Republic of Yemen

Dhamar University

Facuity of Engineering

Department of Mechatronics

MQ GAS SENSOR SERIES

Supervised by :Dr.Khaled Taher Al-Hussaini

Student Research:Kamal Al-Rawafi

Date:7/9/2025

MQ Gas Sensor Series

1. Index

2. Abstract

This academic research provides a comprehensive overview of the MQ Gas Sensor Series, widely recognized for their cost-effectiveness and versatility in detecting various gases. The paper delves into the fundamental principles of gas sensing, the specific characteristics of different MQ sensor types (from MQ-2 to MQ-214), their internal structure, and practical applications across diverse sectors. A comparative analysis of key MQ sensors is presented, highlighting their sensitivity, accuracy, response time, and other critical parameters. Furthermore, the research addresses the limitations and challenges associated with these sensors, such as accuracy issues, sensitivity to environmental factors, and long- term stability. Finally, the paper concludes with a summary of key findings and offers insights into future developments and research recommendations in the field of gas sensing technology. This research aims to serve as a valuable resource for students, researchers, and professionals working with gas detection systems, providing a detailed understanding of MQ sensors in accordance with academic and international research standards.

3. Introduction

A gas sensor is an electronic device designed to detect the presence and often the concentration of specific gases within an environment. These devices play a critical role in ensuring safety, monitoring environmental quality, and facilitating various industrial processes. The selection of a gas sensor is crucial, as different applications require varying levels of sensitivity, selectivity, and operational stability.

The MQ series gas sensors have emerged as a popular and widely adopted solution in gas detection due to their affordability, ease of use, and broad range of detectable gases. This series is particularly significant in modern applications, spanning from domestic safety systems to complex industrial monitoring and environmental control. Their compatibility with common microcontroller platforms like Arduino and ESP32 further enhances their appeal to hobbyists, students, and professionals alike.

This research aims to provide a detailed and comprehensive analysis of the MQ gas sensor series. We will explore their underlying working principles, delve into the specific characteristics and applications of individual sensor types, and examine their internal structure and integration methods. The primary objectives of this research are:

- To provide a foundational understanding of gas sensors and the significance of the MQ series.
- To categorize and detail the various types of MQ sensors, outlining their target gases and prominent applications.
- To explain the chemical and electronic principles governing the operation of MQ sensors.
- To illustrate the internal components and structural design of these sensors.
- To discuss practical aspects of connecting and integrating MQ sensors with control systems.
- To present a comparative analysis of selected MQ sensors based on critical performance parameters.
- To identify and analyze the limitations and challenges associated with the use of MQ sensors.
- To offer conclusions based on the findings and propose future research directions in gas sensor technology.

This study seeks to answer the following key questions:

- What are the fundamental principles behind the operation of MQ gas sensors?
- How do different MQ sensor types vary in their gas detection capabilities and applications?
- What are the practical considerations for integrating MQ sensors into electronic systems?
- What are the strengths and weaknesses of MQ sensors compared to other gas sensing technologies?
- What are the current limitations and future prospects for the development and application of MQ sensors?

4. Overview of the MQ Series

The MQ gas sensor series represents a family of metal oxide semiconductor (MOS) gas sensors, renowned for their ability to detect a wide range of combustible and toxic gases. Developed with a focus on efficiency and cost- effectiveness, these sensors have become a cornerstone in various gas detection applications, from household safety to industrial monitoring.

Purpose of Development

The primary purpose behind the development of the MQ series was to provide reliable and affordable solutions for gas leakage detection. Given the widespread use of combustible gases like methane, LPG, and propane in domestic and industrial settings, and the health risks associated with toxic gases such as carbon monoxide, there was a significant demand for accessible sensing technology. The MQ series addresses this need by offering sensors that are sensitive to specific gas types while being relatively inexpensive to manufacture and integrate.

Basic Information about their Mode of Operation

MQ sensors operate on the principle of chemiresistance. Their sensitive element is typically made of tin dioxide (SnO_2), which has lower electrical conductivity in clean air. When the sensor comes into contact with a target gas, the gas molecules interact with the surface of the SnO_2, causing a change in its electrical resistance. This change in resistance is proportional to the concentration of the gas in the environment.

The sensor usually contains a heating element (often a coil) that maintains the SnO2 at an optimal operating temperature. This heating is crucial for the chemical reactions to occur efficiently and for the sensor to achieve its specified sensitivity and response time. The change in resistance is then converted into an electrical signal (voltage) that can be read by a microcontroller or other electronic circuits.

Types of MQ Sensors

The MQ series encompasses a variety of sensors, each optimized for detecting a particular set of gases. While they share a common operating principle, their sensitive materials are often doped or treated differently to enhance selectivity towards specific gases. This specialization allows for targeted detection in diverse applications. The following table provides a general overview of some common MQ sensor types and their primary target gases:

Sensor Model	Target Gases
MQ-2	Methane, Butane, LPG, Smoke
MQ-3	Alcohol, Ethanol, Smoke
MQ-4	Methane, CNG
MQ-5	Natural gas, LPG
MQ-6	LPG, Butane gas
MQ-7	Carbon monoxide gas
MQ-8	Hydrogen gas
MQ-9	Carbon monoxide, and flammable gases
MQ-131	Ozone
MQ-135	Carbon monoxide, Benzene, Ammonia, Alcohol, Smoke, CO2
MQ-136	Hydrogen Sulfide
MQ-137	Ammonia
MQ-138	Benzene, Toluene, Alcohol, Acetone, Propane, Formaldehyde, Hydrogen
MQ-214	Methane, Natural gas

This table provides a snapshot of the versatility of the MQ series, demonstrating their applicability in detecting a wide array of gases critical for safety and environmental monitoring. Each sensor type has specific characteristics, including detection range, sensitivity, and response time, which are detailed in their respective datasheets and will be further explored in subsequent sections.

5. Types of MQ Sensors

This section provides a detailed overview of individual MQ gas sensors, highlighting their specific detection capabilities, typical applications, and key operational characteristics. Each sensor is designed to be highly sensitive to a particular set of gases, making them suitable for a wide range of specialized applications.

MQ-2 Gas Sensor

The MQ-2 gas sensor is a highly versatile and widely used sensor for detecting various flammable gases and smoke. Its sensitive material is SnO2, which exhibits lower conductivity in clean air. When combustible gases are present, the sensor's conductivity increases proportionally to the gas concentration.

Gases Detected: Methane (CH_4), Butane (C_4H_{10}), Liquefied Petroleum Gas (LPG), Hydrogen (H_2), Alcohol, Propane, and Smoke.

Prominent Applications:

- **Domestic Gas Leakage Alarms:** Commonly used in homes to detect leaks of LPG, natural gas, and coal gas, providing early warnings of potential hazards.
- **Industrial Safety Systems:** Integrated into safety systems in factories and industrial environments to monitor flammable gas levels and prevent explosions.
- **Fire and Smoke Detection:** Effective in detecting smoke, making it suitable for fire alarm systems.
- **Portable Gas Detectors:** Due to its compact size and low power consumption, it is often used in portable gas detection devices.

Key Features:

- High sensitivity to flammable gases and smoke.
- Fast response time and quick recovery.
- Stable and long operational life.
- Simple drive circuit, making it easy to interface with microcontrollers like Arduino.
- Adjustable sensitivity via a potentiometer on the module.

MQ-3 Gas Sensor

The MQ-3 gas sensor is specifically designed for the detection of alcohol vapor. It has a high sensitivity to alcohol and a good resistance to interference from gasoline, smoke, and vapor, making it ideal for applications where alcohol detection is critical.

Gases Detected: Alcohol (Ethanol), with some sensitivity to Benzene, Methane, Hexane, LPG, and Carbon Monoxide.

Prominent Applications:

- **Breathalyzers:** Widely used in portable and stationary breathalyzer devices to measure alcohol concentration in exhaled breath.
- **Automotive Alcohol Detectors:** Integrated into vehicle systems to prevent drunk driving or to monitor alcohol levels in commercial vehicles.
- **Industrial Alcohol Monitoring:** Used in industries where alcohol production or usage is prevalent, such as distilleries and chemical plants.
- **Environmental Monitoring:** Can be used to detect alcohol spills or leaks in various environments.

Key Features:

- High sensitivity and selectivity to alcohol.
- Fast response and recovery characteristics.
- Stable performance and long lifespan.
- Low cost and simple drive circuit.
- Adjustable sensitivity for various detection thresholds.

MQ-4 Gas Sensor

The MQ-4 gas sensor is primarily used for the detection of methane (CH_4) and Compressed Natural Gas (CNG). It offers high sensitivity to these gases while having low sensitivity to alcohol and smoke, ensuring reliable detection in environments where methane is a primary concern.

Gases Detected: Methane (CH_4), Compressed Natural Gas (CNG), Propane, and Butane.

Prominent Applications:

- **Natural Gas Leak Detection:** Essential for detecting leaks in natural gas pipelines, residential gas lines, and industrial gas storage facilities.
- **Biogas Monitoring:** Used in biogas plants to monitor methane levels, which is a key component of biogas.
- **Mining Safety:** Employed in coal mines and other mining operations to detect methane, a highly explosive gas.
- **Agricultural Applications:** Can be used to monitor methane emissions from livestock or agricultural waste.

Key Features:

- High sensitivity and good selectivity to methane and CNG.
- Fast response and long-term stability.
- Simple drive circuit and low power consumption.
- Wide detection range (typically 200-10000 ppm).

MQ-5 Gas Sensor

The MQ-5 gas sensor is highly sensitive to LPG (Liquefied Petroleum Gas), natural gas, and town gas. It also has some sensitivity to alcohol and smoke, making it a versatile sensor for general gas leakage detection in various settings.

Gases Detected: LPG, Natural Gas, Town Gas, Butane, Propane, Methane, and Hydrogen.

Prominent Applications:

- **Home Gas Leakage Alarms:** Widely used in residential areas to detect leaks of cooking gas (LPG and natural gas).
- **Industrial Gas Leak Detection:** Applied in industrial settings to monitor LPG and natural gas leaks in storage tanks, pipelines, and processing units.
- **Portable Gas Detectors:** Suitable for portable devices used by technicians or emergency responders to identify gas leaks.
- **Vehicle Fuel Leak Detection:** Can be used in vehicles that run on LPG or natural gas to detect fuel leaks.

Key Features:

- High sensitivity to LPG, natural gas, and town gas.
- Fast response and high sensitivity.
- Stable and long operational life.
- Simple drive circuit.
- Dual output (analog and digital) for flexible integration.

MQ-6 Gas Sensor

The MQ-6 gas sensor is specifically designed for the detection of LPG (Liquefied Petroleum Gas) and iso-butane. It offers high sensitivity to these gases and is commonly used in applications where the presence of LPG is a primary concern.

Gases Detected: LPG, Iso-butane, Propane, and some response to Natural Gas.

Prominent Applications:

- **LPG Leakage Alarms:** Essential for detecting leaks in LPG cylinders, gas stoves, and heating systems in homes and commercial establishments.
- **Industrial LPG Monitoring:** Used in industries that utilize LPG as a fuel or raw material, ensuring safety and preventing accidents.
- **Automotive LPG Systems:** Can be integrated into vehicles equipped with LPG fuel systems to detect leaks.
- **Portable LPG Detectors:** Suitable for handheld devices used for quick checks of LPG presence.

Key Features:

- High sensitivity and good selectivity to LPG and iso-butane.
- Fast response and recovery characteristics.
- Stable and long operational life.
- Low cost and simple drive circuit.
- Wide detection range (typically 200-10000 ppm).

MQ-7 Gas Sensor

The MQ-7 gas sensor is highly sensitive to carbon monoxide (CO). It operates on a unique cycle of high and low temperatures to achieve accurate CO detection while minimizing interference from other gases.

Gases Detected: Carbon Monoxide (CO), with some sensitivity to Hydrogen (H_2).

Prominent Applications:

- **Carbon Monoxide Alarms:** Crucial for safety in homes, offices, and industrial settings to detect dangerous levels of CO, a colorless and odorless toxic gas.
- **Automotive Exhaust Monitoring:** Can be used to monitor CO levels in vehicle exhaust fumes.
- **Industrial Process Control:** Employed in industrial processes where CO is a byproduct or a critical component, such as in metallurgy or chemical synthesis.
- **Fire Safety:** Integrated into fire detection systems to identify CO produced during incomplete combustion.

Key Features:

- High sensitivity and selectivity to carbon monoxide.
- Operates with a cyclic high and low-temperature heating method for improved accuracy.
- Fast response and stable performance.
- Long operational life.
- Simple drive circuit for easy integration.

MQ-8 Gas Sensor

The MQ-8 gas sensor is specifically designed for the detection of hydrogen (H_2) gas. It exhibits high sensitivity to hydrogen and has good anti-interference capabilities against other gases, making it suitable for applications where hydrogen detection is critical.

Gases Detected: Hydrogen (H_2), with some sensitivity to alcohol, LPG, and cooking fumes.

Prominent Applications:

- **Hydrogen Leak Detection:** Essential for detecting leaks in hydrogen fuel cells, hydrogen storage facilities, and industrial processes that use or produce hydrogen.
- **Battery Charging Rooms:** Used to monitor hydrogen gas buildup in battery charging areas, where hydrogen can be released during charging.
- **Industrial Safety:** Integrated into safety systems in chemical plants and other industries where hydrogen is present.
- **Fuel Cell Technology:** Plays a role in monitoring hydrogen levels in fuel cell research and development.

Key Features:

- High sensitivity and selectivity to hydrogen gas.
- Fast response and recovery characteristics.
- Stable and long operational life.
- Simple drive circuit.
- Wide detection range (typically 100-10000 ppm).

MQ-9 Gas Sensor

The MQ-9 gas sensor is a versatile sensor capable of detecting both carbon monoxide (CO) and flammable gases like methane (CH_4) and LPG. It operates with a cyclic high and low-temperature heating method, similar to the MQ-7, to achieve optimal detection for both types of gases.

Gases Detected: Carbon Monoxide (CO), Methane (CH_4), and LPG.

Prominent Applications:

- **Multi-Gas Leak Detection:** Ideal for applications requiring the detection of both toxic CO and flammable gases in residential, commercial, and industrial settings.
- **Fire Safety Systems:** Can be used in fire alarms to detect CO produced by incomplete combustion and flammable gases that indicate a fire risk.
- **Industrial Safety:** Employed in various industries to monitor gas levels and ensure worker safety.
- **HVAC Systems:** Integrated into heating, ventilation, and air conditioning systems to detect gas leaks.

Key Features:

- High sensitivity to both carbon monoxide and flammable gases.
- Cyclic temperature operation for enhanced selectivity.
- Fast response and stable performance.
- Long operational life.
- Simple drive circuit.

MQ-131 Gas Sensor

The MQ-131 gas sensor is designed for the detection of ozone (O_3). It also shows sensitivity to strong oxidizing gases such as Cl_2 (Chlorine) and NO_2 (Nitrogen Dioxide), making it useful for air quality monitoring applications.

Gases Detected: Ozone (O_3), Chlorine (Cl_2), and Nitrogen Dioxide (NO_2).

Prominent Applications:

- **Ozone Concentration Monitoring:** Used in air quality monitoring stations, ozone generators, and industrial processes where ozone levels need to be controlled.
- **Medical and Sterilization Equipment:** Employed in medical facilities and sterilization processes that use ozone.
- **Water Treatment Plants:** Can be used to monitor ozone levels in water purification systems.
- **Environmental Air Quality Monitoring:** Contributes to assessing overall air quality by detecting harmful oxidizing gases.

Key Features:

- High sensitivity and good selectivity to ozone.
- Fast response and stable performance.
- Long operational life.
- Simple drive circuit.
- Wide detection range (typically 10-1000 ppb for ozone).

MQ-135 Gas Sensor

The MQ-135 gas sensor is a general-purpose air quality sensor capable of detecting a wide range of harmful gases. It is commonly used for indoor air quality monitoring due to its broad detection spectrum.

Gases Detected: Ammonia (NH_3), Nitrogen Oxides (NO_x), Alcohol, Benzene, Smoke, Carbon Dioxide (CO_2), and other harmful gases.

Prominent Applications:

- **Indoor Air Quality Monitoring:** Widely used in homes, offices, and public spaces to assess overall air quality and detect pollutants.
- **Environmental Monitoring Stations:** Integrated into systems that monitor ambient air pollution levels. •
Ventilation Control Systems: Can be used to trigger ventilation systems when air quality deteriorates. •
Smart Home Systems: Employed in smart home setups to provide real-time air quality data.

Key Features:

- Wide detecting scope for various harmful gases.
- Fast response and high sensitivity.
- Stable and long operational life.
- Simple drive circuit.
- Adjustable sensitivity.

MQ-136 Gas Sensor

The MQ-136 gas sensor is specifically designed for the detection of hydrogen sulfide (H_2S) gas. It offers high sensitivity to H_2S and is less sensitive to normal combustible gases, making it ideal for applications where H_2S detection is critical.

Gases Detected: Hydrogen Sulfide (H_2S), with some sensitivity to other sulfur-containing vapors.

Prominent Applications:

- **Wastewater Treatment Plants:** Essential for monitoring H_2S levels, which is a toxic gas produced during wastewater decomposition.

- **Oil and Gas Industry:** Used in oil refineries, gas processing plants, and drilling sites to detect H2S, a highly toxic and corrosive gas.
- **Biogas Plants:** Can be used to monitor H2S levels in biogas, which needs to be removed before use.
- **Environmental Monitoring:** Contributes to monitoring air quality in areas prone to H2S emissions.

Key Features:

- High sensitivity and selectivity to hydrogen sulfide.
- Fast response and stable performance.
- Long operational life.
- Simple drive circuit.
- Wide detection range (typically 1-200 ppm for H2S).

MQ-137 Gas Sensor

The MQ-137 gas sensor is primarily used for the detection of ammonia (NH3) gas. It also shows sensitivity to organic amines such as trimethylamine and ethanolamine, making it suitable for applications where ammonia or related compounds are present.

Gases Detected: Ammonia (NH3), Trimethylamine, and Ethanolamine.

Prominent Applications:

- **Agricultural and Livestock Facilities:** Essential for monitoring ammonia levels in barns, poultry farms, and other agricultural settings to ensure animal welfare and worker safety.
- **Refrigeration Systems:** Used to detect ammonia leaks in industrial refrigeration units.
- **Chemical Plants:** Employed in chemical manufacturing processes where ammonia is produced or used.
- **Wastewater Treatment:** Can be used to monitor ammonia levels in wastewater treatment processes.

Key Features:

- High sensitivity and selectivity to ammonia.
- Fast response and stable performance.
- Long operational life.
- Simple drive circuit.
- Wide detection range (typically 5-500 ppm for NH3).

MQ-138 Gas Sensor

The MQ-138 gas sensor is designed for the detection of various volatile organic compounds (VOCs), including benzene, toluene, alcohol, acetone, propane, formaldehyde, and hydrogen. Its broad detection capabilities make it suitable for general air quality monitoring and VOC detection.

Gases Detected: Benzene, Toluene, Alcohol, Acetone, Propane, Formaldehyde, and Hydrogen.

Prominent Applications:

- **Indoor Air Quality Monitoring:** Used to detect VOCs emitted from building materials, furniture, cleaning products, and other sources, contributing to healthier indoor environments.
- **Industrial VOC Monitoring:** Employed in industries such as painting, printing, and chemical manufacturing to monitor VOC emissions and ensure compliance with environmental regulations.

- **Environmental Monitoring:** Can be used to detect VOCs in ambient air, which are often precursors to ozone formation.
- **Research and Development:** Useful in laboratories for studying the presence and concentration of various organic vapors.

Key Features:

- Wide detecting scope for various VOCs.
- Fast response and high sensitivity.
- Stable and long operational life.
- Simple drive circuit.
- Adjustable sensitivity.

MQ-214 Gas Sensor

The MQ-214 gas sensor is specifically designed for the detection of methane (CH_4) and natural gas. It offers high sensitivity to these gases and is commonly used in applications where the presence of methane is a primary concern.

Gases Detected: Methane (CH_4), Natural Gas, LPG, LNG, Iso-butane, and Propane.

Prominent Applications:

- **Natural Gas Leak Detection:** Essential for detecting leaks in natural gas pipelines, residential gas lines, and industrial gas storage facilities.
- **Biogas Monitoring:** Used in biogas plants to monitor methane levels.
- **Mining Safety:** Employed in coal mines and other mining operations to detect methane.
- **Industrial Safety:** Integrated into safety systems in industries that use or produce methane.

Key Features:

- High sensitivity and good selectivity to methane and natural gas.
- Fast response and long-term stability.
- Low power consumption.
- Simple drive circuit.
- Wide detection range (typically 500-10000 ppm).

6. Working Principle

The operation of MQ gas sensors is fundamentally based on the principles of chemiresistance, where the electrical resistance of a sensing material changes in the presence of specific gases. This section elaborates on the chemical and electronic aspects of this working principle.

Chemical Principle: The Interaction of Gas with the Sensitive Substance

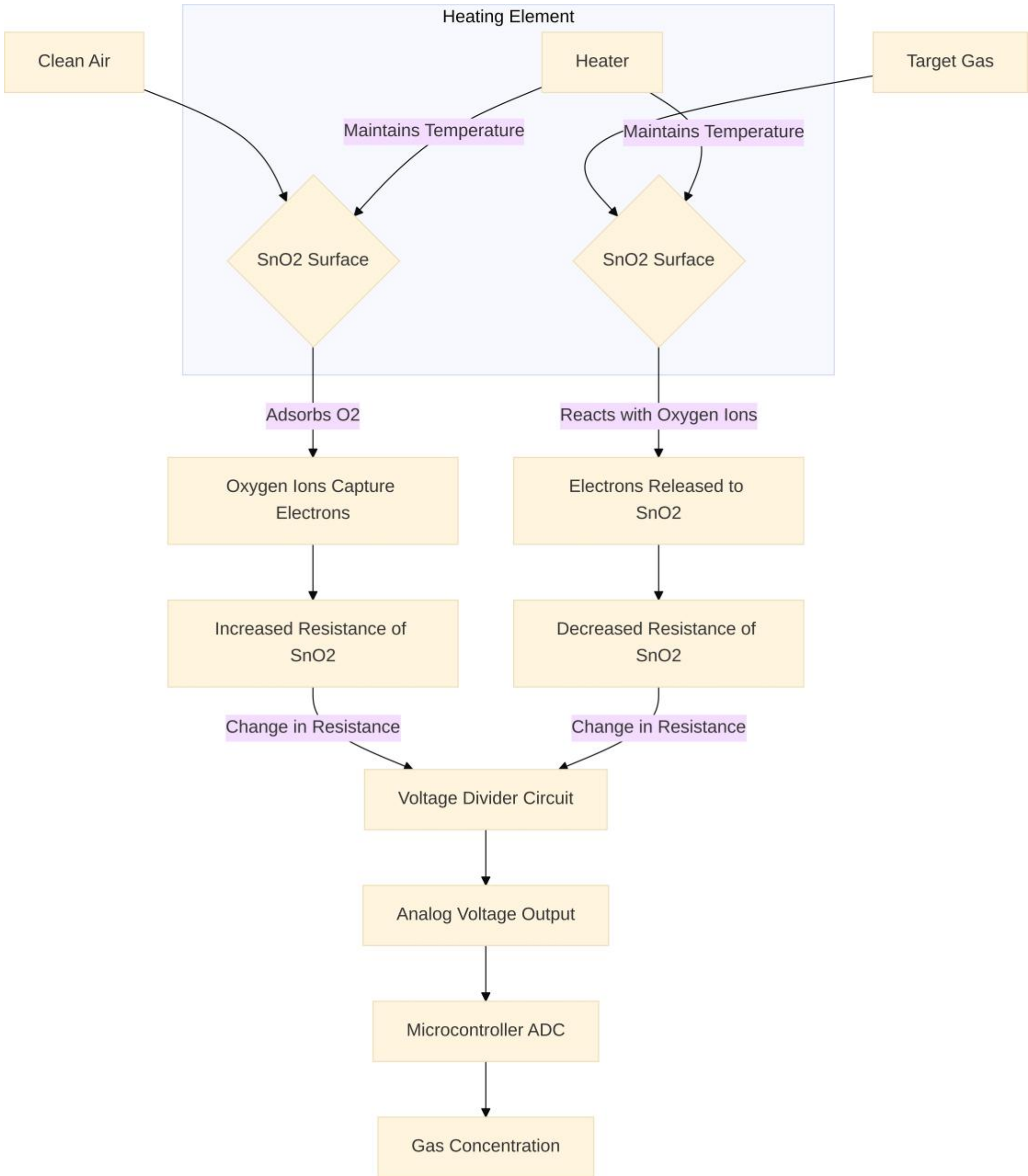
At the core of every MQ gas sensor is a sensitive material, typically a metal oxide semiconductor (MOS), with tin dioxide (SnO_2) being the most common choice. This material is deposited as a thin film on a ceramic substrate, often with a heating element embedded within or beneath it.

In clean air, oxygen molecules (O_2) from the atmosphere are adsorbed onto the surface of the SnO_2 sensing layer. These adsorbed oxygen molecules capture electrons from the SnO_2, forming oxygen ions (O^-, O_2^-, or O^{2-} depending on the temperature). This process reduces the electron concentration within the SnO_2, leading to a higher electrical resistance of the sensor.

When the sensor is exposed to a target gas (e.g., methane, alcohol, carbon monoxide), these gas molecules react with the adsorbed oxygen ions on the SnO_2 surface. This reaction releases the trapped electrons back into the SnO_2 conduction band. The increase in electron concentration within the SnO_2 causes its electrical resistance to decrease significantly. The magnitude of this resistance change is directly proportional to the concentration of the target gas in the surrounding environment.

Different MQ sensors are designed to detect specific gases by modifying the sensitive material (e.g., doping SnO_2 with catalysts like palladium or platinum) or by operating at different temperatures. These modifications enhance the selectivity and sensitivity of the sensor to particular gas molecules, ensuring that it responds most strongly to the intended gas while minimizing interference from others.

Electronic Principle: Output Signal and Circuit



The change in the electrical resistance of the SnO2 sensing element is not directly readable by microcontrollers. Therefore, the sensor is typically integrated into a simple voltage divider circuit. This circuit converts the resistance change into a measurable voltage signal.

A common configuration involves connecting the sensing element (Rs) in series with a fixed load resistor (RL). A constant voltage (Vcc, typically 5V) is applied across this series combination. The voltage across the load resistor (VRL) or the voltage across the sensor (Vout) can then be measured. As the sensor's resistance (Rs) changes in the presence of gas, the voltage distribution across Rs and RL also changes. According to Ohm's Law and the voltage divider rule, the output voltage (Vout) will vary with the gas concentration.

Simplified Technical Explanation of the Detection Process:

1. **Heating:** The internal heating element raises the temperature of the SnO2 sensing layer to its optimal operating temperature (typically 200-400° C). This high temperature is crucial for the chemical reactions and for preventing condensation.
2. **Oxygen Adsorption:** In clean air, oxygen molecules adsorb onto the heated SnO2 surface, drawing electrons from the semiconductor and increasing its resistance.
3. **Gas Exposure:** When the target gas is present, its molecules react with the adsorbed oxygen ions. This reaction releases electrons back into the SnO2, causing its resistance to drop.
4. **Voltage Output:** The change in sensor resistance (Rs) alters the voltage across the load resistor (RL) in the voltage divider circuit. This analog voltage signal (Vout) is then read by an Analog-to-Digital Converter (ADC) of a microcontroller.
5. **Concentration Calculation:** The microcontroller processes the analog voltage reading. By using a calibration curve (often derived from the sensor's datasheet or experimental data), the microcontroller can convert the voltage value into a gas concentration in parts per million (ppm) or percentage (%).

Some MQ sensor modules also provide a digital output (DO) in addition to the analog output (AO). The digital output is typically triggered when the gas concentration exceeds a preset threshold, which can often be adjusted using a potentiometer on the module. This provides a simple high/low signal for alarm systems or basic detection, while the analog output offers more precise concentration measurements.

Understanding this working principle is essential for proper calibration, integration, and interpretation of data from MQ gas sensors, ensuring their effective deployment in various gas detection applications.

7. Internal Structure

The internal structure of MQ gas sensors is designed to facilitate the chemical reactions necessary for gas detection and to provide a stable environment for the sensitive material. While the exact construction may vary slightly between different MQ sensor models, the core components remain consistent.

Sensor Components

Typically, an MQ gas sensor consists of the following main components:

1. **Sensing Element (SnO2 Layer):** This is the heart of the sensor, a thin film of tin dioxide (SnO2) deposited on a ceramic substrate. The SnO2 is the material whose electrical resistance changes in the presence of target gases. It is often doped with various catalysts (e.g., Palladium, Platinum) to enhance its sensitivity and selectivity to specific gases.

2. **Ceramic Tube/Substrate:** The SnO2 sensing layer is typically coated onto a small ceramic tube or substrate. This ceramic material provides mechanical support and electrical insulation for the sensing element.

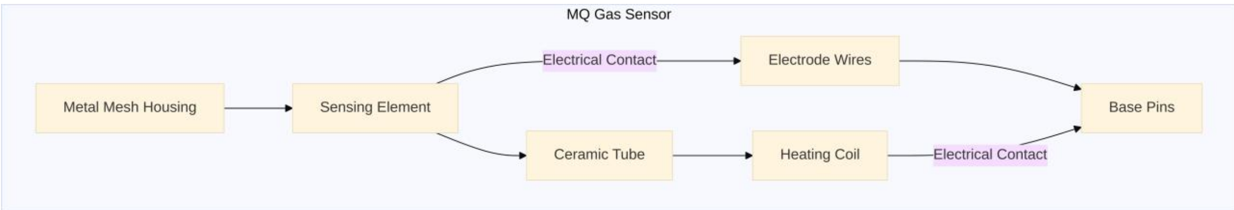
3. **Heating Coil/Element:** A crucial component, the heating coil (usually made of a resistive wire like Kanthal) is embedded within or wound around the ceramic tube. Its purpose is to heat the SnO2 sensing layer to a specific operating temperature. This elevated temperature is essential for the chemical reactions between the gas molecules and the SnO2 surface to occur efficiently and for the sensor to function correctly.

4. **Electrode Wires:** Platinum or gold wires are typically used as electrodes to make electrical contact with the SnO2 sensing layer. These wires allow the measurement of the sensor's resistance.

5. **Housing/Mesh:** The entire sensing assembly is enclosed within a double-layer stainless steel mesh or a similar protective housing. This mesh serves several purposes:
    - **Protection:** It protects the delicate sensing element from physical damage and contamination.
    - **Anti-explosion:** For flammable gas sensors, the mesh acts as a flame arrestor, preventing the ignition of surrounding gases in case of an internal spark.
    - **Gas Diffusion:** It allows gases to diffuse into the sensing element while preventing direct contact with particles or droplets.

6. **Base/Pins:** The sensor assembly is mounted on a sturdy plastic or bakelite base with several pins (typically 4 or 6). These pins provide electrical connections for the heating element and the sensing element, allowing the sensor to be easily integrated into a circuit board.

Simplified Interior Scheme



Imagine a small ceramic cylinder. Around this cylinder, a heating coil is wrapped, which heats the cylinder to a high temperature. On the surface of this heated ceramic cylinder, a thin layer of tin dioxide (SnO2) is coated. This SnO2 layer is the actual gas-sensing material. Two electrodes are connected to this SnO2 layer to measure its electrical resistance. The entire setup is then placed inside a metal mesh casing, which has small openings to allow gas to enter but keeps out dust and other particles.

How Does This Installation Support the Sensing Process?

The integrated design of the MQ sensor components is critical for its effective operation:

- **Optimal Temperature Maintenance:** The heating element ensures that the SnO2 layer is maintained at a precise, elevated temperature. This temperature is vital for the adsorption and desorption processes of oxygen and target gas molecules on the SnO2 surface, which directly influence the sensor's sensitivity and response time. Without proper heating, the sensor would not function or would provide inaccurate readings.
- **Protection and Stability:** The metal mesh housing provides robust protection against environmental factors like dust, humidity, and physical impact, which could otherwise damage the sensitive SnO2 layer or interfere with its operation. It also helps in maintaining a stable internal environment for the sensing element.
- **Efficient Gas Interaction:** The porous nature of the SnO2 film and the design of the mesh allow for efficient diffusion of gas molecules to the sensing surface. This ensures that the sensor can quickly detect changes in gas concentration in the surrounding air.
- **Electrical Connectivity:** The electrode wires and pins provide reliable electrical pathways for applying power to the heating element and for measuring the resistance changes of the SnO2 layer, enabling the sensor to

communicate its readings to external circuitry.

In essence, the internal structure of an MQ gas sensor is a carefully engineered system that optimizes the chemical interaction between gases and the sensing material, while providing the necessary electrical and environmental conditions for accurate and reliable gas detection.

8. Connection and Integration

Integrating MQ gas sensors into electronic systems is relatively straightforward, making them popular choices for various projects, from simple alarms to complex IoT applications. This section will cover the basic connection methods, circuit explanations, and the differences between analog and digital outputs, as well as their role in modern communication protocols.

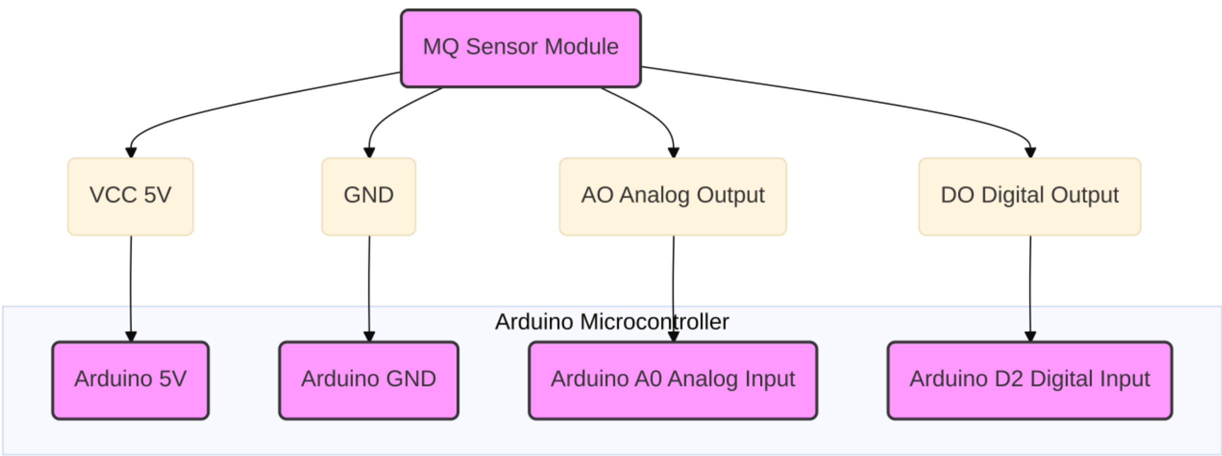
How to Connect Sensors with Controllers such as Arduino or PIC

MQ gas sensors typically come as modules that simplify their integration. These modules usually include the MQ sensor itself, a voltage comparator (like the LM393), a potentiometer for adjusting sensitivity, and header pins for power, ground, analog output, and digital output. The most common microcontrollers used for interfacing with MQ sensors are Arduino boards (e.g., Arduino Uno, ESP32) and PIC microcontrollers.

Basic Connection Steps:

1. **Power Supply (VCC and GND):** The MQ sensor module requires a stable power supply, typically 5V DC. Connect the VCC pin of the module to the 5V output of the microcontroller board (e.g., Arduino 5V pin) and the GND pin of the module to the GND pin of the microcontroller.
2. **Analog Output (AO):** The analog output pin of the MQ sensor module provides a voltage signal that is proportional to the gas concentration. This analog signal needs to be connected to an Analog-to-Digital Converter (ADC) pin on the microcontroller. For Arduino boards, these are typically labeled A0, A1, etc. The microcontroller then reads this analog voltage and converts it into a digital value for processing.
3. **Digital Output (DO):** Many MQ sensor modules also feature a digital output pin. This pin provides a binary signal (HIGH or LOW) based on whether the detected gas concentration exceeds a preset threshold. This threshold can be adjusted using the potentiometer on the module. The digital output pin is connected to a digital input pin on the microcontroller. This is useful for triggering alarms or simple on/off actions when a certain gas level is reached.

Explanation of a Simple Connection Circuit



A typical connection circuit for an MQ gas sensor with an Arduino microcontroller would look like this:

- **MQ Sensor Module:**
  - `VCC` -> Arduino `5V`
  - `GND` -> Arduino `GND`
  - `AO` (Analog Output) -> Arduino `A0` (Analog Input Pin)
  - `DO` (Digital Output) -> Arduino `D2` (Digital Input Pin, or any available digital pin)
- **Arduino Code Logic (Pseudocode):**

  ```cpp void setup() { Serial.begin(9600); // Initialize serial communication for debugging pinMode(D2, INPUT); // Set digital pin as input for DO }

  void loop() { int analogValue = analogRead(A0); // Read analog value from AO int digitalValue = digitalRead(D2); // Read digital value from DO

  // Process analog value (e.g., convert to PPM using a calibration curve) // Print values to Serial Monitor Serial.print("Analog Value: "); Serial.print(analogValue); Serial.print(" | Digital Value: "); Serial.println(digitalValue);

  if (digitalValue == HIGH) { Serial.println("Gas detected above threshold!"); // Trigger alarm, LED, etc. }

  delay(1000); // Wait for a second before next reading } ```

This simple setup allows the microcontroller to continuously monitor gas levels using the analog output for precise measurements and react to threshold breaches using the digital output.

## The Difference Between Analog and Digital Outputs

Understanding the distinction between analog and digital outputs is crucial for effective sensor integration:

- **Analog Output (AO):**
  - **Nature:** Provides a continuous range of voltage values that directly correspond to the concentration of the detected gas. The voltage changes smoothly as the gas concentration varies.
  - **Precision:** Offers higher precision and allows for quantitative measurement of gas concentration (e.g., in PPM). This requires calibration and often more complex processing in the microcontroller to convert the raw analog voltage into meaningful concentration units.
  - **Use Cases:** Ideal for applications requiring detailed monitoring, data logging, and analysis of gas levels over time, or for systems that need to react to subtle changes in concentration.
- **Digital Output (DO):**
  - **Nature:** Provides a discrete, binary signal (typically HIGH or LOW, representing 5V or 0V, or 3.3V or 0V depending on the module). This signal indicates whether the gas concentration has crossed a predefined threshold.
  - **Simplicity:** Simpler to use for basic detection and alarm systems. No complex calibration or calculation is needed to determine if a gas is present above a dangerous level.
  - **Use Cases:** Perfect for triggering alarms (buzzers, LEDs), activating ventilation systems, or sending simple alerts when a hazardous gas level is detected. The threshold is usually set via a potentiometer on the sensor module.

In many applications, both outputs are utilized: the digital output for immediate alerts and the analog output for more detailed data collection and analysis.
  ```

Communication Protocols in Intelligent Systems and the Internet of Things

For more advanced intelligent systems and IoT applications, MQ sensors often communicate with central hubs or cloud platforms using various protocols. While the sensors themselves provide raw analog or digital signals, the microcontrollers or gateway devices handle the communication protocols.

- **UART (Universal Asynchronous Receiver-Transmitter):** A common serial communication protocol used for direct communication between the microcontroller and other modules (e.g., Wi-Fi modules, Bluetooth modules).
- **SPI (Serial Peripheral Interface) and I2C (Inter-Integrated Circuit):** These are synchronous serial communication protocols often used for short-distance communication between microcontrollers and peripherals (e.g., LCD displays, other sensors). While MQ sensors typically don't directly use these, the microcontroller might use them to send processed sensor data to other components.
- **Wi-Fi (e.g., ESP32, ESP8266):** Microcontrollers with built-in Wi-Fi capabilities (like the ESP32) can connect to local networks and send sensor data to cloud platforms (e.g., AWS IoT, Google Cloud IoT, Thingspeak) using protocols like MQTT or HTTP. This enables remote monitoring and control.
- **Bluetooth (BLE):** For short-range wireless communication, Bluetooth Low Energy (BLE) can be used to send sensor data to smartphones or other BLE-enabled devices. This is common in portable gas detectors.
- **MQTT (Message Queuing Telemetry Transport):** A lightweight messaging protocol designed for constrained devices and low-bandwidth, high-latency networks. It is widely used in IoT for publishing sensor data to a central broker, which then distributes it to subscribed clients.
- **HTTP/HTTPS:** For web-based applications, sensor data can be sent to web servers using HTTP or HTTPS protocols, often in JSON or XML format.
- **LoRaWAN/NB-IoT:** For long-range, low-power IoT applications, protocols like LoRaWAN or Narrowband IoT (NB-IoT) can be used to transmit sensor data over long distances with minimal power consumption, suitable for remote environmental monitoring.

By leveraging these communication protocols, MQ gas sensors can be integrated into sophisticated intelligent systems, enabling real-time monitoring, data analytics, and automated responses to gas hazards in smart homes, smart cities, and industrial IoT environments.

9. Practical Applications

MQ gas sensors, owing to their versatility, affordability, and ease of integration, have found widespread use across numerous practical applications. Their ability to detect a variety of gases makes them invaluable in ensuring safety, monitoring environmental conditions, and enabling smart systems.

Applications in Homes, Cars, Factories, and Security Systems

1. **Homes (Domestic Safety):**
    - **Gas Leakage Alarms:** This is perhaps the most common application. MQ-2, MQ-5, and MQ-6 sensors are frequently integrated into home gas alarms to detect leaks of LPG, natural gas, and coal gas from cooking stoves, water heaters, and heating systems. They provide early warnings, often triggering audible alarms or sending alerts to homeowners via smart home systems.
    - **Carbon Monoxide Detectors:** MQ-7 sensors are crucial for detecting carbon monoxide (CO), a colorless, odorless, and highly toxic gas produced by incomplete combustion from faulty furnaces, water heaters, or car exhausts. These detectors are vital for preventing CO poisoning in residential settings.
    - **Air Quality Monitoring:** MQ-135 sensors are used to monitor general indoor air quality, detecting pollutants like ammonia, benzene, and smoke, contributing to healthier living environments.

2. **Cars (Automotive Applications):**

    - **Alcohol Detection Systems:** MQ-3 sensors are used in breathalyzers and in-car alcohol detection systems to prevent drunk driving. Some systems may even prevent the engine from starting if alcohol levels are detected above a safe limit.
    - **LPG/CNG Leak Detection:** For vehicles running on alternative fuels like LPG or CNG, MQ-5 or MQ-6 sensors can be installed to detect fuel leaks, enhancing vehicle safety.
    - **Exhaust Gas Monitoring:** While more sophisticated sensors are often used for precise emissions control, MQ sensors can provide basic monitoring of harmful gases like CO in vehicle exhaust.

3. **Factories (Industrial Safety and Process Control):**

    - **Industrial Gas Leak Detection:** In chemical plants, manufacturing facilities, and refineries, MQ sensors (e.g., MQ-2, MQ-4, MQ-6, MQ-8, MQ-136) are deployed to detect leaks of flammable gases (methane, LPG, hydrogen) and toxic gases (H_2S, CO, ammonia). This is critical for preventing explosions, protecting workers, and ensuring compliance with safety regulations.
    - **Process Monitoring:** In certain industrial processes, monitoring gas concentrations is essential for quality control or process optimization. For example, MQ-4 can monitor methane levels in biogas production.
    - **Confined Space Monitoring:** Before personnel enter confined spaces, MQ sensors can be used to check for hazardous gas levels, ensuring a safe working environment.

4. **Security Systems:**

    - **Perimeter Security:** MQ sensors can be part of broader security systems to detect unusual gas releases that might indicate a breach or a hazardous event.
    - **Fire Detection Integration:** Beyond simple smoke alarms, MQ sensors can provide additional layers of fire detection by identifying specific combustible gases released during the early stages of a fire.

Examples of Integration in Intelligent Systems and the Internet of Things (IoT)

The low cost and ease of interfacing MQ sensors with microcontrollers have made them popular components in intelligent systems and IoT deployments:

1. **Smart Home Systems:**

    - **Automated Ventilation:** An MQ-135 sensor detecting poor air quality can trigger smart vents or air purifiers to activate, improving indoor air circulation automatically.
    - **Remote Monitoring:** Sensor data (e.g., gas levels, temperature, humidity from other sensors) can be sent to a central hub or cloud platform via Wi-Fi (ESP32/ESP8266) or Zigbee. Homeowners can then monitor gas levels remotely via a smartphone app and receive instant alerts in case of a leak.
    - **Integrated Safety:** In a smart home, an MQ-2 detecting an LPG leak could not only sound an alarm but also automatically shut off the gas supply via a smart valve and notify emergency services.

2. **Environmental Monitoring:**

    - **Air Quality Stations:** Networks of MQ-135, MQ-131, and other sensors can be deployed in urban areas or industrial zones to create real-time air quality monitoring stations. Data collected can be transmitted to a central server for analysis, public display, and informing policy decisions.
    - **Pollution Mapping:** Drones or mobile platforms equipped with MQ sensors can map gas concentrations across larger areas, identifying pollution hotspots or sources of emissions.

3. **Smart Agriculture:**

- **Livestock Monitoring:** MQ-137 sensors can monitor ammonia levels in animal enclosures, ensuring healthy conditions for livestock and preventing respiratory issues.
- **Greenhouse Gas Monitoring:** In controlled agricultural environments, MQ-4 sensors can monitor methane levels, while other MQ sensors can track CO2 or other gases relevant to plant growth or decomposition processes.

4. **Industrial IoT (IIoT):**
    - **Predictive Maintenance:** By continuously monitoring gas levels around machinery or pipelines, unusual gas emissions detected by MQ sensors can indicate impending equipment failure, allowing for proactive maintenance.
    - **Worker Safety Wearables:** Portable devices equipped with MQ sensors can be worn by industrial workers to monitor their immediate environment for hazardous gases, providing personal safety alerts.
    - **Supply Chain Monitoring:** In logistics, MQ sensors can monitor gas levels in storage facilities or transportation containers for sensitive goods, ensuring product integrity and safety.

Real Use Cases

- **Smart Kitchens:** An MQ-5 sensor integrated with a smart kitchen system can detect natural gas leaks and automatically shut off the gas valve, turn on exhaust fans, and send alerts to the homeowner's phone.
- **Underground Parking Garages:** MQ-7 sensors are often installed in underground parking facilities to monitor carbon monoxide levels from vehicle exhausts. If CO levels exceed a safe threshold, the system can automatically activate ventilation fans to clear the air.
- **Landfill Gas Monitoring:** MQ-4 sensors are used to monitor methane emissions from landfills, which is a potent greenhouse gas. This data helps in managing emissions and potentially capturing methane for energy generation.
- **Poultry Farm Ventilation:** MQ-137 sensors are deployed in large poultry farms to monitor ammonia levels. High ammonia concentrations can be detrimental to bird health. The sensors trigger automated ventilation systems to maintain optimal air quality, improving animal welfare and productivity.
- **DIY Air Quality Monitors:** Many hobbyists and educational projects utilize MQ-135 sensors with Arduino or Raspberry Pi to build low-cost air quality monitors that display data on an LCD screen or send it to a web dashboard.

These examples demonstrate the broad impact and practical utility of MQ gas sensors in creating safer, smarter, and more efficient environments across various domains.

10. Comparison of Species (Comparative Analysis)

This section provides a comprehensive comparative analysis of various MQ gas sensors, focusing on their technical specifications, detection capabilities, and performance characteristics. Understanding these differences is crucial for selecting the appropriate sensor for a given application.

Technical Comparison of MQ2, MQ3, MQ4, MQ5, MQ6, MQ7, MQ8, MQ9, MQ131, MQ135, MQ136, MQ137, MQ138, MQ214

The following table summarizes the key features and performance metrics for a range of MQ gas sensors. While specific values can vary slightly between manufacturers and individual sensor units, these represent typical characteristics based on datasheets and common usage.

MQ Gas Sensor Series

MQ Gas Sensor Series : Pinout, Datasheet, Price, Packages, Working Principle, Features, Power Ratings, Electrical Characteristics, Equivalents, Uses, Applications.

Sensor Model	Target Gases	Detection Range (ppm)	Sensitivity	Response Time	Heating Time	Cost (General)	Advantages	Disadvantages
MQ-2	Methane, Butane, LPG, Smoke, H2, Alcohol, Propane	200-10000	High	Fast	~24 hours (preheat)	Low	Versatile, wide detection, fast response	Sensitive to multiple gases, requires preheating
MQ-3	Alcohol, Ethanol, Benzene, Methane, Hexane, LPG, CO	50-10000 (Alcohol)	High (Alcohol)	Fast	~24 hours (preheat)	Low	High selectivity to alcohol, good resistance to interference	Primarily for alcohol detection
MQ-4	Methane, CNG, Propane, Butane	200-10000	High (Methane, CNG)	Fast	~24 hours (preheat)	Low	High selectivity to methane/CNG, stable	Less sensitive to other gases
MQ-5	Natural Gas, LPG, Butane, Propane, Methane, H2	200-10000	High	Fast	~24 hours (preheat)	Low	Versatile for flammable gases, dual output	Sensitive to multiple flammable gases
MQ-6	LPG, Iso-butane, Propane, Natural Gas	200-10000	High (LPG, Iso-butane)	Fast	~24 hours (preheat)	Low	High selectivity to LPG/Iso-butane, stable	Less sensitive to other gases
MQ-7	Carbon Monoxide (CO), H2	20-2000	High (CO)	Fast	Cyclic (high/low temp)	Low	High selectivity to CO, stable	Requires cyclic heating, sensitive to H2
MQ-8	Hydrogen (H2), Alcohol, LPG, Cooking Fumes	100-10000	High (H2)	Fast	~24 hours (preheat)	Low	High selectivity to H2, good anti-interference	Primarily for H2 detection
MQ-9	Carbon Monoxide (CO), Methane, LPG	20-10000	High	Fast	Cyclic (high/low temp)	Low	Detects both CO and flammable gases	Requires cyclic heating
MQ - 131	Ozone (O3), Cl2, NO2	10-1000 (O3)	High (O3)	Fast	~24 hours (preheat)	Low	High selectivity to O3, also detects strong oxidizers	Primarily for O3 detection
MQ - 135	NH3, NOx, Alcohol, Benzene, Smoke, CO2	10-1000 (NH3, Alcohol, Benzene)	High	Fast	~24 hours (preheat)	Low	Wide detection for air quality, versatile	Sensitive to multiple pollutants
MQ - 136	Hydrogen Sulfide (H2S), Sulfur-containing vapors	1-200	High (H2S)	Fast	~24 hours (preheat)	Low	High selectivity to H2S, stable	Primarily for H2S detection

Sensor Model	Target Gases	Detection Range (ppm)	Sensitivity	Response Time	Heating Time	Cost (General)	Advantages	Disadvantages
MQ - 137	Ammonia (NH3), Trimethylamine, Ethanolamine	5-500	High (NH3)	Fast	~24 hours (preheat)	Low	High selectivity to NH3, stable	Primarily for NH3 detection
MQ - 138	Benzene, Toluene, Alcohol, Acetone, Propane, Formaldehyde, H2	5-500 (VOCs)	High (VOCs)	Fast	~24 hours (preheat)	Low	Wide detection for VOCs, versatile	Sensitive to multiple VOCs
MQ - 214	Methane, Natural Gas, LPG, LNG, Iso- butane, Propane, H2	500- 10000	High (Methane, Natural Gas)	Fast	~24 hours (preheat)	Low	High selectivity to methane/natural gas, stable	Primarily for methane/natural gas detection

Comparison Criteria: Sensitivity, Accuracy, Cost, Response Time, Heating Time, Range

- **Sensitivity:** Refers to the smallest change in gas concentration that the sensor can detect. Most MQ sensors offer high sensitivity to their target gases, allowing for the detection of even low concentrations. However, their sensitivity can be affected by environmental factors like temperature and humidity.
- **Accuracy:** The degree to which the sensor's reading matches the true gas concentration. While MQ sensors are generally considered accurate for their price point, they are not as precise as laboratory-grade instruments. Their accuracy can be influenced by cross-sensitivity to other gases and calibration variations.
- **Cost:** One of the most significant advantages of the MQ series is their low cost, making them accessible for hobbyists, educational projects, and cost-sensitive commercial applications. This affordability has contributed significantly to their widespread adoption.
- **Response Time:** The time it takes for the sensor to react to a change in gas concentration. Most MQ sensors boast a fast response time, typically within seconds, which is crucial for safety-critical applications where rapid detection of gas leaks is necessary.
- **Heating Time:** The time required for the sensor's heating element to reach its optimal operating temperature. For most MQ sensors, this preheating time can be substantial (around 24 hours for initial power-up), during which the sensor's readings may not be stable or accurate. Some sensors, like MQ-7 and MQ-9, use a cyclic heating method to optimize detection for different gases, which affects their operational heating time.
- **Range:** The minimum and maximum concentrations of a gas that the sensor can reliably detect. The detection range varies significantly between different MQ sensor models, tailored to the typical concentrations of their target gases in relevant applications.

A Comprehensive Table + Analysis of the Advantages and Disadvantages of Each Type

As seen in the table above, each MQ sensor type is optimized for specific gases, leading to distinct advantages and disadvantages:

- **Versatility vs. Selectivity:** Sensors like MQ-2 and MQ-135 are highly versatile, detecting a broad spectrum of gases. This is advantageous for general-purpose air quality monitoring or detecting multiple potential hazards. However, this versatility comes at the cost of selectivity; they might respond to several gases, making it challenging to identify the exact gas present without additional sensors or sophisticated algorithms. In contrast, sensors like MQ-3 (Alcohol), MQ-4 (Methane/CNG), MQ-7 (CO), MQ-8 (Hydrogen), MQ-131 (Ozone), MQ-136 (H2S), and MQ-137 (Ammonia) offer higher selectivity to their primary target gases, making them more suitable for specific gas detection tasks.

- **Heating Requirements:** Most MQ sensors require a significant preheating time to stabilize their readings. This can be a disadvantage in applications requiring immediate startup. The cyclic heating of MQ-7 and MQ-9 addresses specific detection needs but adds complexity to their operation.

- **Environmental Sensitivity:** A common limitation across the MQ series is their sensitivity to environmental factors such as temperature and humidity. These factors can influence sensor readings, necessitating environmental compensation or calibration to maintain accuracy. This is why datasheets often specify optimal operating conditions.

- **Cost-Effectiveness:** The primary advantage of the entire MQ series is their low cost, which makes them highly attractive for mass-market applications and educational purposes. This affordability allows for the deployment of gas detection systems in areas where more expensive, high-precision sensors would be prohibitive.

- **Ease of Use:** Most MQ sensor modules come with built-in circuitry (like potentiometers for sensitivity adjustment and digital outputs), simplifying their integration with microcontrollers. This plug-and-play nature makes them popular among hobbyists and rapid prototyping.

In summary, while MQ sensors offer a cost-effective and generally reliable solution for gas detection, their application requires careful consideration of their specific characteristics, including their target gases, sensitivity, and potential for cross-interference. For critical applications demanding high precision and selectivity, more advanced and often more expensive sensor technologies might be necessary. However, for a vast array of general-purpose and safety-oriented applications, the MQ series provides an excellent balance of performance and affordability.

11. Limitations and Challenges

Despite their widespread use and numerous advantages, MQ gas sensors, like all sensing technologies, come with certain limitations and challenges that need to be considered for accurate and reliable deployment.

Accuracy Problems

One of the primary challenges with MQ sensors is their inherent limitation in terms of absolute accuracy. While they are effective at detecting the presence of gases and providing relative concentration changes, achieving highly precise quantitative measurements can be difficult. This is due to several factors:

- **Cross-Sensitivity:** MQ sensors are not perfectly selective. Many sensors respond to a range of gases, not just their primary target. For example, an MQ-2 sensor designed for LPG and methane also shows sensitivity to alcohol and smoke. This cross-sensitivity can lead to false positives or inaccurate readings if multiple gases are present in the environment.
- **Non-Linear Response:** The relationship between gas concentration and sensor resistance is often non-linear, especially across a wide detection range. Accurate conversion of resistance values to PPM requires complex calibration curves, which can be challenging to implement precisely without specialized equipment.
- **Batch Variation:** There can be variations in performance between individual sensors from the same batch or different manufacturing runs. This necessitates individual calibration for each sensor if high accuracy is required.

Sensitivity to Heat and Humidity

Environmental conditions significantly impact the performance of MQ gas sensors:

- **Temperature:** The operating temperature of the SnO2 sensing element is critical for its chemical reactions. Fluctuations in ambient temperature can affect the sensor's internal temperature, leading to changes in resistance readings even if the gas concentration remains constant. Most datasheets specify an optimal operating temperature range, and deviations from this range can compromise accuracy.
- **Humidity:** Humidity levels can also interfere with sensor readings. Water vapor can adsorb onto the SnO2 surface, affecting the adsorption of target gas molecules and altering the sensor's resistance. High humidity can lead to reduced sensitivity or slower response times.

To mitigate these issues, environmental compensation techniques (e.g., using temperature and humidity sensors like DHT11/DHT22 alongside the MQ sensor) and careful calibration are often necessary, especially in environments with fluctuating conditions.

Initial Heating Time

MQ sensors require a significant initial heating time (often referred to as

preheat time or burn-in time) before they provide stable and accurate readings. This period can range from several minutes to 24 hours or even longer, depending on the specific sensor and manufacturer recommendations. During this time, the sensor's characteristics are stabilizing as the SnO2 material reaches its optimal operating temperature and its surface chemistry equilibrates. This long heating time can be a significant drawback for applications requiring immediate startup or intermittent operation.

Long-term Stability

Over extended periods of operation, the performance of MQ gas sensors can degrade. This degradation, often referred to as 'drift,' can manifest as a change in sensitivity, baseline resistance, or response characteristics. Factors contributing to long-term instability include:

- **Aging of the Sensing Material:** The SnO2 material can undergo irreversible changes over time due to continuous exposure to gases, high temperatures, or environmental contaminants.
- **Heater Degradation:** The heating element can degrade, leading to inconsistent operating temperatures and affecting sensor performance.
- **Poisoning:** Exposure to certain chemicals or high concentrations of gases can permanently damage or 'poison' the sensing element, leading to a loss of sensitivity or complete failure.

Regular recalibration or replacement of sensors is often necessary to maintain accuracy and reliability in long-term deployments.

Challenges of Use in Different Environments

Deploying MQ sensors in diverse real-world environments presents several challenges:

- **Dust and Particulates:** Dusty environments can clog the sensor's mesh, impeding gas diffusion and leading to inaccurate readings or sensor damage.
- **Vibration and Mechanical Shock:** While generally robust, excessive vibration or mechanical shock can damage the delicate internal components of the sensor.
- **Corrosive Gases:** Exposure to highly corrosive gases, even if not the target gas, can degrade the sensor's materials over time.

- **Power Consumption:** The heating element in MQ sensors consumes a continuous amount of power. While relatively low, this can be a consideration for battery-powered or energy-constrained applications.
- **Calibration Complexity:** Accurate calibration of MQ sensors for specific gas concentrations often requires access to known gas mixtures and controlled environmental conditions, which can be challenging for individual users or small-scale deployments.

Addressing these limitations often involves careful sensor selection, robust system design, environmental compensation, and periodic maintenance and recalibration. Despite these challenges, the cost-effectiveness and broad applicability of MQ sensors continue to make them a popular choice for a wide range of gas detection needs.

12. Conclusion and Future Vision

General Summary of the Most Important Results

This academic research has provided a comprehensive exploration of the MQ Gas Sensor Series, highlighting their fundamental principles, diverse types, practical applications, and inherent limitations. We have established that MQ sensors operate on the chemiresistance principle, utilizing a metal oxide semiconductor (primarily SnO2) whose electrical resistance changes upon interaction with target gas molecules. The internal heating element is crucial for maintaining optimal operating temperatures, facilitating the chemical reactions necessary for detection.

Our detailed analysis of individual MQ sensor types (MQ-2 to MQ-214) revealed their specialized detection capabilities, ranging from flammable gases (LPG, methane, hydrogen) to toxic gases (carbon monoxide, hydrogen sulfide, ammonia) and volatile organic compounds (VOCs). These sensors have found widespread practical applications in domestic safety alarms, automotive systems, industrial monitoring, and environmental air quality assessment, often integrated into intelligent systems and IoT frameworks due to their ease of use and affordability.

Review of Strengths and Weaknesses

The primary **strengths** of MQ gas sensors include:

- **Cost-Effectiveness:** Their low manufacturing cost makes them highly accessible for a broad range of applications and users.
- **Versatility:** The wide array of sensor types allows for the detection of numerous gases, catering to diverse needs.
- **Ease of Integration:** Most MQ sensor modules are designed for straightforward interfacing with microcontrollers like Arduino, simplifying development and deployment.
- **Fast Response Time:** They generally offer quick detection of gas presence, crucial for safety-critical applications.

However, MQ sensors also possess notable **weaknesses**:

- **Limited Accuracy and Selectivity:** They are prone to cross-sensitivity, meaning they can respond to multiple gases, making precise identification of a single gas challenging without advanced algorithms or additional sensors. Their absolute accuracy is also lower compared to more expensive, specialized sensors.
- **Environmental Sensitivity:** Performance is significantly affected by variations in temperature and humidity, necessitating environmental compensation for reliable readings.
- **Long Preheat Time:** Many MQ sensors require a substantial initial heating period to stabilize, which can be a drawback for applications requiring immediate operation.
- **Long-term Drift and Degradation:** Their performance can degrade over time due to aging of the sensing material or exposure to contaminants, requiring periodic recalibration or replacement.

Future Vision for the Development of Sensors

The future of gas sensor technology, including the evolution of MQ-like sensors, is likely to focus on addressing current limitations and expanding capabilities:

- **Enhanced Selectivity and Accuracy:** Future developments will aim for more sophisticated sensing materials and fabrication techniques to improve gas selectivity and measurement accuracy, potentially reducing cross-sensitivity issues.
- **Miniaturization and Low Power Consumption:** Continued advancements in MEMS (Micro-Electro-Mechanical Systems) technology will lead to smaller, more energy-efficient gas sensors, enabling their integration into even smaller, battery-powered devices and wearable technologies.
- **Integration with AI and Machine Learning:** The combination of gas sensors with advanced AI and machine learning algorithms will enable more intelligent gas detection systems capable of differentiating between gas mixtures, predicting gas events, and self-calibrating for improved long-term stability.
- **Multi-Sensor Arrays:** Instead of relying on single sensors, future systems will increasingly utilize arrays of different gas sensors, coupled with advanced data fusion techniques, to provide a more comprehensive and accurate profile of the gaseous environment.
- **Self-Calibration and Self-Healing Capabilities:** Research into materials science and smart algorithms could lead to sensors that can self-calibrate or even self-heal minor degradation, extending their operational lifespan and reducing maintenance requirements.
- **Novel Sensing Materials:** Exploration of new nanomaterials (e.g., graphene, carbon nanotubes, metal-organic frameworks) and advanced composites could yield sensors with unprecedented sensitivity, selectivity, and stability.

Research Recommendations

Based on the findings and future vision, the following research areas are recommended:

1. **Advanced Calibration Techniques:** Develop and validate more robust and user-friendly calibration methods for MQ sensors that account for environmental variations and cross-sensitivity, potentially leveraging machine learning models.
2. **Material Science Innovation:** Investigate novel metal oxide semiconductor compositions and doping strategies to enhance the selectivity and long-term stability of low-cost gas sensors.
3. **Miniaturized and Low-Power Heating Elements:** Research and develop more efficient heating mechanisms that reduce power consumption and startup time, enabling wider adoption in portable and IoT devices.
4. **Data Fusion and AI for Gas Identification:** Explore advanced data processing and machine learning algorithms to accurately identify specific gases from the responses of multi-sensor arrays, even in complex gas mixtures.
5. **Long-term Performance Characterization:** Conduct extensive long-term studies on MQ sensors in various real-world environments to better understand their degradation mechanisms and develop predictive models for sensor lifespan.
6. **Standardization of Performance Metrics:** Advocate for more standardized and comprehensive performance metrics for low-cost gas sensors to facilitate easier comparison and selection for specific applications.

By pursuing these research avenues, the utility and reliability of MQ gas sensors, and gas sensing technology as a whole, can be significantly advanced, contributing to safer environments and more intelligent systems globally.

13. References

- The Engineering Projects. (2024, April 4). *MQ Gas Sensor Series*. Retrieved from https://www.theengineeringprojects.com/2024/04/mq-gas-sensor-series.html
- MySensors. (n.d.). *TECHNICAL DATA MQ-138 GAS SENSOR*. Retrieved from https://www.mysensors.org/dl/57c3ebeb071cb0e34c90057a/design/MQ-138.pdf
- Winsen Sensor. (n.d.). *Gas Sensor for VOC Gas - (Model：MQ138)*. Retrieved from https://www.winsen-sensor.com/d/files/PDF/Semiconductor%20Gas%20Sensor/MQ138%20(Ver1.4)%20-%20Manual.pdf
- Cirkit Designer. (n.d.). *How to Use MQ 138: Pinouts, Specs, and Examples*. Retrieved from https://docs.cirkitdesigner.com/component/8ad7f557-2090-4534-b114-acc75ea8bc1d/mq-138
- Winsen Sensor. (n.d.). *MQ138 VOC Gas Sensor*. Retrieved from https://www.winsen-sensor.com/sensors/voc-sensor/mq138.html
- MySensors. (n.d.). *TECHNICAL DATA MQ-214 GAS SENSOR*. Retrieved from https://www.mysensors.org/dl/57c3ebeb071cb0e34c90057a/design/1341.pdf
- The Engineering Projects. (2024, March 27). *MQ214 Natural Gas Sensor*. Retrieved from https://www.theengineeringprojects.com/2024/03/mq214-natural-gas-sensor.html
- KitsGuru. (n.d.). *MQ-214 Methane and Combustible Gas Sensor Module*. Retrieved from https://kitsguru.com/products/mq-214-sensor-module
- REES52. (n.d.). *MQ-214 Methane Sensor / Combustible Gas Sensor - NB007*. Retrieved from https://rees52.com/products/mq-214-methane-sensor-combustible-gas-sensor-nb007
- RobotShop. (n.d.). *MQ-2 Gas Sensor*. Retrieved from https://www.robotshop.com/products/mq-2-gas-sensor
- SunFounder. (n.d.). *MQ-2 Gas Sensor Module*. Retrieved from https://www.sunfounder.com/products/mq-2-gas-sensor-module
- The Pi Hut. (n.d.). *MQ-3 Gas Sensor (Alcohol Ethanol)*. Retrieved from https://thepihut.com/products/mq-3-gas- sensor-alcohol-ethanol
- Geek Factory. (n.d.). *MQ-4 Sensor de gas metano*. Retrieved from https://www.geekfactory.mx/producto/mq-4-sensor-de-gas-metano/
- UNIT Electronics. (n.d.). *MQ-5 Detector de Gas LP*. Retrieved from https://uelectronics.com/producto/mq-5- detector-de-gas-lp/
- Geek Factory. (n.d.). *MQ-6 Sensor de gas LP*. Retrieved from https://www.geekfactory.mx/producto/mq-6-sensor-de-gas-lp/
- SparkFun Electronics. (n.d.). *Hydrogen Gas Sensor - MQ-8*. Retrieved from https://www.sparkfun.com/products/9407
- X2 Robotics. (n.d.). *MQ-9 Carbon Monoxide and Flammable Gas Sensor*. Retrieved from https://x2robotics.ca/products/mq-9-carbon-monoxide-and-flammable-gas-sensor
- DFRobot WIKI EN. (n.d.). *Analog Gas Sensor MQ131 SKU SEN0134*. Retrieved from https://wiki.dfrobot.com/Analog_Gas_Sensor_MQ131_SKU_SEN0134
- RobotShop. (n.d.). *MQ-135 Gas Sensor*. Retrieved from https://www.robotshop.com/products/mq-135-gas-sensor
- SparkFun Electronics. (n.d.). *Hydrogen Sulfide Gas Sensor - MQ-136*. Retrieved from https://www.sparkfun.com/products/12932
- Amazon.com. (n.d.). *HUABAN 1PCS MQ-137 MQ137 Ammonia NH3 Detection Gas Sensor Module*. Retrieved from https://www.amazon.com/HUABAN-MQ-137-Ammonia-Detection-Sensor/dp/B082386TW7
- Amazon.com. (n.d.). *HUABAN 1PCS MQ-138 MQ138 Formaldehyde HCHO Volatile Organic Compounds*. Retrieved from https://www.amazon.com/HUABAN-Formaldehyde-Volatile-Organic-Compounds/dp/B082386TW7
- A Yani, AYP Wardoyo, D Anggraeni. (2024). *Development of a measurement system of ethanol gas based on TGS-2600, TGS-2603, and MQ-138 sensors*. AIP Conference Proceedings.
- TI Nasution, R Asrosa. (2018). *Application of MQ-138 semiconductor sensor for breath acetone detection*. Journal of Physics: Conference Series.

- S Viciano-Tudela, S Sendra, L Parra, JM Jimenez. (2023). *Proposal of a Gas Sensor-Based Device for Detecting Adulteration in Essential Oil of Cistus ladanifer*. Sustainability.
- P Sharma, S Madan. (2021). *Comparative analysis and experimental study on MQ sensor series*. Healthcare and Knowledge Management.
- TM Ajibola, MO Ibitoye, YK Ahmed. (2022). *Non-invasive glucometer using acetone gas sensor for low income earners' diabetes monitoring*. ELEKTRIKA-Journal of Electrical Engineering.
- A Sudarmaji, A Margiwiyatno. (2023). *Characteristics of array MOS gas sensors in detection of adulteration on patchouli oil with candlenut oil*. AIP Conference Proceedings.
- Y Uwamahoro, DG Nyambo, A Sam. (2022). *Smart System for Monitoring and Controlling Oxygen Gas Level in High Purity Germanium Detector Room*. Lecture Notes in Embedded and Mobile Computing.

- C Salinas Alvarez, D Sierra-Sosa, B Garcia-Zapirain. (2019). *Detection of volatile compounds emitted by bacteria in wounds using gas sensors*. Sensors.
- MI Shukur, MKA Al-Adilee. (2021). *Portable gas leak detection system using IoT and off-the shelf sensor node*. Indonesian Journal of Electrical Engineering and Computer Science.
- R Menaka, J Sandhiya, MR Thanusri. (2025). *Smart IoT based Air Quality Monitoring and Alert System using WEMOS D1*. International Conference on Advances in Computing and Virtual Mobile Systems.
- V Piyathilake, AP Sayakkara. (2024). *A Low-Cost, Off-the-Shelf Prototyping Platform for Molecular Communications Research*. 2024 17th International Conference on Information and Automation for Sustainability (ICIAfS).
- D Matthies, O Sellhorn, M Gabrecht, J Schuljak. (2023). *NOSEwrist: Natural Olfactory Substitution and Extension wrist*. Proceedings of Mensch und Computer.
- N Barsan. (2018). *Application of SMOX-based*. Gas Sensors Based on Conducting Metal Oxides.
- KS Sobreira. (2025). *O uso e aplicação de sensores baseados em arduino para análises ambientais multiparamétricas: uma revisão bibliométrica*. Repositorio UFC.
- A Navarro Núñez. (2021). *Diseño de un sistema electrónico para un la medida de la calidad del aire en una oficina*. RIUNET.
- P Sharma, S Madan. (2021). *Comparative analysis and experimental study on MQ sensor series*. Healthcare and Knowledge Management.
- T. M. Ajibola, M. O. Ibitoye, Y. K. Ahmed. (2022). *Non-invasive glucometer using acetone gas sensor for low income earners' diabetes monitoring*. ELEKTRIKA-Journal of Electrical Engineering.
- A. Sudarmaji, A. Margiwiyatno. (2023). *Characteristics of array MOS gas sensors in detection of adulteration on patchouli oil with candlenut oil*. AIP Conference Proceedings.
- Y. Uwamahoro, D. G. Nyambo, A. Sam. (2022). *Smart System for Monitoring and Controlling Oxygen Gas Level in High Purity Germanium Detector Room*. Lecture Notes in Embedded and Mobile Computing.
- C. Salinas Alvarez, D. Sierra-Sosa, B. Garcia-Zapirain. (2019). *Detection of volatile compounds emitted by bacteria in wounds using gas sensors*. Sensors.
- S. Viciano-Tudela, S. Sendra, L. Parra, J. M. Jimenez. (2023). *Proposal of a Gas Sensor-Based Device for Detecting Adulteration in Essential Oil of Cistus ladanifer*. Sustainability.
- M. I. Shukur, M. K. A. Al-Adilee. (2021). *Portable gas leak detection system using IoT and off-the shelf sensor node*. Indonesian Journal of Electrical Engineering and Computer Science.
- R. Menaka, J. Sandhiya, M. R. Thanusri. (2025). *Smart IoT based Air Quality Monitoring and Alert System using WEMOS D1*. International Conference on Advances in Computing and Virtual Mobile Systems.
- V. Piyathilake, A. P. Sayakkara. (2024). *A Low-Cost, Off-the-Shelf Prototyping Platform for Molecular Communications Research*. 2024 17th International Conference on Information and Automation for Sustainability (ICIAfS).
- D. Matthies, O. Sellhorn, M. Gabrecht, J. Schuljak. (2023). *NOSEwrist: Natural Olfactory Substitution and Extension wrist*. Proceedings of Mensch und Computer.
- N. Barsan. (2018). *Application of SMOX-based*. Gas Sensors Based on Conducting Metal Oxides.
- K. S. Sobreira. (2025). *O uso e aplicação de sensores baseados em arduino para análises ambientais multiparamétricas: uma revisão bibliométrica*. Repositorio UFC.
- A. Navarro Núñez. (2021). *Diseño de un sistema electrónico para un la medida de la calidad del aire en una oficina*. RIUNET.

- Sciepub. (2023, July 2). *Development and Comparison of Arduino Based MQ-2 and MQ-6*. Retrieved from https://www.sciepub.com/portal/downloads?doi=10.12691/ajst-7-1-1&filename=ajst-7-1-1.pdf
- ResearchGate. (2023, July 4). *Development and Comparison of Arduino Based MQ-2 and MQ-6 LPG Leak Sensors*. Retrieved from https://www.researchgate.net/publication/372079389_Development_and_Comparison_of_Arduino_Based_MQ-2_and_MQ-6_LPG_Leak_Sensors
- E3S Conferences. (2024). *Analysis of automation through sensors through gas sensors in*. Retrieved from https://www.e3s-conferences.org/articles/e3sconf/pdf/2024/38/e3sconf_greenenergy2024_06004.pdf
- IC-Components. (2024, October 29). *MQ4 Gas Sensor Guide: Operational Principles, Pin Configuration*. Retrieved from https://www.ic-components.com/blog/mq4-gas-sensor-guide-operational-principles,pin-configuration,and-calibration.jsp
- Medium. (2022, April 23). *MQ-2, MQ-3, MQ-4, MQ-135, MQ-6, MQ-7, MQ-8, MQ-9 air sensors*. Retrieved from https://farmaker47.medium.com/mq-2-mq-3-mq-4-mq-135-mq-6-mq-7-mq-8-mq-9-air-sensors-combined- together-in-a-raspberry-b4523540f63d
- Robocraze. (n.d.). *All About MQ Series Gas Sensor*. Retrieved from https://robocraze.com/blogs/post/mq-series- gas-sensor
- Techatronic. (2024, March 15). *MQ Series Gas Sensor Information | MQ-6 | MQ-3 | MQ-2*. Retrieved from https://techatronic.com/mq-series-gas-sensor-information/
- Adafruit. (2024, June 3). *Comparison and Experimentation with Flammable Gas Sensors*. Retrieved from https://cdn-learn.adafruit.com/downloads/pdf/gas-sensor-comparison.pdf
- MySensors. (n.d.). *Gas Sensor - Create your own Connected Home Experience*. Retrieved from https://www.mysensors.org/build/gas
- Huskie Commons. (2013, January 1). *Characterization of MQ-Series Gas Sensor Behavior*. Retrieved from https://huskiecommons.lib.niu.edu/studentengagement-honorscapstones/279/
- MDPI. (n.d.). *Precision and limits of detection for selected commercially available, low-cost carbon dioxide and methane gas sensors*. Retrieved from https://www.mdpi.com/1424-8220/19/14/3157
- IEEE Xplore. (n.d.). *Predicting low-cost gas sensor readings from transients using long short-term memory neural networks*. Retrieved from https://ieeexplore.ieee.org/abstract/document/9079462/
- ResearchGate. (n.d.). *Design and calibration of a microcontroller based mq-4 gas sensor for domestic cooking gas system*. Retrieved from https://www.researchgate.net/profile/James-Ngaruiya/publication/335972347_Design_and_Calibration_of_a_Microcontroller_Based_MQ-4_Gas_Sensor_for_Domestic_Cooking_Gas_System/links/5e0c356292851c8364a9317a/Design-and-Calibration-of-a-Microcontroller-Based-MQ-4-Gas-Sensor-for-Domestic-Cooking-Gas-System.pdf
- Repositorio UFC. (2025). *O uso e aplicação de sensores baseados em arduino para análises ambientais multiparamétricas: uma revisão bibliométrica*. Retrieved from https://repositorio.ufc.br/handle/riufc/82215
- RIUNET. (2021). *Diseño de un sistema electrónico para un la medida de la calidad del aire en una oficina*. Retrieved from https://riunet.upv.es/bitstreams/c6125d19-1df0-4db8-9b28-b6d8fdc8d5c5/download
- IOPscience. (2018). *Application of MQ-138 semiconductor sensor for breath acetone detection*. Retrieved from https://iopscience.iop.org/article/10.1088/1742-6596/1116/3/032023/meta
- MDPI. (2023). *Proposal of a Gas Sensor-Based Device for Detecting Adulteration in Essential Oil of Cistus ladanifer*. Retrieved from https://www.mdpi.com/2071-1050/15/4/3357
- MDPI. (2019). *Detection of volatile compounds emitted by bacteria in wounds using gas sensors*. Retrieved from https://www.mdpi.com/1424-8220/19/7/1523
- Springer. (2022). *Smart System for Monitoring and Controlling Oxygen Gas Level in High Purity Germanium Detector Room*. Retrieved from https://link.springer.com/chapter/10.1007/978-3-031-56603-5_23
- AIP Publishing. (2023). *Characteristics of array MOS gas sensors in detection of adulteration on patchouli oil with candlenut oil*. Retrieved from https://pubs.aip.org/aip/acp/article-abstract/2586/1/070016/2870253

- AIP Publishing. (2024). *Development of a measurement system of ethanol gas based on TGS-2600, TGS-2603, and MQ-138 sensors*. Retrieved from https://pubs.aip.org/aip/acp/article-abstract/3132/1/030011/3296635
- Taylor & Francis Online. (2021). *Comparative analysis and experimental study on MQ sensor series*. Retrieved from https://api.taylorfrancis.com/content/chapters/edit/download?identifierName=doi&identifierValue=10.1201/9781003168638-12&type=chapterpdf
- ELEKTRIKA-Journal of Electrical Engineering. (2022). *Non-invasive glucometer using acetone gas sensor for low income earners' diabetes monitoring*. Retrieved from https://elektrika.utm.my/index.php/ELEKTRIKA_Journal/article/view/285
- IEEE Xplore. (2025). *Smart IoT based Air Quality Monitoring and Alert System using WEMOS D1*. Retrieved from https://ieeexplore.ieee.org/abstract/document/11086040/
- IEEE Xplore. (2024). *A Low-Cost, Off-the-Shelf Prototyping Platform for Molecular Communications Research*. Retrieved from https://ieeexplore.ieee.org/abstract/document/10815760/
- ACM Digital Library. (2023). *NOSEwrist: Natural Olfactory Substitution and Extension wrist*. Retrieved from https://dl.acm.org/doi/abs/10.1145/3603555.3608528
- Google Books. (2018). *Application of SMOX-based*. Retrieved from https://books.google.com/books?hl=en&lr=&id=v6RBDwAAQBAJ&oi=fnd&pg=PA217&dq=MQ-214+gas+sensor+detected+gases&ots=JSCuMRzila&sig=LkWq1KEojWNOBnTesYuYwFEiQZs
- UNAD Repository. (n.d.). *Rediseño de una cámara de medida y de concentración de compuestos volátiles de un sistema de lfato electrónico para el control de calidad del cacao*. Retrieved from https://repository.unad.edu.co/handle/10596/41986
- Mouser. (n.d.). *benzene, toluene, acetone, formaldehyde sensor mq138 breakout*. Retrieved from https://www.mouser.lt/datasheet/2/1398/Soldered_333128-3395219.pdf?srsltid=AfmBOop6Ei-PUsNpIgaW3Zs7U9WIanp_NfqZ93piOoS0paedO7y5bHO
- Soldered Electronics. (n.d.). *VOC sensor MQ138 breakout*. Retrieved from https://soldered.com/product/voc-sensor-mq138-breakout/?srsltid=AfmBOoqi_KTjmr_zFUW96b2Avl96fATSw1V23PJKcpYRAIbZHZraOY7r
- Amazon.com. (n.d.). *HUABAN 1PCS MQ-138 MQ138 Formaldehyde HCHO Volatile Organic Compounds*. Retrieved from https://www.amazon.com/HUABAN-Formaldehyde-Volatile-Organic-Compounds/dp/B082386TW7
- L-Com. (n.d.). *VOC Sensor Module, 5-500 ppm, Analog and TTL level Output*. Retrieved from https://www.l- com.com/voc-sensor-modulemq138-sraq-g020?srsltid=AfmBOorenvlEkafp8GWeaMDzqsbloLOJgT7kHaffw7PtlSukzL-PklTr
- Robot Pi Shop. (n.d.). *MQ138 Formaldehyde Gas Sensor Module*. Retrieved from https://robotpishop.com/products/mq138-formaldehyde-gas-sensor-module?srsltid=AfmBOoor_dDtWcmzdd9DDEKBs1b2kU8TLUG9B5VyOBp7Zafp3MLMDgkF
- Cirkit Designer. (n.d.). *How to Use MQ-138 SENSOR FORMALDEHYDE GAS V2*. Retrieved from https://docs.cirkitdesigner.com/component/a796c81-f317-439e-85c6-1b8a08ebd86d/mq-138-sensor-formaldehyde-gas-v2
- eBay. (n.d.). *MQ-136/131/137/138/139 Combustible Gas Detector Carbon*. Retrieved from https://www.ebay.com/itm/296809066745
- JDH Labs Tech. (n.d.). *MQ138 Organic Steam Sensor Module Solvents Smog detection*. Retrieved from https://jdhlabstech.com/jdhshop/en/sensors-and-transducers/gas-sensors/mq138-organic-steam-sensor-module.html
- Alldatasheet. (n.d.). *MQ-214 Datasheet, PDF*. Retrieved from https://www.alldatasheet.com/view.jsp?Searchword=MQ-214
- RoboticsBD. (n.d.). *MQ-214 Methane Sensor Combustible Gas Sensor*. Retrieved from https://store.roboticsbd.com/sensors/3116-mq-214-methane-sensor-combustible-gas-sensor-robotics-bangladesh.html?srsltid=AfmBOorzOl69OxrXEnGu_kKhJmJ5i3885tvdbgYYHLNyp01Rx6SpuQKJ

- Besomi. (n.d.). *MQ-214 ,Gas Sensor Methane and Natural Gas Detection*. Retrieved from https://besomi.com/ae_en/stsx0116-mq-214-gas-sensor-modulemethane-and-natural-gas-detection.html?srsltid=AfmBOorzOI69OxrXEnGu_kKhJmJ5i3885tvdbgYYHLNyp01Rx6SpuQKJ
- Campus Component. (n.d.). *MQ214-SE-727-D*. Retrieved from https://www.campuscomponent.com/products/e3a94cbc7e/2208614000001860570?srsltid=AfmBOopjfeIqKTwA1SkpDheby7kwTKPvTZcbrbo43MUX-kqeVdzSLd7q
- Flyrobo. (n.d.). *MQ Gas and Dust sensors Introduction*. Retrieved from https://www.flyrobo.in/blog/mq-sensor-series?srsltid=AfmBOoq_6xtwUPXuiCzb-hDjPDyDkp-q1-63ehRfXHOJKNereur-0710
- RoboticsBD. (n.d.). *MQ214 Gas Sensor Methane Detector*. Retrieved from https://store.roboticsbd.com/gas/3648- mq214-gas-sensor-methane-detector-robotics-bangladesh.html?srsltid=AfmBOor5uO96pyFvxDdFuJlYegsqF4n1DJ4Y38MyYKgxLG4Lue20GQc2
- Baby Electronics DXB. (n.d.). *MQ-214 GAS SENSOR MODULE (Methane and Natural Gas Sensor)*. Retrieved from https://babyelectronicsdxb.com/product/mq-214-gas-sensor-module-methane-and-natural-gas-sensor/
- Amazon.com. (n.d.). *1 Pack MQ-2 MQ-3 MQ-4 MQ-5 MQ-6 MQ-7 MQ-8 MQ-9 MQ-135*. Retrieved from https://www.amazon.com/Pack-MQ-135-Sensor-Module-Starter/dp/B07838YTZW
- eBay. (n.d.). *MQ2/MQ4/MQ5/MQ7/MQ9/MQ6/MQ8/MQ135 Gas Propane Methane*. Retrieved from https://www.ebay.com/itm/144130326983
- Quartz Components. (n.d.). *MQ-9 Gas Sensor Module for CO, Methane and LPG*. Retrieved from https://quartzcomponents.com/products/mq-9-gas-sensor-module-for-co-methane-and-lpg
- DFRobot WIKI EN. (n.d.). *Analog Gas Sensor MQ9 SKU SEN0134*. Retrieved from https://wiki.dfrobot.com/Analog_Gas_Sensor_MQ9_SKU_SEN0134
- Amazon.ca. (n.d.). *2PCS MQ-3 MQ3 Sensor Module*. Retrieved from https://www.amazon.ca/2PCS-MQ-3-MQ3- Sensor-Module/dp/B07838YTZW
- STEMpedia Education. (n.d.). *MQ3 Gas Sensor Tutorial: Measuring Gas Concentration with*. Retrieved from https://ai.thestempedia.com/tutorials/mq3-gas-sensor-tutorial-measuring-gas-concentration-with-arduino/
- Amazon.com. (n.d.). *HUABAN 1PCS MQ-136 MQ136 Hydrogen Sulfide H2S Detection Gas*. Retrieved from https://www.amazon.com/HUABAN-MQ-136-Hydrogen-Sulfide-Detection/dp/B082386TW7
- Amazon.com. (n.d.). *MQ-137 NH3 NOx Ammonia Gas Sensor Detector Module Range 5-500ppm For Arduino*. Retrieved from https://www.amazon.com/MQ-137-Ammonia-Sensor-Detector-Module/dp/B07838YTZW
- Amazon.com. (n.d.). *1 pcs lot Formaldehyde Gas Detection Sensor*. Retrieved from https://www.amazon.com/Formaldehyde-Detection-Sensor-Module-MQ138/dp/B07838YTZW
- Soldered Electronics. (n.d.). *VOC sensor MQ138 breakout*. Retrieved from https://soldered.com/product/voc-sensor-mq138-breakout/?srsltid=AfmBOooGkxk6cbHmaGkojXgL-6sVBCxLxS-75gHYjFRuMyQdQyqjMTLB
- Amazon.com. (n.d.). *9PCS/Lot Gas Detection Sensor Module MQ-2 MQ-3*. Retrieved from https://www.amazon.com/9PCS-Detection-Sensor-Module-Starter/dp/B07838YTZW
- ProtoSupplies. (n.d.). *Methane Gas Sensor MQ-4 Module*. Retrieved from https://protosupplies.com/product/methane-gas-sensor-mq-4-module/
- REES52. (n.d.). *MQ-214 Methane Sensor / Combustible Gas Sensor - NB007*. Retrieved from https://rees52.com/products/mq-214-methane-sensor-combustible-gas-sensor-nb007?srsltid=AfmBOoqmA93wiTS9c6VCsgg_shXbejSym7yFCGlvOXmYqNeIPeTiJBPI
- REES52. (n.d.). *MQ-214 Methane Sensor / Combustible Gas Sensor - NB007*. Retrieved from https://rees52.com/products/mq-214-methane-sensor-combustible-gas-sensor-nb007?srsltid=AfmBOoqn6f0kxDMBOgSHUopdlfT5h6zAGjcF_u3dDvZ_TE5UMv2qbk2A
- Babyelectronicsdxb. (n.d.). *MQ-214 GAS SENSOR MODULE (Methane and Natural Gas Sensor)*. Retrieved from https://babyelectronicsdxb.com/product/mq-214-gas-sensor-module-methane-and-natural-gas-sensor/

- Soldered Electronics. (n.d.). *VOC sensor MQ138 breakout*. Retrieved from https://soldered.com/product/voc-sensor-mq138-breakout/?srsltid=AfmBOoqi_KTjmr_zFUW96b2Avl96fATSw1V23PJKcpYRAIbZHZraOY7r
- Jdhlabstech. (n.d.). *MQ138 Organic Steam Sensor Module Solvents Smog detection*. Retrieved from https://jdhlabstech.com/jdhshop/en/sensors-and-transducers/gas-sensors/mq138-organic-steam-sensor-module.html
- Robotpishop. (n.d.). *MQ138 Formaldehyde Gas Sensor Module*. Retrieved from https://robotpishop.com/products/mq138-formaldehyde-gas-sensor-module?srsltid=AfmBOoor_dDtWcmzdd9DDEKBs1b2kU8TLUG9B5VyOBp7Zafp3MLMDgkF
- L-com. (n.d.). *VOC Sensor Module, 5-500 ppm, Analog and TTL level Output*. Retrieved from https://www.l- com.com/voc-sensor-modulemq138-sraq-g020?srsltid=AfmBOorenvlEkafp8GWeaMDzqsbloLOJgT7kHaffw7PtlSukzL-PklTr
- Cirkitdesigner. (n.d.). *How to Use MQ 138: Pinouts, Specs, and Examples*. Retrieved from https://docs.cirkitdesigner.com/component/8ad7f557-2090-4534-b114-acc75ea8bc1d/mq-138
- Winsen-sensor. (n.d.). *MQ138 VOC Gas Sensor*. Retrieved from https://www.winsen-sensor.com/sensors/voc-sensor/mq138.html
- Winsen-sensor. (n.d.). *Manual*. Retrieved from https://www.winsen-sensor.com/d/files/manual/mq138.pdf
- Winsen-sensor. (n.d.). *Gas Sensor for VOC Gas - (Model：MQ138)*. Retrieved from https://www.winsen-sensor.com/d/files/PDF/Semiconductor%20Gas%20Sensor/MQ138%20(Ver1.4)%20-%20Manual.pdf
- MySensors. (n.d.). *TECHNICAL DATA MQ-138 GAS SENSOR*. Retrieved from https://www.mysensors.org/dl/57c3ebeb071cb0e34c90057a/design/MQ-138.pdf
- MySensors. (n.d.). *TECHNICAL DATA MQ-214 GAS SENSOR*. Retrieved from https://www.mysensors.org/dl/57c3ebeb071cb0e34c90057a/design/1341.pdf
- Theengineeringprojects. (2024, March 27). *MQ214 Natural Gas Sensor*. Retrieved from https://www.theengineeringprojects.com/2024/03/mq214-natural-gas-sensor.html
- Kitsguru. (n.d.). *MQ-214 Methane and Combustible Gas Sensor Module*. Retrieved from https://kitsguru.com/products/mq-214-sensor-module
- Alldatasheet. (n.d.). *MQ-214 Datasheet, PDF*. Retrieved from https://www.alldatasheet.com/view.jsp?Searchword=MQ-214
- Rees52. (n.d.). *MQ-214 Methane Sensor / Combustible Gas Sensor - NB007*. Retrieved from https://rees52.com/products/mq-214-methane-sensor-combustible-gas-sensor-nb007
- Roboticsbd. (n.d.). *MQ-214 Methane Sensor Combustible Gas Sensor*. Retrieved from https://store.roboticsbd.com/sensors/3116-mq-214-methane-sensor-combustible-gas-sensor-robotics-bangladesh.html
- Besomi. (n.d.). *MQ-214 ,Gas Sensor Methane and Natural Gas Detection*. Retrieved from https://besomi.com/ae_en/stsx0116-mq-214-gas-sensor-modulemethane-and-natural-gas-detection.html
- Campuscomponent. (n.d.). *MQ214-SE-727-D*. Retrieved from https://www.campuscomponent.com/products/e3a94cbc7e/2208614000001860570
- Flyrobo. (n.d.). *MQ Gas and Dust sensors Introduction*. Retrieved from https://www.flyrobo.in/blog/mq-sensor-series
- Roboticsbd. (n.d.). *MQ214 Gas Sensor Methane Detector*. Retrieved from https://store.roboticsbd.com/gas/3648-mq214-gas-sensor-methane-detector-robotics-bangladesh.html
- Babyelectronicsdxb. (n.d.). *MQ-214 GAS SENSOR MODULE (Methane and Natural Gas Sensor)*. Retrieved from https://babyelectronicsdxb.com/product/mq-214-gas-sensor-module-methane-and-natural-gas-sensor/
- Theengineeringprojects. (2024, April 4). *MQ Gas Sensor Series*. Retrieved from https://www.theengineeringprojects.com/2024/04/mq-gas-sensor-series.html

- Sciepub. (2023, July 2). *Development and Comparison of Arduino Based MQ-2 and MQ-6*. Retrieved from https://www.sciepub.com/portal/downloads?doi=10.12691/ajst-7-1-1&filename=ajst-7-1-1.pdf
- Researchgate. (2023, July 4). *Development and Comparison of Arduino Based MQ-2 and MQ-6 LPG Leak Sensors*. Retrieved from https://www.researchgate.net/publication/372079389_Development_and_Comparison_of_Arduino_Based_MQ-2_and_MQ-6_LPG_Leak_Sensors
- E3s-conferences. (2024). *Analysis of automation through sensors through gas sensors in*. Retrieved from https://www.e3s-conferences.org/articles/e3sconf/pdf/2024/38/e3sconf_greenenergy2024_06004.pdf
- Ic-components. (2024, October 29). *MQ4 Gas Sensor Guide: Operational Principles, Pin Configuration*. Retrieved from https://www.ic-components.com/blog/mq4-gas-sensor-guide-operational-principles,pin-configuration,and-calibration.jsp
- Medium. (2022, April 23). *MQ-2, MQ-3, MQ-4, MQ-135, MQ-6, MQ-7, MQ-8, MQ-9 air sensors*. Retrieved from https://farmaker47.medium.com/mq-2-mq-3-mq-4-mq-135-mq-6-mq-7-mq-8-mq-9-air-sensors-combined- together-in-a-raspberry-b4523540f63d
- Robocraze. (n.d.). *All About MQ Series Gas Sensor*. Retrieved from https://robocraze.com/blogs/post/mq-series- gas-sensor
- Techatronic. (2024, March 15). *MQ Series Gas Sensor Information / MQ-6 / MQ-3 / MQ-2*. Retrieved from https://techatronic.com/mq-series-gas-sensor-information/
- Adafruit. (2024, June 3). *Comparison and Experimentation with Flammable Gas Sensors*. Retrieved from https://cdn-learn.adafruit.com/downloads/pdf/gas-sensor-comparison.pdf
- MySensors. (n.d.). *Gas Sensor - Create your own Connected Home Experience*. Retrieved from https://www.mysensors.org/build/gas
- Huskiecommons. (2013, January 1). *Characterization of MQ-Series Gas Sensor Behavior*. Retrieved from https://huskiecommons.lib.niu.edu/studentengagement-honorscapstones/279/
- Mdpi. (n.d.). *Precision and limits of detection for selected commercially available, low-cost carbon dioxide and methane gas sensors*. Retrieved from https://www.mdpi.com/1424-8220/19/14/3157
- Ieee. (n.d.). *Predicting low-cost gas sensor readings from transients using long short-term memory neural networks*. Retrieved from https://ieeexplore.ieee.org/abstract/document/9079462/
- Researchgate. (n.d.). *Design and calibration of a microcontroller based mq-4 gas sensor for domestic cooking gas system*. Retrieved from https://www.researchgate.net/profile/James-Ngaruiya/publication/335972347_Design_and_Calibration_of_a_Microcontroller_Based_MQ-4_Gas_Sensor_for_Domestic_Cooking_Gas_System/links/5e0c356292851c8364a9317a/Design-and-Calibration-of-a-Microcontroller-Based-MQ-4-Gas-Sensor-for-Domestic-Cooking-Gas-System.pdf
- Repositorio.ufc. (2025). *O uso e aplicação de sensores baseados em arduino para análises ambientais multiparamétricas: uma revisão bibliométrica*. Retrieved from https://repositorio.ufc.br/handle/riufc/82215
- Riunet.upv. (2021). *Diseño de un sistema electrónico para un la medida de la calidad del aire en una oficina*. Retrieved from https://riunet.upv.es/bitstreams/c6125d19-1df0-4db8-9b28-b6d8fdc8d5c5/download.