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Toward an Advanced Gas Composition Measurement Device for Chemical Reaction Analysis

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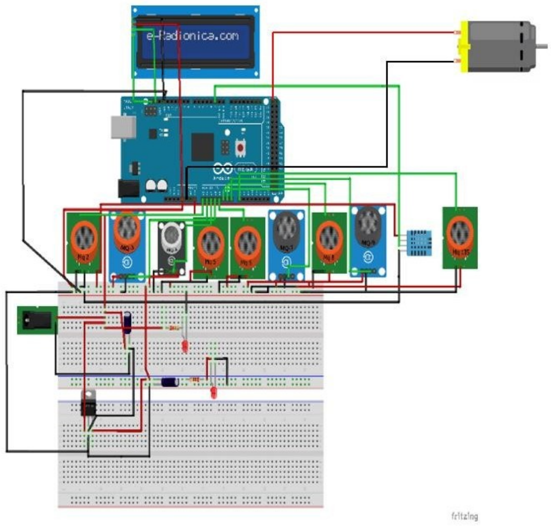
ABSTRACT



The research details the development of a reactor-based monitoring system designed to identify and monitor gases generated within industrial chemical reactors. Consisting of nine MQ and DHT11 sensors, this reactor design allows for simultaneous measurement of temperature and humidity within the sample. Using a sensor array methodology, this research utilizes multiple sensors to collect and process analog signals to improve the accuracy of gas identification within samples. These analog signals obtained from the sensors are processed by an Arduino Mega 2560 microcontroller using the Arduino IDE software. The research, conducted on ten different samples, shows methane (CH_4), hydrogen (H_2), and alcohol (C_2H_6O) as the most concentrated gases. Notably, certain samples such as batik waste, honey, Robusta coffee, and sambal have a significant impact on methane gas concentrations. In addition, substances such as Robusta Coffee, Sprite, Syrup, and Oyster Sauce have a significant effect on hydrogen gas concentrations, while Robusta Coffee, Sambal, Arabica Coffee, and Pepper have a significant effect on alcohol gas concentrations. In addition, of the nine MQ sensors used, the MQ3, MQ4, and MQ8 are particularly effective at detecting alcohol, methane, and hydrogen gases, respectively, in the samples tested.

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1. INTRODUCTION

Gases, such as air and light, are a critical but often overlooked aspect of our environment [1]. Familiar gases like oxygen, hydrogen, carbon dioxide, and carbon monoxide permeate our daily experiences, arising from both natural processes and industrial activities [2],[3]. In the industrial sphere, tanks and chemical reactors are pivotal vessels for converting raw materials into valuable chemicals. However, these reactors also generate various gases as by products, some of which pose inherent risks to the well-being of workers and supervisors [4]. If left unmonitored, hazardous gases such as carbon monoxide, carbon dioxide, and acidic compounds can impose serious health threats within these environments.

In this research, an MQ-type gas sensor is used. The MQ sensor functions to detect gas based on the data sheet on the MQ sensor. When researching the type of gas, 1 sensor is not enough to find the accuracy of the sensor measurements, so more than one sensor is needed so that the resulting output is better than using only 1 sensor gas [5]. Because of some of the problems described, research related to MQ sensors with multiple sensor methods or sensor arrays is very interesting to do and research. In previous research related to MQ sensors. The tool made can detect gas concentrations such as carbon monoxide (CO), carbon dioxide (CO2), methane (CH4), ammonium (NH4), acetone, toulene and ethanol. The results obtained are very good, but in the study relies only on a gas sensor without any calculation of sensor calibration [6].

The design in this study is to make a tool that can see or measure (monitor) gas in a chemical reactor, both toxic and non-toxic gases. This tool has 9 gas sensors, namely MQ 2 [7], 3 [8], 4 [9], 5 [10], 6 [11], 7 [12], 8 [13], 9 and 135 [10] sensors whose role is to detect gas levels in the air and DHT11, namely temperature and humidity sensors [14] to detect the temperature and humidity of the surrounding environment using Arduino Mega 2560 as the microcontroller. The samples that will be used in this study amounted to 10 samples, namely arabica coffee, sambal, pepper, kapal api coffee, honey, robusta coffee, oyster sauce, sprite, syrup and batik waste. Ten samples are used because the test is general and can be used for various conditions of the substance being measured. The method used in this research is a sensor array where many sensors are used to increase the accuracy of the sensor readings.

The primary objective of this research is to develop a prototype for advanced gas detection in chemical reactors. This will involve creating a sophisticated monitoring system capable of distinguishing between different gases, ensuring timely identification and mitigation of potential hazards in industrial environments. The significance of this research lies in its profound impact on workplace safety and industrial efficiency. By developing an advanced gas detection prototype, this study seeks to revolutionize safety measures within industrial environments, promoting a safer working environment while optimizing operational processes.

2. METHODS

There is a design of a gas measurement system in a chemical reaction using an Arduino Atmega 2560 microcontroller as an intermediary in processing analog/acoustic data from the gas that appears in the sample. The chemical reactor used in this study adopts a sensor array-based structure consisting of 9 different MQ gas sensors. A bucket was chosen as the container to hold the sample to be analyzed [15] The MQ sensors were mounted on a perforated bucket lid with a total of 10 sample, one of which was reserved for the temperature sensor (DHT11). The strategic positioning of these sensors allows effective observation of the sample. The structure is enclosed by a black box containing a PCB with the Arduino Atmega 2560 microcontroller and the sensors used.

2.1. Block Diagram System

The System Block Diagram serves as a comprehensive visual representation of the fundamental components and their interrelationships within the mold design. This diagram encapsulates essential elements that are critical to the design of the mold. The primary objective of creating a block diagram is to facilitate the understanding of the tool's components and operational processes. It acts as a basic design blueprint for the prototype under development.

By structuring the components, inputs, system outputs, and sequential processes in a coherent manner, the block diagram enhances comprehension and clarity. It uses directional arrows to indicate the flow of inputs, patterns, and outputs within the tool. Typically, inputs are positioned at the beginning, progress through the system components, and culminate in the final output stages.

Specifically, the block diagram created illustrates the I2C communication line from the Arduino Mega 2560 to the LCD display unit. Additionally, it outlines the communication line for the MQ sensor using the analog pin interface. This visual representation clarifies the interrelationship and data flow between the various components, providing a central reference for the development and functionality of the tool. Figure 1 shows the block diagram in this research.

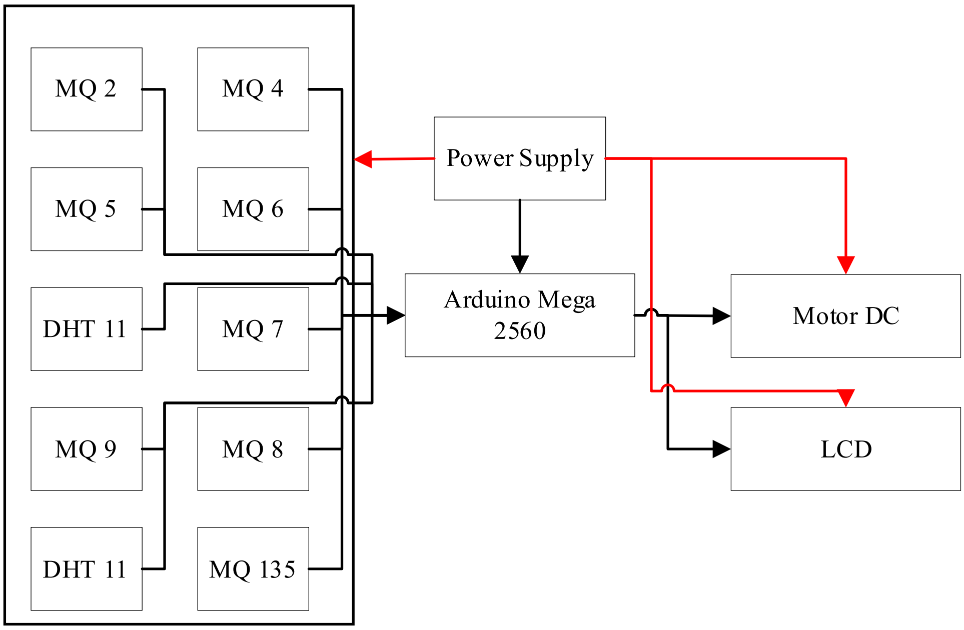


Figure 1. Block diagram system

Based on Figure 1, this chemical reactor uses 9 MQ type gas sensors that are able to read gas from an object that is brought close to the sensor. As can be seen in the block diagram above, the gas from the solution/sample will rise due to the stirring of the DC motor in the reactor which is able to rotate the solution so that the gas from the sample can rise and stabilize to be detected by the sensor. Do not forget also the presence of temperature and humidity sensors, namely DHT11, which functions to monitor temperature and humidity when the solution is not stirred and when it is stirred. The gases detected by the MQ sensor according to the detection specifications of some of these sensors, as well as the temperature and humidity read by the DHT11 sensor, are sent as sensor reading data to the Arduino Mega 2560 for processing and later output as results in the form of values on the serial monitor and LCD 4x20.

2.2. Flowchart System

This research project focuses on devising a robust gas measurement system for chemical reactions, employing nine MQ sensors and a DHT11 sensor. The primary goal is to create a sophisticated mechanism capable of precisely detecting and monitoring gas levels within a reactor. Through the integration of these sensors with an Arduino Mega 2560 microcontroller, this system aims to offer an advanced solution for accurate gas measurement in chemical processes. Figure 2 illustrates the Block Diagram System showcasing the components and their interconnections within the system.

Based on Figure 2 shows the flow chart of the portable gas reactor system. The system begins by placing the substance to be measured for gas content into the substance container, then initializing the nine MQ and DHT11 sensors. The reactor is then sealed. If the substance to be measured requires stirring, a DC motor is activated to drive the stirrer. The stirring time is adapted to the type of substance being measured. If no stirring is required, the DC motor is deactivated. Next, the gas content, temperature and humidity are measured by sensors connected to the microcontroller. The duration of the readings is adapted to the effective reaction for each measured substance. The results of the data read by the microcontroller are converted into digital format and displayed on the 20x4 LCD located on the outside of the controller box every 4 seconds.

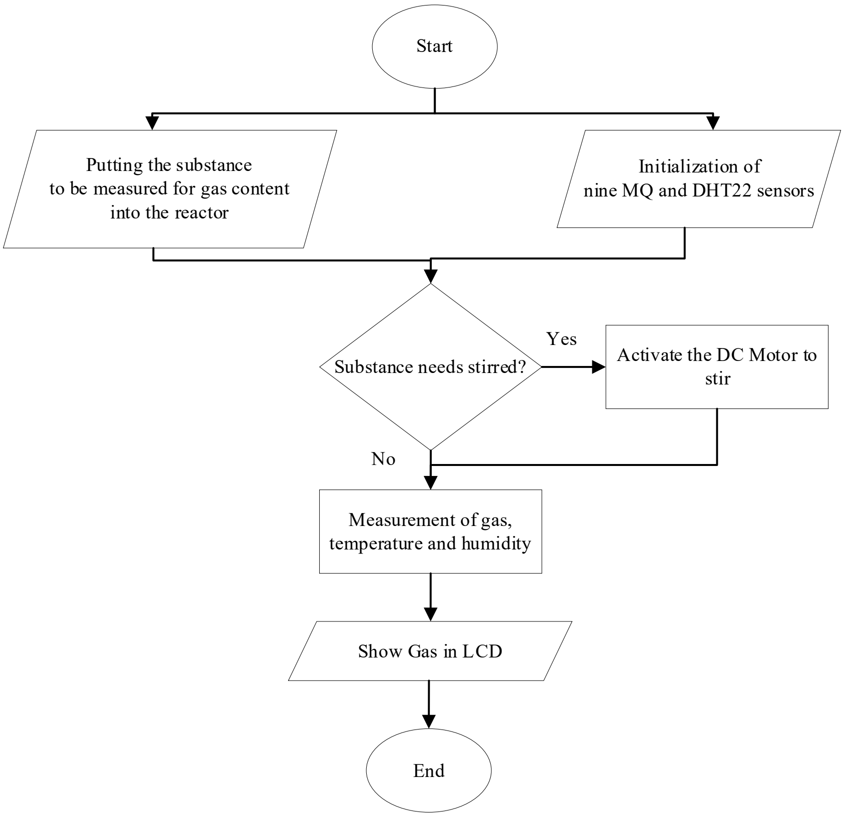
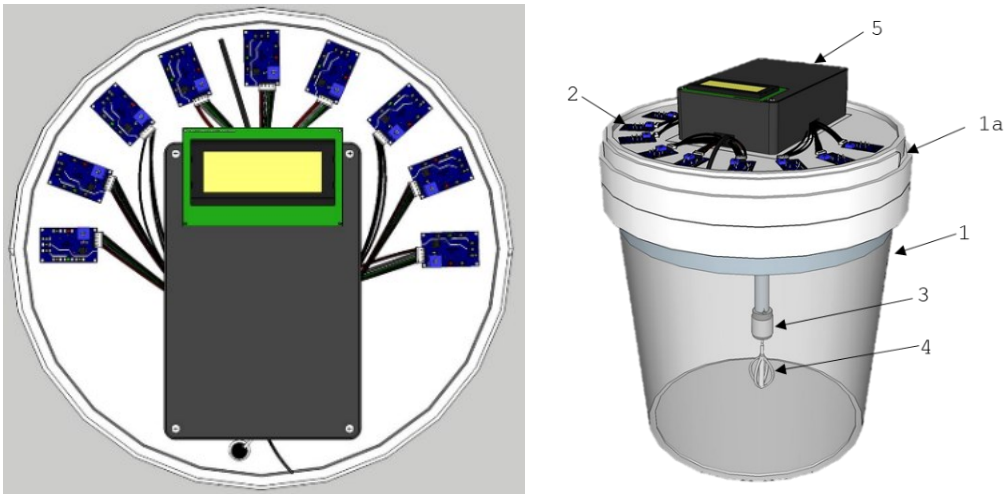


Figure 2. Block diagram system

2.3. Design System

The gas-type measurement device devised for chemical reactions in this study integrates an Arduino Mega 2560 microcontroller alongside a sensor array featuring 9 MQ sensors. The prototype's blueprint was meticulously crafted using 3D image processing and graphics application tools, drawing inspiration from SketchUp for device visualization and design. Figure 3 elucidates the prototype's intricate design schematic and layout, offering a comprehensive visualization of its structural complexities and precise sensor placements within the apparatus.



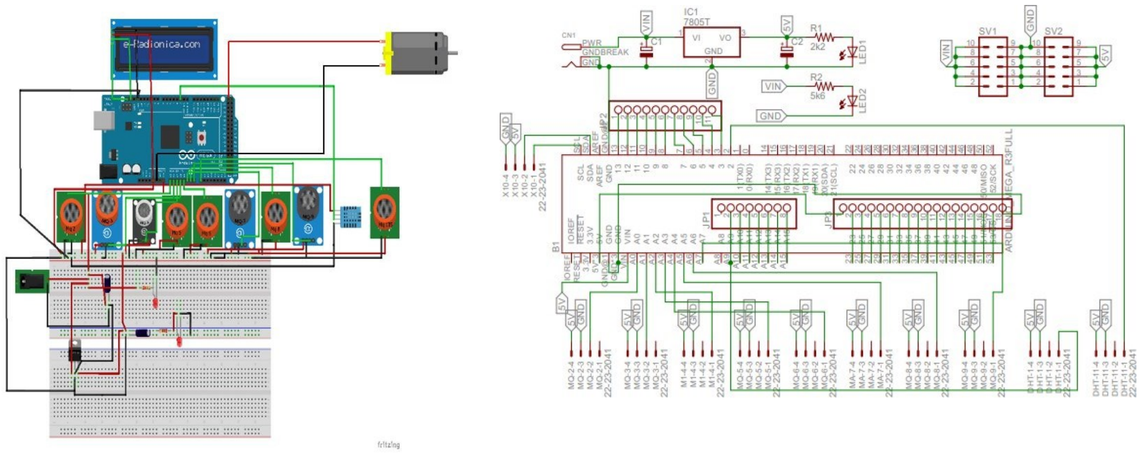
(a) (b)

Figure 3. Wiring diagram system (a) Top view, (b) Perspective view

Based on Figure 3, the portable gas measurement reactor in this innovative design includes a substance container (1) that serves as the vessel for gas content analysis. It is equipped with a reactor cover (1a) on which nine MQ sensors (2) are positioned. Internally, the reactor cover (1a) houses a DC motor (3) and a stirrer (4) attached to the motor shaft. This assembly is complemented by a control box (5) that houses a power supply and DHT11 sensors for temperature and humidity measurements. In particular, the MQ sensors (2) and the agitator (4) are mounted on the shaft of the DC motor (3), ensuring their synchronized operation. In addition, the control box (5) contains a power supply and DHT11 sensors for temperature and humidity measurements. The MQ sensors (2) and the DHT11 sensors are interconnected and transmit digital data to the Arduino Mega 2560 located in the control box (5) to perform the gas content measurement process systematically.

2.4. Wiring Diagram and Schematic

The wiring diagram is pivotal in the gas monitoring prototype within the chemical reactor setup. This diagram elucidates the intricate interconnections between various components, detailing their relationships and placements, commencing from the wiring layout to the positioning of sensors. Figure 4 presents the chemical reactor's wiring diagram and schematic representation of the gas monitoring prototype, illustrating the comprehensive setup. The prototype is equipped with 9 MQ-type gas sensors specifically designed to detect gases emitted by objects close to the sensors.



(a) (b)

Figure 4. (a) Wiring diagram system, (b) Schematic system

2.5. MQ Sensor Type and Gas Composition

Gas is a form and form of a substance that has shape and volume and has conditions that change according to the space it occupies. The nature of the gas itself is colorless, odorless, tasteless and slightly soluble in water. Each gas has a special composition that varies depending on the type of gas that exists. In this study, the gas that will be studied is in accordance with the function of the MQ sensor in detecting gases such as LPG, propane, butane, methane, alcohol, carbon monoxide, even clean air and many more. Table 1 displays the composition of the gas that can be detected by the MQ sensor.

Table 1. MQ Sensor Type and Gas Composition

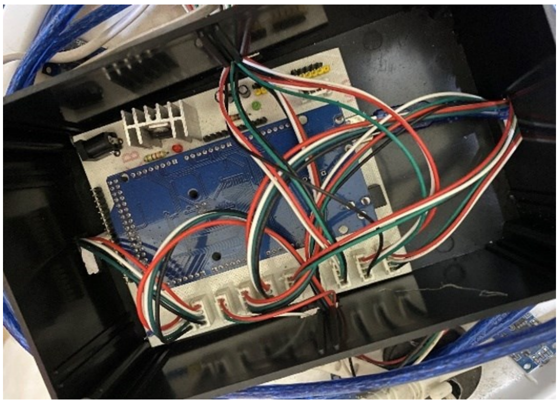
Sensor Type	Type of gas detected	Empirical Formula	Gas Reading Range
MQ-2	LPG, Hydrogen, Propane or smoke and Methane. [16]	C3H8, C4H10, CH4, and H2	300 – 1000 ppm [17]
MQ-3	Alcohol dan Benzena [18]	C2H6O and C6H6	300 – 1000 ppm [19]
MQ-4	Methane and Natural Ggas [13]	CH4 and C2H6	200 – 10,000 ppm [13]
MQ-5	LPG dan Natural Gas [20]	C4H10 and CH4	300 – 1000 ppm [10]
MQ-6	LPG, Iso-Butana, and Propana [21]	C4H10 and C3H8	200 – 10,000 ppm [22]
MQ-7	Carbon Monoxida [23]	CO	20 – 2000 ppm [24]
MQ-8	Hydrogen	H2	200 – 10,000 ppm [13]
MQ-9	Carbon Monoxida, Methana, and LPG	CO, CH4, and LPG	10-1000 ppm [25]
MQ-135	Clean air quality detection (suitable for detection of Ammonia, Nitrogen Oxide, Alcohol, Benzene and Carbon Dioxide).	NH3, NOx, C2H6, C6H6, and CO2	0 – 50,000 ppm [26]

3. RESULT AND DISCUSSION

The results obtained from the experiment using 10 samples successfully showed the reaction/response of several MQ sensors used. From this data, it can be seen that in the samples tried, there are several gases / substances that can be read by several MQ sensors in accordance with the function of the gas sensor and the influence of temperature and humidity on the sample in a closed reactor. In this research, there are several test results from 10 samples, Arabica coffee, Robusta coffee, Kapal Api coffee, pepper, honey, sambal, oyster sauce, sprite, syrup and batik waste. Below are the results obtained from several samples used in the study.

3.1. System Hardware

The hardware setup incorporates a 25L bucket to contain both the circuitry and the test samples. Atop the bucket, a black box serves as the housing for the microcontroller. Figure 5 provides a visual representation of the ultimate prototype design, elucidating the component's combination and spatial arrangement within the system.



(a)

(b)

Figure 5. (a) Controller, (b) Device gas composition measurement

3.2. Arabica Coffee

The sample utilized in this study consists of pure ground Arabica Pujon coffee, distinguished by its natural processing without any blending. Arabica coffee, hailing from the Coffea genus, is one of the earliest cultivated coffee species. The sample was carefully positioned within the reactor and allowed to undergo a prolonged duration of observation. With a tare weight of 400 g, the sample was combined with 1 liter of water heated for 1 minute as part of the experimental procedure. Figure 6 shows the gas composition measurement.

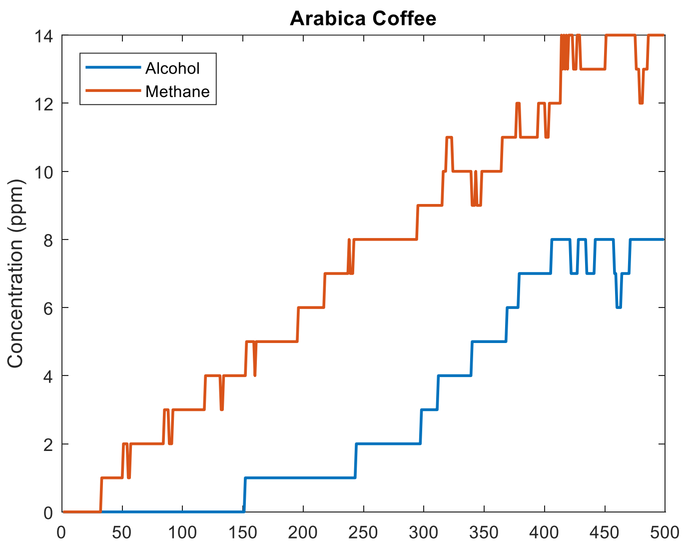


Figure 6. Gas composition on Arabica Coffee

The results obtained from the arabica coffee sample are shown in Figure 6, show methane gas as the most prominent, registered at 20 ppm, followed by alcohol at 15 ppm, represented by the blue graph, and smoke gas at 8 ppm, represented by the silver graph. The methane gas was detected using the MQ 4 sensor, while the alcohol gas was identified using the MQ 3 sensor. Notably, an increase in temperature and humidity correlated with the presence of these gases in the Arabica coffee sample. The volatile compounds found in this coffee consist mainly of alcohol compounds and an alkane compound, methane. These volatile compounds play an important role in determining the quality, flavor and aroma of the coffee. A higher concentration of volatile compounds generally indicates better quality, flavor and aroma in the coffee. All of the sensors were positioned above the reactor to effectively monitor and measure the presence of various gases in the coffee sample and to elucidate the diverse composition and its potential impact on the coffee's characteristics.

3.3. Robusta Coffee

Robusta coffee samples were placed in a sealed reactor and allowed to sit for a period of 2 hours. The amount of sample used in this study was 600 grams, mixed with 1 liter of water and subjected to a heating process for 1 minute. The resulting gas reactions can be observed and analyzed in Figure 7, which illustrates the gas composition generated by this specific sample within the experimental.

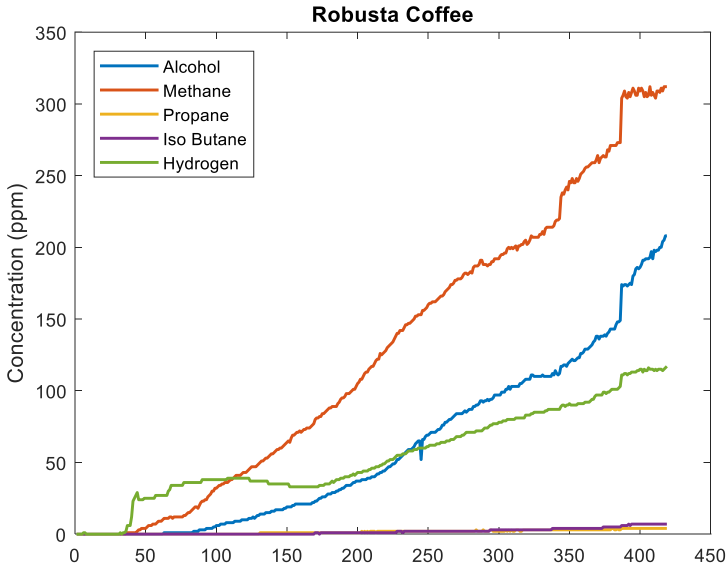


Figure 7. Gas composition on Robusta Coffee

According to the data presented in Figure 7, the gas analysis of the Robusta coffee revealed notable concentrations of various gases. Methane showed a significant presence at 312 ppm, followed by alcohol at 208 ppm, hydrogen at 117 ppm, isobutane at 7 ppm, and propane at 4 ppm within the analyzed sample. These results indicate a diverse composition of gases present in Robusta coffee, with significant concentrations of methane and alcohol in addition to hydrogen, iso-butane, and propane. Such an extensive array of gases suggests a complex chemical profile within Robusta coffee, possibly due to its organic nature or specific processing methods that contribute to the diverse gas composition observed in this sample.

3.4. Kapal Api Coffee

In this experiment, Kapal Api coffee is brewed with water and stirred by a stirrer inside the reactor. Figure 8 shows the gas composition measurement on Kapal Api Coffee. Based on Figure 8, The powdered Kapal Api coffee was placed directly into the container inside the reactor. Unlike the pepper sample, the Kapal Api coffee sample required a longer period of time for the gas to rise sufficiently, initially filling only a limited space within the reactor. It took approximately two to three hours for the gas produced by this sample to sufficiently occupy the space within the reactor. However, it was observed that the gas produced needed to be more concentrated compared to the other samples tested. This affected the methane gas produced by the Kapal Api coffee, resulting in a lower concentration of 2 ppm compared to the other samples. This observation suggests that the concentration or intensity of the gas produced by the Kapal Api coffee may have affected the methane levels, thus affecting the rate or volume of gas release during the experiment.

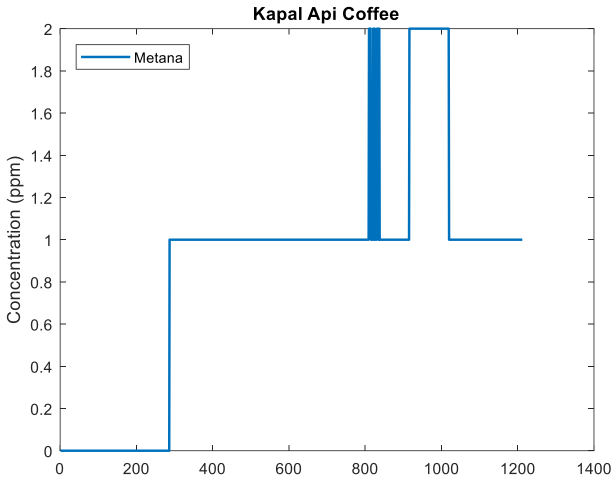


Figure 8. Gas composition on Kapal Api Coffee

3.5. Pepper

Pepper, also known as pepper with the latin name *Piper nigrum*, is a plant commonly used as a spice or flavoring in foods. This plant has been known for tens of centuries. The type/brand of pepper used as a sample in this study is pepper powder. Gas data was collected on this sample by placing the pepper powder in the reactor. Data analysis of this sample takes two to three hours. This is because the gas emitted from the pepper sample is not immediately concentrated compared to other samples. The results of the gas data collected on the pepper sample show an increase of 5 ppm of alcohol gas. Figure 9 shows the gas composition on pepper.

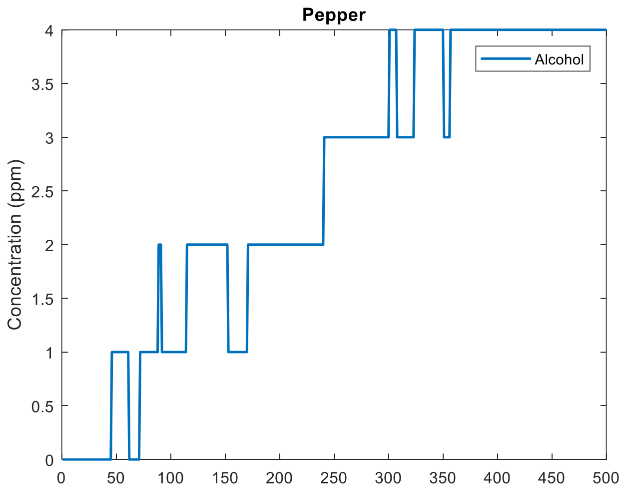


Figure 9. Gas composition on pepper

Based on the information provided, the experiment involved 24 grams of pepper combined with 500 milliliters of water heated for 1.30 minutes. Referring to Figure 9, the analysis revealed the presence of alcohol in the pepper sample, albeit at a minimal level of 4 ppm. Although alcohol is commonly used in food preparation for flavoring purposes, the concentration detected in this particular pepper sample remained relatively low. This finding underscores the limited presence of alcohol in the analyzed pepper sample, suggesting its minor contribution to the overall composition, possibly indicating a minimal impact on the characteristics of the sample in this context.

3.6. Honey

The 1.35liter experimental honey sample was poured directly into the reactor for analysis. Figure 10 shows gas composition measurement on honey.

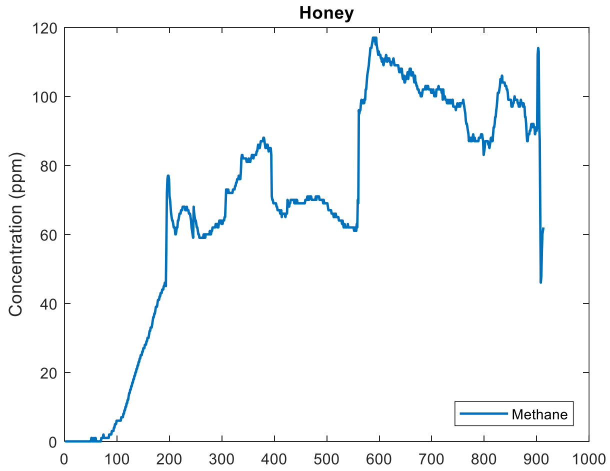


Figure 10. Gas composition on Honey

Based on Figure 10, honey shows alkane compounds, especially methane gas with a concentration of 122 ppm. In addition, a secondary component detected besides methane is smoke or vapor, registered at a value of 8 ppm. However, the sensitivity of smoke detection is significantly lower compared to methane in the sample. Smoke, classified as a solid aerosol, appears next to methane, classified as a gas, showing a clear difference in their nature and concentration levels within the analyzed honey sample. This delineation underscores the significant predominance of methane over smoke in the gas composition of honey, emphasizing their different sensitivities and classifications as gas and solid aerosol, respectively.

3.7. Chili Sauce (Sambal)

Chilli sauce (Sambal) has been a food flavoring for a long time. The sample is left in the preheated reactor for a while so that the gas reading from the sensor is more optimal. The dose for this sample is 1 kg of chili sauce with 300 ml of water, which is heated for 1 minute. Figure 11 shows the gas composition measurement on chilli sauce.

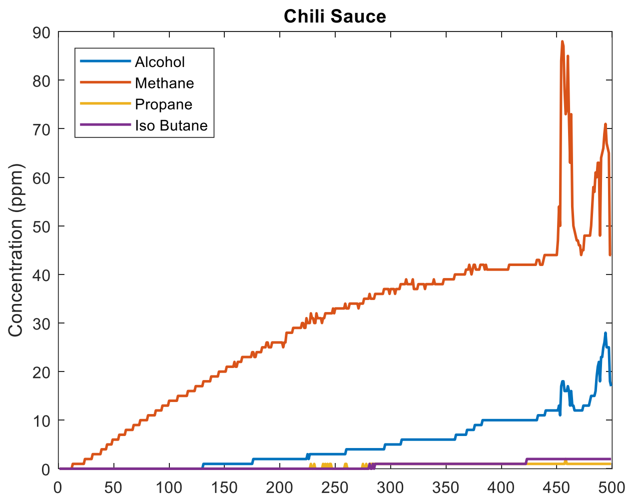


Figure 11. Gas composition on Chili Sauce

Based on Figure 11, methane is the dominant gas detected by the MQ 4 sensor, reaching a maximum concentration of 90 ppm. In addition, alcohol gas, detected by the MQ 3 sensor, registers at 30 ppm, indicating a significant presence in the analyzed sample. Conversely, propane and isobutane exhibit minimal concentrations of 1 ppm and 2 ppm, respectively, compared to the more prominent methane and alcohol gases. This observation highlights the relative abundance of methane and alcohol compared to the negligible amounts of propane and iso-butane within the gas composition, emphasizing their varying levels of presence in the measured sample.

3.8. Oyster Sauce

Oyster sauce with a dose of 1.20 kg, which has been preheated for 1 minute, is added to the reactor for 2 hours. The type of gas that reacted in this sample is shown in the blue graph. The measurements show that one type of gas reacts, namely hydrogen in the sample, with the value of the gas increase obtained at 15 ppm. Figure 12 shows the gas composition of oyster sauce.

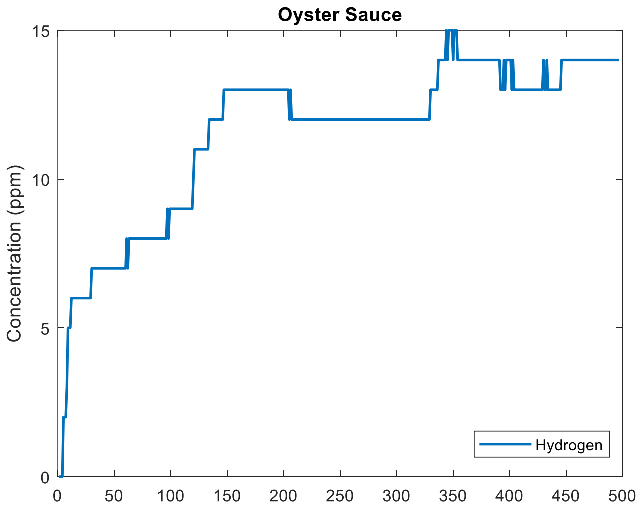


Figure 12. Gas composition on Oyster Sauce

Based on Figure 12, gas composition analysis of the oyster sauce revealed the presence of hydrogen gas at a concentration of 15 ppm. This detection was made in a sample weighing 1.2 kilograms, with measurements taken over a period of 2 hours. The specified sample weight and time frame provide contextual information regarding the detected concentration of hydrogen within the oyster sauce, providing insight into the gas composition of this particular sample and the duration over which the measurements were observed.

3.9. Soda Drinks

Carbonated drinks are poured/placed in the reactor. The data collection time for this sample is 2 hours with a dose of 1 L. The measurement gas composition on this sample can be seen in Figure 13.

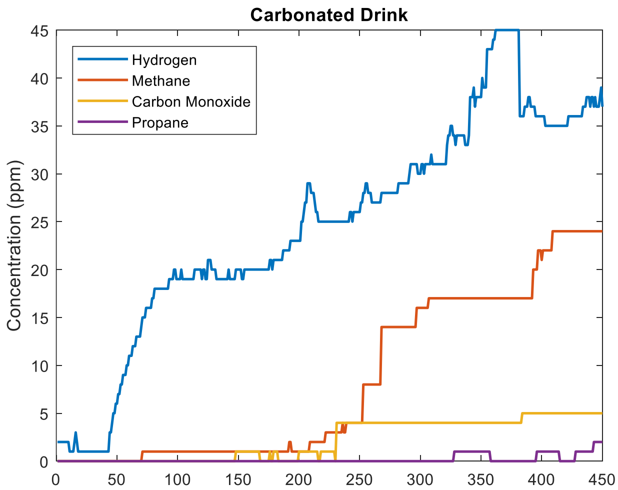


Figure 13. Gas composition on Carbonated Drink

Based on Figure 13, analysis of the carbonated beverage samples revealed the presence of four different gases: hydrogen at 45 ppm, methane at 24 ppm, propane at 2 ppm, and carbon monoxide at 5 ppm. Of these gases, hydrogen and methane proved to be the most sensitive detections, with hydrogen detectable with the MQ 8 sensor and methane measurable with the MQ 4 sensor. This observation underscores the ability of specific MQ sensors-MQ 8 for hydrogen and MQ 4 for methane-to detect these gases in the carbonated beverage samples, providing valuable insight into their gas composition and sensor sensitivity in this context.

3.10. Syrup

The syrup was placed in the reactor for 2 hours. The sensor was preheated before the sample was added. The syrup sample is 800 ml with 300 ml of water heated for 1 minute. Figure 14 shows the gas composition measurement on syrup.

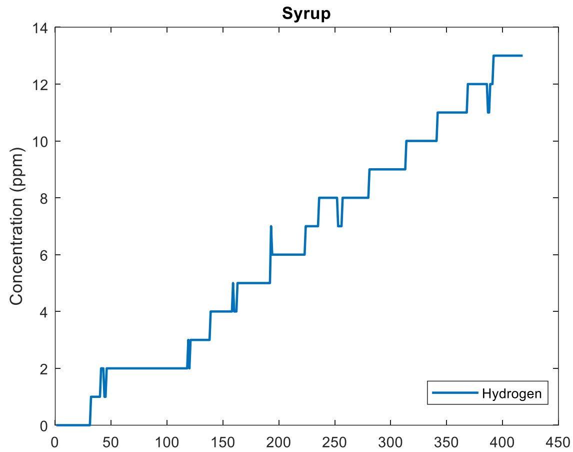


Figure 14. Gas composition on Syrup

Based on Figure 14 the detected gas composition prominently featured hydrogen, which was recorded at 14 ppm within an experimental setup consisting of an 800 ml sample volume accompanied by 300 ml of water. This observation highlights the prevalence of hydrogen within the measured gas composition, suggesting its significant presence relative to other gases in the sample volume analyzed. The combination of the specified sample volume and water content within the experimental setup provides valuable context for understanding the relative concentration of hydrogen detected in this particular setting.

3.11. Batik Waste

Batik waste is collected directly from batik artisans. Before the batik waste is poured/placed into the reactor, the MQ sensor above the ceiling of the reactor is preheated so that the reading of the MQ sensor on what kind of gas is contained in the waste sample can run well. The waste is immediately placed in a closed reactor, stirred with a stirring motor inside the reactor, and left for 4 hours. Figure 15 shows the gas composition measurement of batik waste.

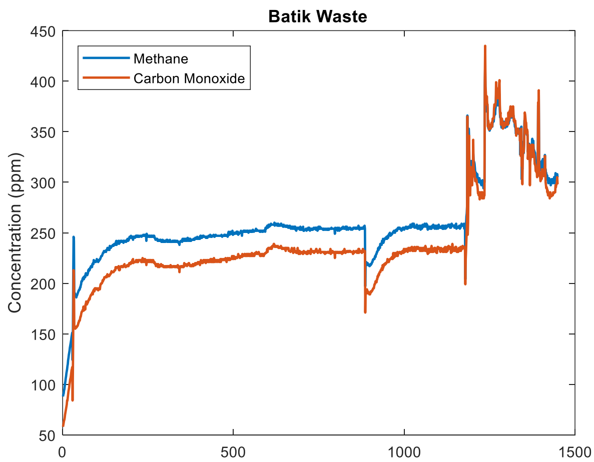


Figure 15. Gas composition on Batik Waste

Figure 15 The results of treating batik waste with a Fe/C catalyst showed fluctuations in methane and carbon monoxide concentrations over a series of measurements. Initially, the methane concentration was 417 ppm and showed a fluctuating range throughout the measurements. Simultaneously, carbon monoxide concentrations ranged from 435 ppm, also showing variability across the recorded data points. These fluctuations in methane and carbon monoxide concentrations suggest dynamic transformations within the batik waste, indicating potential changes in decomposition or anaerobic processes catalyzed by the Fe/C treatment. Further analysis of these fluctuations could provide insight into the efficacy of the Fe/C catalyst in altering gas compositions and elucidate its impact on the dynamics of waste decomposition.

3.12. Gas Composition Measurement

After conducting 10 measurements on various samples, the test data obtained from measuring the gas composition of each sample with a time 2 hours, Table 2 shows a comparison of gas composition each sample.

Table 2. Gas Composition Comparison of each sample

Sample	Gas Composition Measurement (ppm)					
	Hydrogen	Methane	Propane	Iso Butane	Carbon Monoxide	Alcohol
Arabica Coffee	-	14	-	-	-	15
Robusta Coffee	117	312	4	7	-	208
Kapal Api Coffee	-	2	-	-	-	-
Pepper	-	-	-	-	-	4
Honey	-	122	-	-	-	-
Chili Sauce	-	90	1	2	-	30
Oyster Sauce	15	-	-	-	-	-
Carbonated Drink	45	24	2	-	5	-
Syrup	14	-	-	-	-	-
Batik Waste	-	417	-	-	435	-

Based on Table 2, the gas composition measurements for the samples reveal distinct characteristics: arabica coffee exhibits low methane 14 ppm and alcohol 15 ppm levels, suggesting minimal fermentation. robusta coffee displays higher concentrations of hydrogen 117 ppm, methane 312 ppm, propane 4 ppm, iso butane 7 ppm, and alcohol 208 ppm, indicating a richer composition possibly due to organic compounds and fermentation. kapal api coffee shows minimal methane 2 ppm, implying limited biological activity or fermentation. pepper and syrup present trace or low levels of gases, pepper with only alcohol 4 ppm and syrup with minimal hydrogen 14 ppm, suggesting inert gas compositions. Honey displays moderate methane 122 ppm, hinting at microbial activity or fermentation. Chili sauce indicates moderate methane 90 ppm, slight propane 1 ppm and iso butane 2 ppm, and alcohol 30 ppm, suggesting potential microbial activity or slight fermentation. Oyster sauce shows a low hydrogen presence 15 ppm. Carbonated drink displays moderate hydrogen 45 ppm, methane 24 ppm, propane 2 ppm, and carbon monoxide 5 ppm, possibly linked to carbonation or production. Batik waste presents notably high methane 417 ppm and significant carbon monoxide 435 ppm, indicating potential anaerobic processes or decomposition in this material. These measurements offer insights into diverse processes like fermentation, organic breakdown, or decomposition within these samples.

4. CONCLUSIONS

This research utilizes the MQ sensor array methodology and employs algorithmic approaches to quantify gas concentrations in various samples. Methane, hydrogen, and alcohol emerge as the primary gases detected, with striking variations observed between samples. In particular, robusta coffee exhibited elevated levels of methane (312 ppm), hydrogen (117 ppm), and alcohol (208 ppm), indicating rich organic compositions and potential fermentation. Batik waste showed unprecedented methane (417 ppm) and significant carbon monoxide (435 ppm) concentrations, suggesting unique anaerobic processes or decomposition. The 30-40 minutes preheating period optimized sensor readings by compensating for individual MQ sensor sensitivities. This approach significantly increased the detection range and provided nuanced insights into fermentation, organic degradation or decomposition processes within the samples studied. The results underscore the efficacy of the sensor array method in comprehensively assessing gas compositions and their effects on various materials, paving the way for refined monitoring and understanding of complex gas dynamics in diverse environments.

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