste dumpsites. Results obtained from the performance evaluation indicated that the system had an efficiency of 90%, establishing the threshold precision, dependability and responsiveness of the prototype. These findings have highlighted that cost-effective IoT-based smart systems can be utilized effectively in metropolitan landfills, dumpsites, and smart city waste management systems. This will enhance proactive ecological protection and hazardous gases accumulation, resulting in toxicity aliments. Lastly, it is recommended that future research include utilization of blockchain services to facilitate transparent waste tracking and evacuation.

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