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IoT-Based Real-Time Carbon Monoxide Mitigation for MSME Indoor Environments

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ABSTRACT

This study aims to develop an IoT-based real-time carbon monoxide mitigation system for monitoring and controlling CO levels in MSME indoor environments. The methods used in this study include problem analysis, and product design, followed by three stages of experiments in which the CO concentration is systematically increased from 50 ppm to above 200 ppm for system response testing. The subjects of this study were MSMEs that use fossil fuel equipment in their daily operations. The results show that the system effectively detects increased CO levels and responds appropriately. At a CO concentration of 58 PPM, Fan 1 is activated, while at a CO concentration of 105 PPM, Fan 1 and Fan 2 are activated with low-intensity buzzer alarms. When the CO concentration exceeds 200 PPM, the system triggers maximum safety action, activating both fans, a high-intensity buzzer, and a red emergency light. In addition, real-time notifications are sent to mobile devices, ensuring alertness and rapid response. The findings of this study indicate that the use of IoT technology in managing workplace safety can significantly increase the speed and effectiveness of responses to CO gas threats, potentially reducing the risks faced by workers in MSME workplaces.

1. INTRODUCTION

Carbon monoxide (CO) is a colorless, odorless toxic gas that is extremely dangerous when it accumulates in confined spaces It is often produced from the incomplete combustion of fossil fuels [1], such as those used in generators, ovens, or heaters [2]. Carbon monoxide exposure is one of the leading causes of poisoning incidents worldwide, causing thousands of deaths each year [3, 4].

MSMEs play a vital role in the global economy [5, 6], particularly in developing countries [7], where they account for a large share of employment [8]. However, the unique characteristics of MSMEs such as limited work space [9], use of non-environmentally friendly fuel-based equipment [10], lack of awareness of carbon monoxide hazards [11], and limited funds to meet safety standards [12]. These situations can increase carbon monoxide incidents that will disrupt business operations, even cause financial losses and even endanger employees, and customers.

Traditional carbon monoxide detection systems, such as gas detector alarms, have been used to mitigate this risk [13, 14]. However, these devices often only provide an alert without any mechanism for automated action. In addition, many systems do not provide real-time monitoring or the ability to send remote notifications to business owners [15-17]. Unfortunately, many MSMEs still do not use detection devices due to limited capital or costs to procure such devices. For MSMEs, complex or expensive solutions are often inaccessible, increasing the need for simpler, more cost-effective, and more effective mitigation systems.

Several previous studies have examined carbon monoxide mitigation systems. For example, research by Chen et al. [17], developed a Multimodal sensors-based system that only provides an alarm without an automatic response to prevent fires. Another study by Ayyappan et al. [18], explored the use of IoT technology for monitoring toxic gases in waste disposal systems, but IoT only provides warning signs of action to minimize the dangers of toxic gases. Research conducted by Lashari et al. [19], created an IoT-based automatic ventilation system, but its use is more directed at an industrial scale with large indoor spaces. In addition, research by Parri et al. [20], showed that sophisticated IoT solutions are often too expensive and complicated to be implemented in MSMEs. Unlike previous studies, this study offers an IoT-based system that is able to monitor carbon monoxide in real-time by sending notifications via mobile phones and providing automatic responses in stages according to the level of carbon monoxide concentration. This system is specifically designed to meet the needs of MSMEs by prioritizing affordable costs, ease of installation, and accessibility via mobile devices.

This study aims to develop an IoT-based real-time carbon monoxide mitigation system integrated with mobile devices for MSME indoor environments. This system is expected to provide an efficient, cost-effective, and easy-to-use solution to reduce the risk of carbon monoxide in closed spaces. The main contributions of this study include filling the literature gap in the development of IoT solutions designed for small business scale, improving occupational safety in MSMEs, and reducing the economic and health impacts caused by carbon monoxide incidents. Thus, this study provides benefits not only for the academic world but also for real practice in the field.

2. LITERATURE REVIEW

The literature discussed in this section focuses on carbon monoxide risk mitigation using IoT-based technologies and their application in closed environments, especially for micro, small, and medium enterprises (MSMEs). IoT technology is increasingly emerging as a modern solution in environmental risk monitoring and management [21], but its specific application to the needs of MSMEs is still limited. Therefore, this review aims to identify key findings in previous literature and uncover research gaps that this study can fill.

Previous research has shown that IoT has great potential in detecting and managing hazardous gases, including carbon monoxide. Research conducted by Polymeni et al. [22], developed an IoT sensor-based system for gas monitoring, which can provide warnings with alarms. However, this system is primarily designed for residential use rather than business environments, which require more robust and scalable solutions. Another study conducted by Siddiqui et al. [23], integrated IoT with machine learning algorithms for air quality analysis. While promising, the approach demands high computational power and complex configurations, making it impractical for MSMEs with limited technical expertise and financial resources.

Another critical aspect of CO mitigation is ventilation control in enclosed spaces. Another study by Guerrero-Ulloa et al. [24], introduced an IoT-based automatic ventilation system that improves airflow in poorly ventilated areas. However, their system is mostly implemented in large buildings and public spaces, ignoring the spatial constraints and specific operational needs of MSMEs. Unlike industrial-scale environments, MSMEs often operate in confined and isolated spaces where large-scale ventilation solutions may not be feasible.

Challenges in technology adoption further complicate the implementation of CO mitigation systems in MSMEs. Cost is a major barrier, as many small businesses struggle to afford advanced safety technologies [25], additionally highlighted that technological complexity hinders adoption, as many business owners lack the expertise to manage sophisticated IoT systems [26]. These findings indicate that existing solutions are often either too expensive or too complex for small business applications.

Despite the advancements in IoT-based gas monitoring, a significant research gap remains in the development of affordable, user-friendly, and scalable mitigation systems tailored specifically for MSMEsThis study addresses this gap by proposing an IoT-based real-time carbon monoxide mitigation system for MSME indoor environments, which not only detects gas concentration but also provides automated responses, such as activating ventilation or sending notifications via mobile devices. Unlike prior research, our approach prioritizes cost-effectiveness, ease of installation, and usability, making it accessible even for MSMEs with minimal technical expertise. Thus, this study not only contributes to the literature on IoT and environmental safety but also provides a practical solution to improve occupational safety in MSMEs.

3. METHOD

This research is a research and development with an approach to modifying the ADDIE model (Analysis, Design, Development, Implementation, Evaluation). The ADDIE model was chosen because of its structured, iterative, and flexible nature, which allows for continuous improvement during the development process. This characteristic is crucial for ensuring that the IoT-based real-time carbon monoxide mitigation system is both functional and practical for MSME indoor environments. This research was conducted through five main stages of Analysis, Design, Development, Implementation, and Evaluation. The research procedure is illustrated in Figure 1.

Analysis Stage: At this stage, initial observations are conducted to understand users' needs in the MSMEs environment that use fossil fuel devices. Needs analysis is conducted to identify the potential risks of carbon monoxide. This process involves analyzing literature related to IoT technology, setting goals, and reviewing relevant issues in depth.

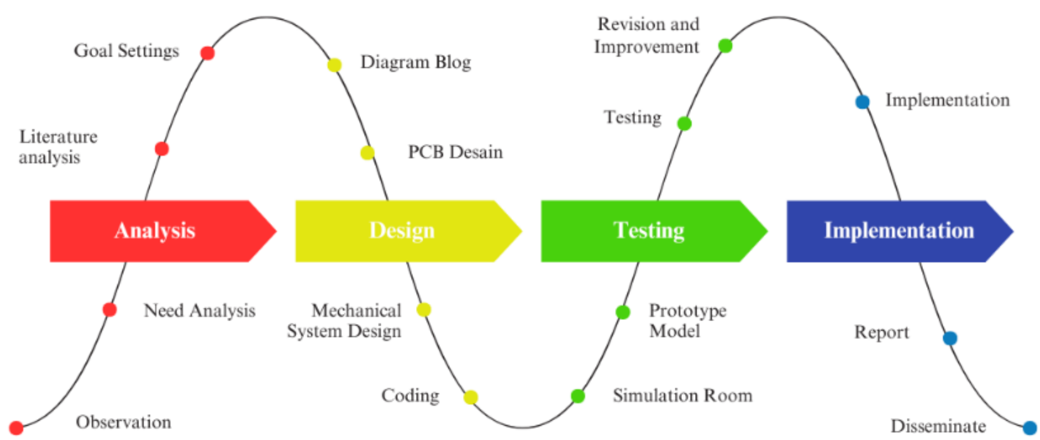
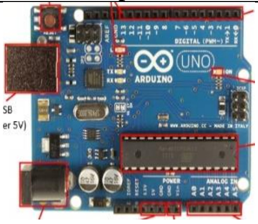
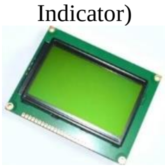
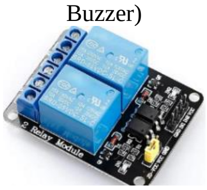
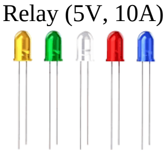
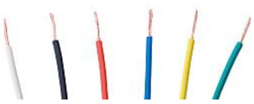


Figure 1. Research procedures

Table 1. Mitigation system components

No	Component	Function
1	 Microcontroller (ATmega328P)	Acts as the brain of the system to control all IoT components. Processes data from sensors, executes program logic, and controls output devices. Operates at 5V with a clock speed of 16MHz.
2	 NodeMCU ESP8266	Wi-Fi module (802.11 b/g/n, 3.3V) that connects the system to the internet, enabling remote data communication and control. Features an onboard TCP/IP stack and supports MQTT protocols.
3	 Sensor MQ-135	Air quality sensor that detects harmful gases, including carbon monoxide (CO), carbon dioxide (CO_2), ammonia (NH_3), and methane (CH_4). Operates at 5V with an analog output.
4	 Pilot Lamp (5V LED Indicator)	Indicator lights that show the working status of the system or certain conditions, such as power on or error.
5	 LCD (16x2 I2C Display)	Displays relevant system information, such as sensor readings, connection status, or notifications. Uses I2C communication for efficient data transfer.
6	 Buzzer (Active 5V Buzzer)	Provides an audible warning when certain conditions are detected, such as high CO levels. Operates at 5V with a frequency range of 2-4kHz.
7	 Relay (5V, 10A)	An electronic switch that allows a microcontroller to control high-current electrical devices, such as motors or lights, using low current.
8	 Light Emitting Diode (LED 5mm, 2V)	Provides visual indications for various statuses, such as operational status or system notifications.
9	 Diode (1N4007, 1000V, 1A)	Directs current flow in one direction only to protect other components from reverse current or power surges.
10	 Cable (Jumper Wires, 22AWG)	Connects all electronic components to ensure effective data and power delivery.

Design Phase: After the analysis phase is complete, the research enters the system design phase. This includes block diagram design (blog diagram) and mechanical system design to map the system elements. This process is completed with PCB design for hardware integration, as well as coding for software that will be used in the IoT system.

Development and Testing Phase: in this stage, a prototype of the system is built and tested in a controlled simulation environment. The hardware and software components are evaluated for their effectiveness in detecting and mitigating carbon monoxide risks. Any identified weaknesses are addressed through iterative refinements to enhance system reliability before real-world implementation.

Implementation Stage: In the final stage, the system that has been developed and tested is implemented in the real environment of MSMEs. The implementation process involves documentation of research results in the form of reports and dissemination of information through scientific publications. This aims to provide solutions that are applicable and can be widely used by small and medium business actors.

3.1 Research subject

This study focuses on the environment of MSMEs that use fossil fuel equipment in their daily operations. The research location includes areas with limited ventilation and high risk of carbon monoxide exposure, such as kitchens. The research subjects consisted of business owners and workers who actively use fossil fuel equipment. In addition, occupational safety experts were also involved to provide input during the Testing and evaluation process.

3.2 Tools and material

This study uses various tools and materials to support the development and implementation of an IoT-based carbon monoxide mitigation system. The tools and materials used can be seen in Table 1.

In addition, Blynk is used as the main application in this system to monitor air quality in real-time and control connected IoT devices. This application allows users to receive direct notifications regarding carbon monoxide concentrations in the surrounding environment. With an intuitive interface, Blynk makes it easy for business owners to monitor data from carbon monoxide sensors, receive alerts based on ISPU categories, and control system responses such as activating ventilation. In addition, the integration between Blynk and the microcontroller allows for fast data transmission to the cloud platform, so users can access information remotely via their mobile devices. This convenience makes Blynk an ideal solution for managing carbon monoxide mitigation systems efficiently. The working process is illustrated in Figure 2 below.

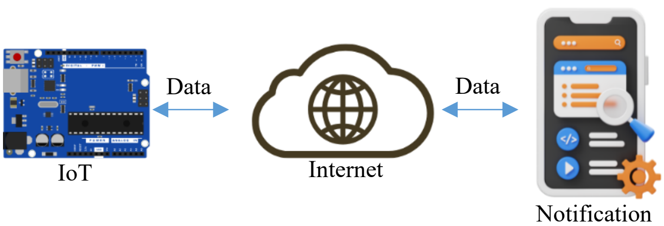


Figure 2. Mitigation system working process

3.3 Data collection

Air quality data is recorded in real-time from sensors to measure carbon monoxide concentration levels in the MSMEs environment, referring to the ISPU (Air Pollutant Standard Index) standard with Parts Per Million (PPM) units. The system works based on the work indicators shown in Table 2 below.

Table 2. Mitigation system work indicator

PPM	Category	Action
0-50	Safe	No action
51-100	Alert	The system automatically activates the fan at light speed.
101-199	Unsafe	The system will increase the fan speed, provide an Unsafe notification to the user, and activate the Buzzer with Low intensity.
200-299	Hazardous	The system provides an emergency alert to the user and activates the Buzzer with medium intensity.
≥300	Critical	The system will activate the Buzzer with high intensity and instruct evacuation.

Overall system performance testing is conducted in three stages, Stage 1: Carbon monoxide concentration is increased to exceed 50 PPM. At this stage, the system is tested for its ability to identify and respond to increases in carbon monoxide that are still considered safe according to ISPU standards. Stage 2: The concentration is further increased to exceed 100 PPM. This stage tests the system's ability to increase its response in the presence of higher pollution levels. Stage 3: Finally, the carbon monoxide concentration is increased to exceed 200 PPM. At this stage, the system must demonstrate its full capability to deal with hazardous conditions by activating all available mitigation measures.

4. RESULT

4.1 Diagram block

The diagram in Figure 3 illustrates the architecture and workflow of the IoT-based carbon monoxide mitigation system that we have developed. Each system component is shown in relation to each other to provide a comprehensive picture of the overall system operation.

The system starts detection from the MQ-135 Sensor, which plays a role in identifying hazardous gases such as carbon monoxide and other gases. This sensor is connected to an Arduino Uno, a microcontroller that functions as a data processing center, processing input from the sensor and sending commands to output components based on the data received. Output components include a buzzer that emits an audible signal when hazardous gas levels exceed safe limits, a relay to activate a fan to increase ventilation, and an additional relay for perfume that improves air quality. Indicator lights—green, yellow, and red—provide visual information about the system status: green indicates normal conditions, yellow for warnings, and red indicates emergency conditions. To enable remote monitoring, an ESP8266 NodeMCU is integrated into the system, connecting it to the Blynk Server via Wi-Fi. Information and status from the system are also displayed locally via a Graphic LCD ensuring that monitoring can be done even without an internet connection.

4.2 Electronic circuit design

The electronic circuit shown in Figure 4 is a circuit developed to support an IoT-based carbon monoxide mitigation system. This circuit shows the configuration of the main components involved in detecting and responding to carbon monoxide levels.

The Arduino is connected to various components through a structured circuit to maximize the detection and response functions for carbon monoxide.

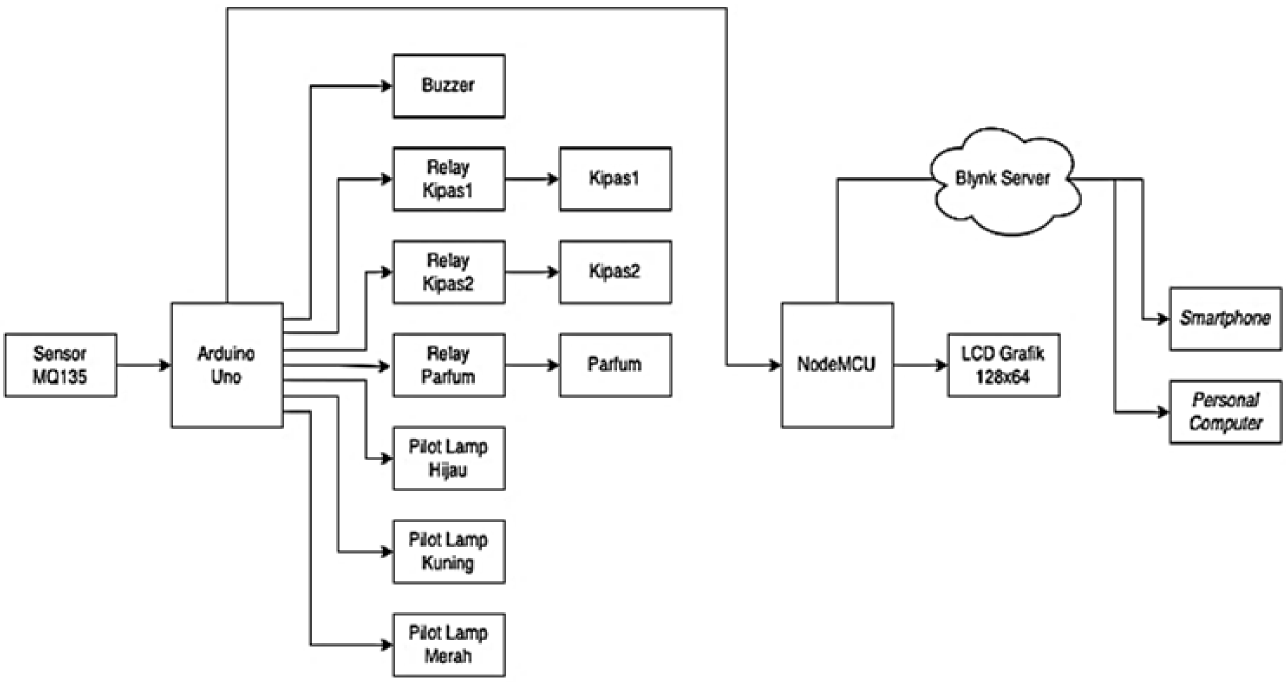


Figure 3. Block diagram of mitigation system

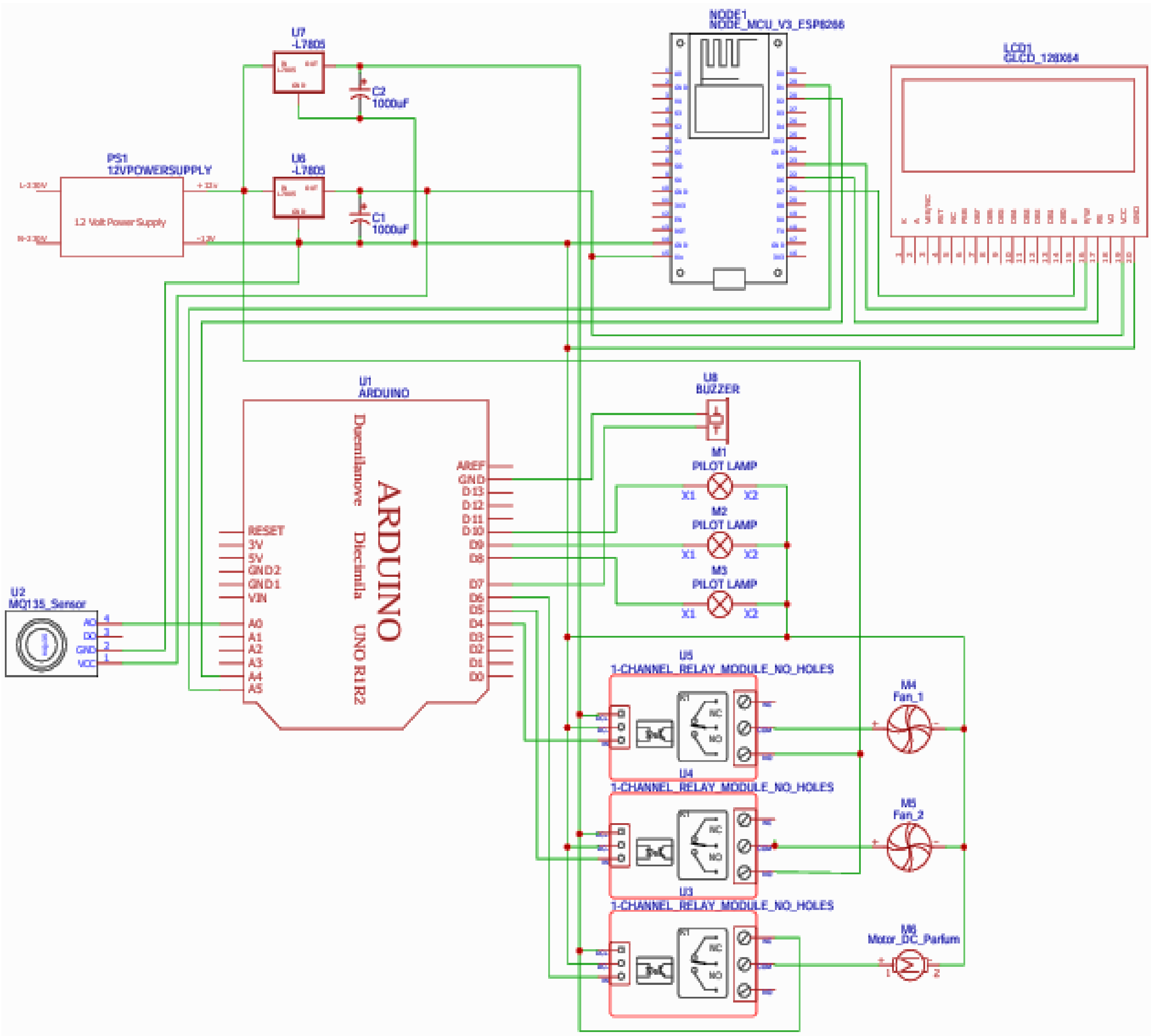


Figure 4. Electronic circuit of mitigation system

In this circuit, the MQ-135 sensor, which is sensitive to carbon monoxide gas, is connected directly to the Arduino to monitor air quality in real time. The MQ-135 sensor undergoes a calibration process to ensure accurate CO detection, achieving an accuracy rate of 95%. Output components include a buzzer and several relays that are activated by the Arduino based on sensor readings. These relays control fans and other systems to optimize room ventilation or turn on other devices in response to detected gas levels. The circuit also includes LED indicator lights in three colors—red, yellow, and green—that provide real-time visualization of system status. The circuit is also designed for integration with a Wi-Fi module via the NodeMCU ESP8266, allowing the circuit to connect to the Blynk Server and provide remote monitoring and control capabilities through the Blynk application.

4.3 Mechanical system design

The next stage in the development of an IoT-based carbon monoxide mitigation system is to assemble the hardware according to the block diagram and the specified electronic circuit design. This process begins with the preparation of the necessary components, then integrated so that they are connected to each other and installed into a panel box to look compact and neat. The appearance of the electronic circuit that has been assembled into the panel box can be seen in Figure 5 below.

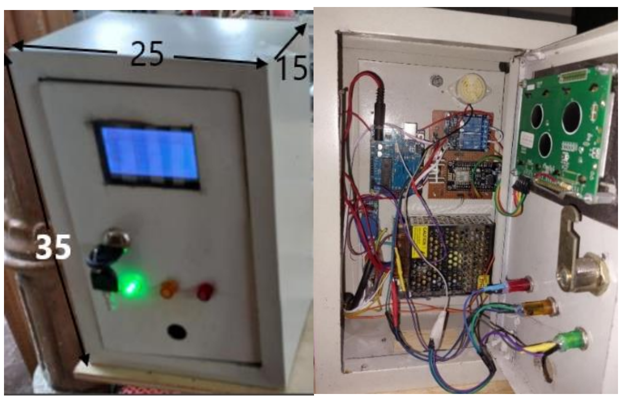


Figure 5. Installation of electronic circuits in the panel box

In addition, considering the high risk in testing, a simulation room was created that resembles the real conditions in which the carbon monoxide mitigation system will be tested, this is done to minimize the risks that can occur during testing. The simulation room for testing can be seen in Figure 6 below.

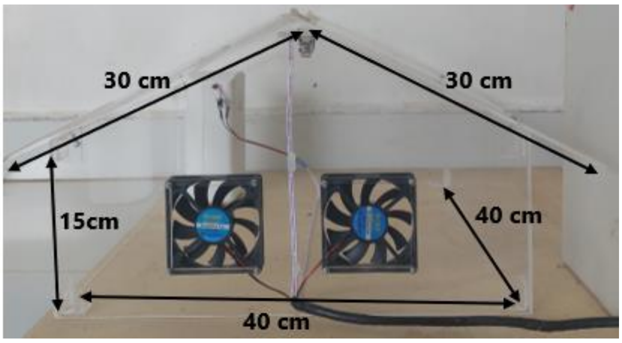


Figure 6. Simulation room design

The simulation room was constructed with dimensions strategically chosen to mimic a typical MSMEs environment, measuring 60 cm long, 40 cm wide, and 20 cm high. The structure is equipped with two fans located on both sides of the short wall, each measuring 8 cm x 8 cm, which serve to simulate the air flow in the room. These fans are essential to test the system's ability to manage ventilation and respond to detected carbon monoxide levels. The room was designed to provide the controlled conditions needed to effectively evaluate the sensor functions, control logic, and response of the developed system.

4.4 Coding

To program an Arduino and NodeMCU based carbon monoxide detection and mitigation system that uses the MQ-135 sensor and communicates with the Blynk application, here is the code used.

```
#include <ESP8266WiFi.h>
#include <BlynkSimpleEsp8266.h>

char ssid[] = "WiFiSSID";
char pass[] = "WiFiPassword";
char auth[] = "BlynkAuthToken";
const int mq135Pin = A0
float sensorValue = 0;
// Pin output
const int buzzerPin = D1;
const int redLedPin = D2;
const int yellowLedPin = D3;
const int greenLedPin = D4;
const int fan1Pin = D5;
const int fan2Pin = D6;
void setup() {
  Serial.begin(9600);
  pinMode(buzzerPin, OUTPUT);
  pinMode(redLedPin, OUTPUT);
  pinMode(yellowLedPin, OUTPUT);
  pinMode(greenLedPin, OUTPUT);
  pinMode(relayPin, OUTPUT);
  pinMode(fan1Pin, OUTPUT);
  pinMode(fan2Pin, OUTPUT);

  digitalWrite(buzzerPin, LOW);
  digitalWrite(redLedPin, LOW);
  digitalWrite(yellowLedPin, LOW);
  digitalWrite(greenLedPin, LOW);
  digitalWrite(relayPin, LOW);

  WiFi.begin(ssid, pass);
  Blynk.begin(auth, ssid, pass);
}

void loop() {
  Blynk.run();
  Int sensorValue = analogRead(mq135Pin);
  Serial.println(sensorValue);
  int ppm = map(sensorValue, 0, 1023, 0, 500);
if (ppm < 51) {
    digitalWrite(greenLedPin, HIGH);
    digitalWrite(yellowLedPin, LOW);
    digitalWrite(redLedPin, LOW);
    digitalWrite(fan1Pin, LOW);
    digitalWrite(fan2Pin, LOW);
    analogWrite(buzzerPin, 0);
    Blynk.notify("FAN ACTIVE");
  } else if (ppm < 101) {
    digitalWrite(greenLedPin, LOW);
    digitalWrite(yellowLedPin, HIGH);
    digitalWrite(redLedPin, LOW);
    digitalWrite(fan1Pin, HIGH);
    digitalWrite(fan2Pin, LOW);
    analogWrite(buzzerPin, 0);
    Blynk.notify("Warning: UNSAFE");
  } else if (ppm < 200) {
    digitalWrite(greenLedPin, LOW);
    digitalWrite(yellowLedPin, LOW);
    digitalWrite(redLedPin, HIGH);
    analogWrite(fanPin, 255);
    analogWrite(buzzerPin, 128);
    Blynk.notify("Warning: HAZARDOUS");
  } else if (ppm < 300) {
    digitalWrite(greenLedPin, LOW);
    digitalWrite(yellowLedPin, LOW);
    digitalWrite(redLedPin, HIGH);
    digitalWrite(fan1Pin, HIGH);
    digitalWrite(fan2Pin, HIGH);
    analogWrite(buzzerPin, 255);
    Blynk.notify("DANGER");
  } else {
    digitalWrite(greenLedPin, LOW);
    digitalWrite(yellowLedPin, LOW);
    digitalWrite(redLedPin, HIGH);
    digitalWrite(fan1Pin, HIGH);
    digitalWrite(fan2Pin, HIGH);
    analogWrite(buzzerPin, 255);
    Blynk.notify("CRITICAL");
  }  delay(1000);
}
```

4.5 Testing

The final stage is the overall system testing where the system is placed in an environment that mimics the real conditions of use in micro, small and medium enterprises. In this test, a series of tests are carried out divided into three stages, each with a different carbon monoxide concentration. The system is tested for its responsiveness to changes in air conditions, the effectiveness of warnings and mitigation actions, and the stability and reliability of long-term operation. The fan, relay and warning system are checked to ensure that they activate appropriately according to the detected carbon monoxide level. The results of the first test with a carbon monoxide concentration between 50-100 PPM can be seen in Table 3 below.

At carbon monoxide concentrations between 50-100 PPM, the system effectively activates fan 1 when the PPM reaches 58 and activates fan 1, indicating a response transition from safe to alert. This indicates that the system is able to detect increasing CO levels and adjust preventive actions accordingly. The green light indicates that the condition is still under control, and the fan will be inactive again when the PPM drops back below 50. A notification is also sent to the mobile phone displaying the information "PPM 67", status "Alert", Fan 1 "Active", and Emergency Light "Green". The first test notification display on the mobile phone can be seen in Figure 7.

The second test was conducted by increasing the concentration of carbon monoxide between 101-199 PPM. The test results can be seen in Table 4.

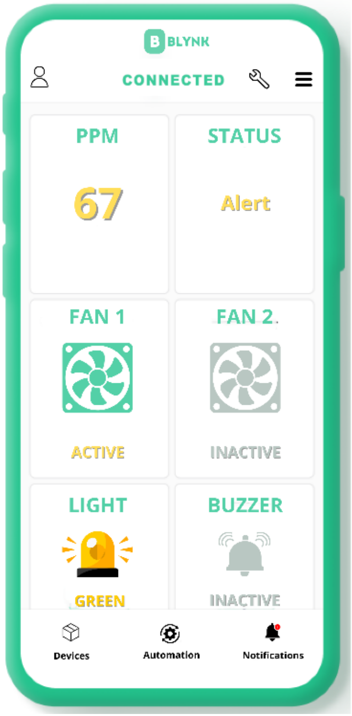


Figure 7. Mobile alert for CO levels 50-100 PPM

In this range, the system shows an increase in fan 1 and 2 activation and buzzer activation at a low level when the PPM exceeds 100. This shows that the system can effectively respond to increased risks by increasing fan speed and providing appropriate buzzer warnings, which are vital in maintaining a safe working environment. Notifications are also sent to the mobile phone displaying information "PPM 119", status "Unsafe", Fan 1 "Active", Fan 2 "Active", Emergency Light "Yellow", and Buzzer "Low". The second test notification display on the mobile phone can be seen in Figure 8.

Next, the third test was carried out by increasing the concentration of carbon monoxide between >200 PPM. The test results can be seen in Table 5 below.

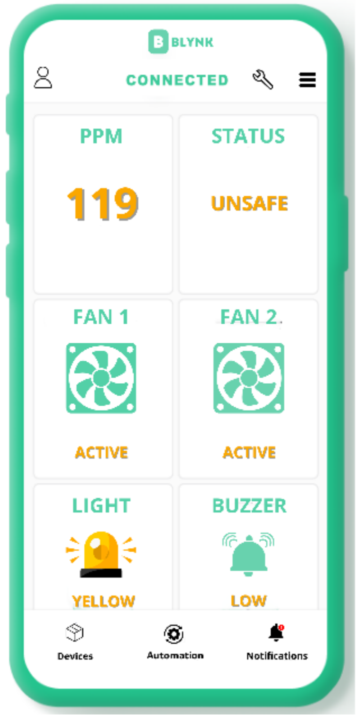


Figure 8. Mobile alert for CO levels 101-199 PPM

At this stage, the red light and both fans are consistently active when the concentration exceeds 200 PPM, with the buzzer emitting a high warning. This response indicates that the system effectively identifies and responds to hazardous conditions by implementing maximum safety measures to reduce risks in highly contaminated environments. Notifications are also sent to the mobile phone displaying information "PPM 215", status "Hazardous", Fan 1 "Active", Fan 2 "Active", Emergency Light "Red", and Buzzer "High". The second test notification display on the mobile phone can be seen in Figure 9.

Figure 9. Mobile alert for CO levels > 200 PPM

Table 3. System response at CO concentration 50-100 PPM

Minute	PPM	Green Light	Yellow Light	Red Light	Fan 1	Fan 2	Buzzer
1	16	On	Off	Off	Off	Off	Off
2	23	On	Off	Off	Off	Off	Off
3	37	On	Off	Off	Off	Off	Off
4	42	On	Off	Off	Off	Off	Off
5	49	On	Off	Off	Off	Off	Off
6	58	On	Off	Off	On	Off	Off
7	67	On	Off	Off	On	Off	Off
8	62	On	Off	Off	On	Off	Off
9	54	On	Off	Off	On	Off	Off
10	42	On	Off	Off	Off	Off	Off
11	29	On	Off	Off	Off	Off	Off

Table 4. System response at CO concentration 101-199 PPM

Minute	PPM	Green Light	Yellow Light	Red Light	Fan 1	Fan 2	Buzzer
1	36	On	Off	Off	Off	Off	Off
2	42	On	Off	Off	Off	Off	Off
3	54	Off	On	Off	On	Off	Off
4	72	Off	On	Off	On	Off	Off
5	92	Off	On	Off	On	Off	Off
6	105	Off	On	Off	On	On	Low
7	119	Off	On	Off	On	On	Low
8	108	Off	On	Off	On	On	Low
9	97	Off	On	Off	On	Off	Off
10	82	Off	On	Off	On	Off	Off
11	60	Off	On	Off	On	Off	Off

Table 5. System response at CO concentration > 200 PPM

Minute	PPM	Green Light	Yellow Light	Red Light	Fan 1	Fan 2	Buzzer
1	48	On	Off	Off	Off	Off	Off
2	74	Off	On	Off	On	Off	Off
3	93	Off	On	Off	On	Off	Off
4	112	Off	Off	On	On	On	Low
5	132	Off	Off	On	On	On	Low
6	154	Off	Off	On	On	On	Low
7	180	Off	Off	On	On	On	Low
8	205	Off	Off	On	On	On	High
9	215	Off	Off	On	On	On	High
10	194	Off	On	Off	On	On	Low
11	172	Off	On	Off	On	On	Low

Thus, the test results show that the developed system is capable of detecting and responding to various levels of carbon monoxide concentration in a precise and efficient manner, with an accuracy rate of 95%. The reliability of the system's response to increased CO levels ensures effective protection in MSMEs environments, making the system a good solution for improving occupational safety. In addition, the application also has the ability to send notifications to the user's mobile phone, which is very important for emergency situations. Integration with Blynk not only enables remote and real-time monitoring but also provides great ease of control and accessibility for the user. This functionality ensures that the user can respond quickly to changing environmental conditions without having to be physically present. This is a major advantage in the MSMEs context, where resources for safety monitoring can be limited.

5. DISCUSSION

The test results that have been carried out show that this carbon monoxide mitigation system is able to respond effectively to increasing CO levels in the MSMEs environment. By using IoT technology, the system successfully adjusts the response based on the severity of the condition, starting from providing early warnings to activating emergency procedures when needed. At higher CO concentrations, the system demonstrated reliability by activating both the fan and the buzzer at the appropriate intensity, according to the tested scenario. Integration with the Blynk application shows how the IoT system can increase user engagement and proactive monitoring of the safety of the work environment. The notification function that provides real-time alerts to users is key in ensuring that action can be taken before conditions become critical. This shows the importance of intuitive and responsive user interface design in IoT-based applications.

The developed IoT-based carbon monoxide mitigation system shows significant advantages compared to several previous studies. Unlike the system developed by Messan et al [27], which only relies on local alarms without integration with mobile apps, the system developed by the author uses the Blynk application to provide real-time control and monitoring via smartphones, expanding the reach and ease of access for users. In contrast to the study by Ramadan et al [28], which uses a carbon monoxide sensor that is monitored in real time with an automatic fan, it does not integrate automatic control of the fan based on the detected PPM level. In addition, in the study by Das et al [29], although the IoT application used for gas detection was designed at a low cost, there was no remote notification functionality or interactivity with the user, while this system ensures that users are not only informed of potential hazards but can also take direct action through a user-friendly interface. In line with the solution proposed by Jumaa et al [30], which uses IoT that has been integrated with notification via mobile phone but requires quite a lot of energy to run the system, while the system that the researcher developed is designed for better energy efficiency, utilizing a control algorithm with PPM level adjustment to reduce energy consumption without sacrificing performance. Overall, this system offers a more integrated, intelligent, and user-friendly approach compared to previous models, showing a significant evolution in hazardous gas mitigation technology.

While these findings demonstrate significant benefits, there are some limitations that require further analysis. One major limitation is the effect of environmental conditions, particularly temperature and humidity, on sensor accuracy. MQ-135 sensor readings can fluctuate due to variations in these factors, potentially affecting response reliability. This issue is particularly relevant in industrial environments where temperature and humidity levels can change dynamically. To mitigate this impact, future research should explore advanced calibration techniques, such as the application of Artificial Intelligence that can be trained on a dataset that includes sensor readings under a variety of environmental conditions, allowing for more accurate estimation of CO levels. Additionally, the application of multisensory fusion—integrating data from multiple gas and environmental sensors—can improve the robustness and reliability of the system. Another limitation involves network dependency. The system requires a stable Wi-Fi connection to send notifications, which may not be possible in all MSME environments, particularly in remote areas or with limited infrastructure. Future improvements could explore alternative communication technologies, such as LoRa or GSM-based messaging, to ensure continuous monitoring even in areas with limited internet access.

These findings could provide significant benefits in industrial environments, especially in MSMEs that may not have the resources for complex safety systems, such applications not only improve workplace safety but also support compliance with occupational health and safety regulations. Furthermore, this technology can be adapted to detect other hazardous gases, providing a flexible and adaptive platform for industrial safety needs. Although the findings of this study are very meaningful, the performance of the sensor and the overall system has drawbacks, namely that it can be affected by environmental conditions such as temperature and humidity, and must be close to Wi-Fi range in order to send notifications to the phone. Therefore, there needs to be an improvement in the sensor calibration algorithm to improve accuracy in various environmental conditions through further research in the future.

6. CONCLUSIONS

Conclusions from the testing of the IoT-based real-time carbon monoxide mitigation system demonstrate its effectiveness in detecting and responding to varying CO concentrations, with response components activated as needed to enhance workplace safety in MSME indoor environments. The system offers significant benefits, particularly in improving occupational safety, enabling remote monitoring and control via the Blynk application, and facilitating rapid responses to hazardous conditions. Practical implications include potential integration with larger building safety systems, increased compliance with occupational health and safety regulations, and adaptability for detecting other hazardous gases, making it a highly valuable solution for MSMEs that often lack sophisticated safety systems.

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