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# THE EFFECT OF TESTING CHAMBER ON THE RESPONSE PATTERNS OF AN ARRAY OF GAS SENSORS IN SENSING ROBUSTA COFFEE AROMA FROM BANGSALSARI AND SIDOMULYO, JEMBER

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## *ABSTRACT*

The gas sensor performance can be improved by optimising the testing chamber design, including volume, shape, gas inlet/outlet positions, and sensor array. We studied the effect of chamber design on the gas sensor's response patterns characteristics in differentiating Robusta coffee aroma from Sidomulyo, and Bangsalsari, Jember. Hemisphere and cylindrical chambers, with three variations for each model, and a ring chamber, were used as model chambers. Eight types of gas sensors (MQ-135, MQ-136, MQ-2, MQ-3, MQ-6, MQ-7, MQ-8, and MQ-9) were used in the sensor array system to examine the gas sensor instrument performance. The resulting responses were analysed using the reproducibility, response time, and principal component analysis (PCA) test. The result shows that the reproducibility value for all hemisphere chamber models, cylindrical chamber model-1, and ring chamber indicated an excellent sensor performance (%RSD<20%).On the other hand, the cylindrical chambers model-2 and 3 resulted in %RSD>20%, indicating the low performance of the gas sensor. Among all variations, hemisphere chamber model-1, a hemisphere chamber with the inlet position lower than the outlet gas position, has the best performance due to the shortest response time, high-intensity signal, and performing ability to distinguish the response patterns characteristics of Robusta coffee aroma from Sidomulyo and Bangsalsari, Jember, Indonesia. In this study, we found that changing the testing chamber design, volume, and inlet/outlet position resulting different gas sensor responses to the coffee aroma. Therefore, the proposed instrument can distinguish the coffee aroma from a different origin.

**Keywords:** electronic nose; chamber; gas sensor; coffee; response patterns

## INTRODUCTION

The gas sensor has been widely used to detect gases in any application, such as environmental monitoring, industry, medicine, food quality, and many others [1]. This instrument offers various advantages over common or traditional instruments. Research on gas sensor development has improved significantly for decades and is still an attractive topic nowadays. A kind of gas sensor instrument, electronic-nose, is an alternative for determining the taste of food and beverages and can be used without the need for expensive and time-consuming methods as other established methods such as chromatography. E-nose offers a low-cost sensor with a wide range of applications, from hazardous gas detection for safety purposes to an electronic nose for food quality assessment [2]. The e-nose performance is affected by various factors [3]. One factor that plays an essential role in a detecting system is testing chamber design, including chamber volume, gas inlet and outlet position, and the sensor array [1,4]. Thus, to develop a sensor, ensuring quality is essential for a qualified sensor response measurement.

Optimised gas testing chamber design is a parameter to achieve this. The design needs to be modelled and simulated to minimise the dead volumes, comprehend the gas flow velocity at the sensor surface, and avoid turbulences [5]. Most Chemical/physics procedures are on the sensor surface, so it is vital to control it and to fulfil all sensor conduct needs [6]. The testing chamber should be designed to optimise the measurement and arranged to ensure the injected volatile compounds are stable and uniformly distributed within the chamber quickly, minimising the stagnant and recirculation area, hence optimising the contact of the gas and the sensor surfaces [5]. Chamber design strongly correlates with the gas flow in the chamber, affecting the resulting sensor responses, since most chemical and physical processes occur at the sensor surface [5-8].

Many published works focused on enhancing the sensor response by materials modifications or sensor design [9], and only a few focused-on chamber optimisations. Due to the chamber design's significant effect, this topic still needs to be studied to optimise the sensor response. Chamber volume and sensor positions are the parameters observed in some studies. Whereas, sensor responses time, stability, reproducibility, and repeatability are the common parameters in investigating the sensor's performance [10]. Annanouch investigated and compared the effect of the gas test chamber design on the sensor’s performance, and indicated that optimising the design and reducing the test chamber volume increases the quality of the sensor response and, therefore, is closer to the actual behaviour of the sensor. Lopez Jr. studied the performance of graphene gas transistors and resulted that the direction of gas flow in the chamber and chamber volume significantly affects the sensitivity and response time of the GFET (graphene field-effect transistor) [2,5].

The most common design of the testing chamber is hemisphere and cylindrical chambers. The hemisphere chamber has the smallest stagnant area with more interaction between gas and sensor. Hence, the sensor's performance in the chamber is optimal [6]. On the other hand, in the cylindrical chambers, gasses will flow inside the chamber, optimising the sensor's interaction. Another chamber design is the ring chamber design. A ring chamber is one of the cylindrical chamber designs with gas flow channels passing through the sensor array resembling a ring. Jayanti has developed this design for detecting Robusta coffee aroma, and the result showed that the sensor with a ring chamber has a good performance with the %RSD<8% [7].

The aroma of coffee is a complex mixture of hundreds of components, which makes it a challenging sample for an electronic nose to analyze. Nevertheless, several studies have reported successful results using electronic noses to distinguish coffee aromas [11-13]. For instance, Fujioka studied canned coffee to improve the electronic nose's ability to describe and differentiate between various coffee aromas [11,12]. Similarly, a correlation study was carried out between portable electronic nose and GC-MS to identify the aroma of Indonesian Robusta coffee with different roasting temperatures, resulting in a unique aroma pattern for each roasting temperature correlated with the number of aromatic compounds detected in GC-MS [13].

In this study, we aimed to investigate the impact of varying the gas inlet/outlet and the sensor array position of the hemisphere, cylindrical, and ring chambers on the sensor performances. Therefore, we evaluated the sensor response time, response intensity (potential difference), and PCA results. The experiment resulted in an optimal chamber testing design that ensures high-quality sensor measurements. Furthermore, we studied the response patterns using PCA analysis to examine their characteristics and the sensor's ability to distinguish between different coffee origins. Therefore, this proposed sensor design could accurately differentiate between coffee samples based on their origin, as reflected by their distinctive response patterns.

## METHOD

### Instrument

Glass apparatus, pump, cylindrical chamber, hemisphere chamber, ring chamber, laptop installed with LabVIEW 2018 software, sensor gas MQ (MQ-135, MQ-136, MQ-2, MQ-3, MQ-6, MQ-7, MQ-8, and MQ 9), and Arduino Mega 2560—the specifications of all gas sensors as in Table 1.

Table 1 Sensor gas and specific gas detection.

| Sensor | Gas Detection |
|---|---|
| MQ-2 | Propane, methane, butane and smoke [14, 15] |
| MQ-3 | Alcohol [14] |
| MQ-6 | Liquefied petroleum gas (LPG), butane [14] |
| MQ-7 | Carbon monoxide (CO)[14] |
| MQ-8 | Hydrogen gas [14] |
| MQ-9 | LPG, CO, $CH_4$, and useful for gas leakage detection [14] |
| MQ-135 | An air quality sensor for detecting a wide range of gases, especially benzene, alcohol, and ammonia, smokes [15] |
| MQ-136 | Hydrogen gas, hydrogen sulfide, with detection range 1-100 ppm [14, 16] |

### Chamber Design

The cylindrical and hemisphere chamber were designed using acrylic materials with a diameter of 10.0 cm, height of 5.0 cm, and inlet and outlet diameter of 1.0 cm. Both cylindrical and hemisphere chambers have three variations. The volume of all cylindrical chambers was 392,5 $cm^3$, and the volume hemisphere chamber was 261,67 $cm^3$. The design for cylindrical chambers was cylindrical model-1 (Cy-1), Cylindrical model-2 (Cy-2), and cylindrical model-3 (Cy-3). The hemisphere chamber designs were hemisphere model-1 (He-1), hemisphere model-2 (He-2), and hemisphere model-3 (He-3). Ring chamber (r) was used as a comparison. All design and their variations, as shown in Figure 1.

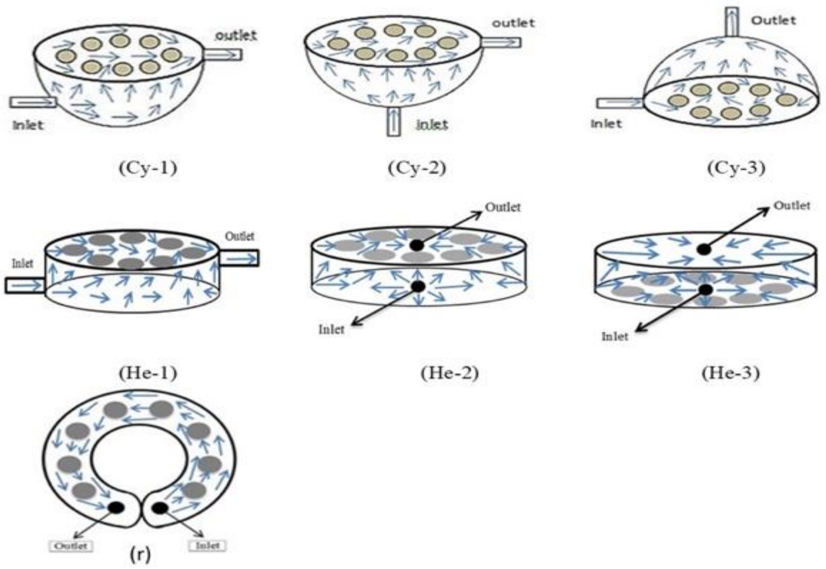


Figure 1. Cylindrical chamber (Cy-1, Cy-2, Cy-3), hemisphere chamber(He-1, He-2, He-3), ring chamber (r).

### Gas Sensor Test

The study aimed to examine the aromas of Robusta coffee from various locations using a gas sensor design, as illustrated in Figure 2. To prepare for the experiment, water and sample solutions were heated to 95°C, and the flow rate was set at 3 mL/min. The first step involved flowing water vapor into the testing chamber for 150 seconds, and the sensor captured this vapor as the baseline signal. Next, the coffee vapor was introduced to the chamber, and the data was monitored until the signal reached a steady state, which varied depending on the chamber design. For example, in Chamber-1 (Cy-1 and He-1), the running time was from 1.05×103 s to 1.2×103 s, while in Chamber-2 (Cy-2 and He-2), it was 1.5×103 s, and in Chamber-3 (Cy-3 and he-3), it was 2×103 s. The Ring chamber (r) had a running time of 450 s.

To ensure the gas sensors' accuracy and reliability, dry gas flowed into the chamber before and after each test to eliminate any residual gas on the sensor surface and testing chamber. The sample response was calculated by subtracting the coffee vapor signal from the baseline signal, and each measurement was repeated ten times to ensure consistency. The reproducibility of the results was verified by conducting tests using all variations of the testing chamber design once a week for five weeks.

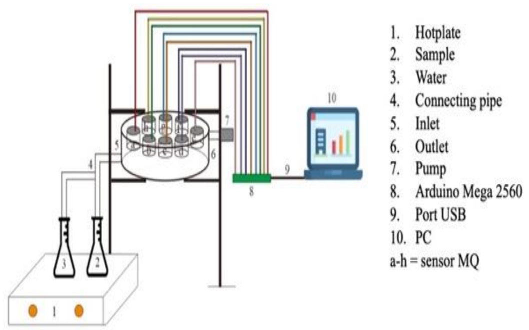


Figure 2. Instrument design for gas sensor of coffee aroma

### Method of Analysis

The obtained data were analysed using LABVIEW software, resulting in a graphic (Voltage Vs time), reproducibility test, and PCA (Principal Component Analysis) test.

## RESULTS AND DISCUSSION

### Effect of Solvent Type and Ratio for Laminarin Extraction

### Gas Sensor's Response Time

We studied how the design of the testing chamber affects the performance of each gas sensor in the array. Each gas sensor in the array has a unique response to the gas sample, and the response time indicates how quickly the sensor can detect the presence of gases on its surface [14-16]. The gas sensor response signal varies for each sensor and each chamber variation, as the sensors have different abilities to detect different gases (as shown in Table 1). For instance, we focused on the MQ-136 sensor, which is particularly sensitive to $H_2S$ gas and can monitor organic vapor. The gas sensor response signal for the MQ-136 sensor in sensing Robusta coffee from Sidomulyo using both hemisphere and cylindrical chambers is illustrated in Figure 3 and 4, respectively.

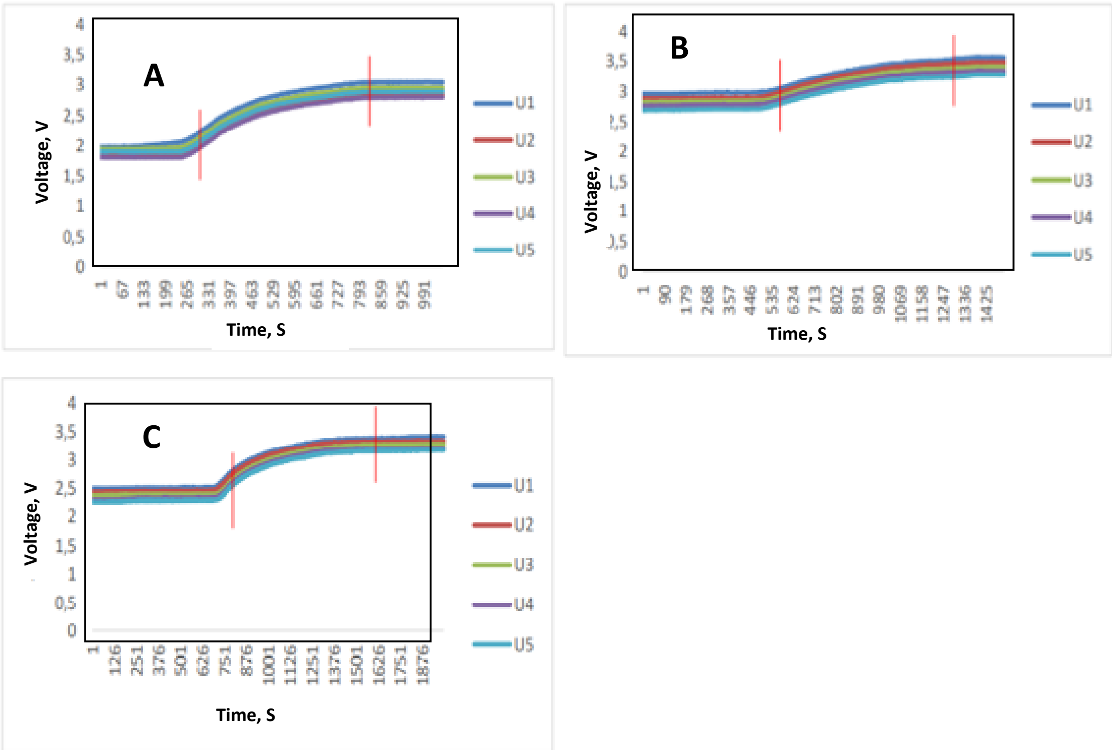


Figure 3. Gas sensor response MQ-136 to Robusta Coffee Sidomulyo for five days (5 repetitions) in hemisphere chamber (a) He-1; (b) He-2; (c) He-3.

The response time was recognised by a significant response change (increasing potential difference), as shown in Figure 3. Chamber model He-1 has the fastest and highest response (potential difference) than He-2 and He-3 models. It is due to the lower position of the gas inlet than the gas outlet, which affects the gas flow. It leads the gases to flow constantly from the bottom to the higher position in the chamber, optimising the gas interaction with the sensor surface on the top of the chamber. This result is by [1] that the sensitivity of the gas sensor is gradually decreased by increasing the inlet and sensor distance.

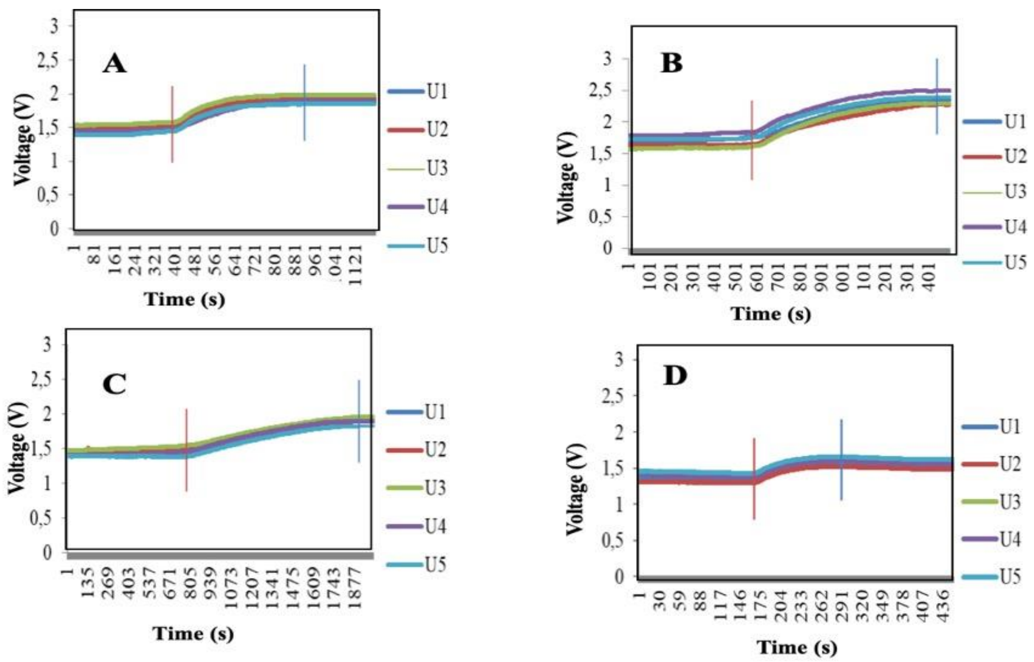


Figure 4. Gas sensor responses MQ-136 to Robusta coffee Sidomulyo for 5 days (5 repetitions) in Cylindrical chamber (a) Cy-1; (b) Cy-2; (c) Cy-3; and (d) r chamber.

According to Figure 3 and 4, we can conclude that the r-chamber has the fastest response time of all chamber designs. The faster response time in the r chamber is due to the volume differences. This phenomenon follows Annanouch (2018) stated that by optimising the design and reducing the volume of the testing chamber, the responses sensor is highly enhanced and faster [5]. The r chamber has the smallest volume, leading to a narrower path of gas flow and minimising the space for gas movement in the chamber. It forces the injected gas flow into the r chamber more quickly following the flow; hence, the gas is in direct contact with the surface of the gas sensor. This condition makes the sensor response time in this chamber faster than in other designs of the hemisphere and cylindrical chambers.

The longer response time in all variations of the hemisphere and cylindrical chambers (he-1, he-2, he-3, cy-1, cy-2, and cy-3) is due to their larger volume than the ring chamber (r). Because of their larger size, it takes more time for the volatile gases to reach and interact with the gas sensor surface, resulting in longer response times [1,5].

**Response Patterns of Gas Sensor in Sensing Robusta Coffee Aroma**

Gas sensor response is highly dependent on the chemical composition of the coffee aroma. This composition is strongly influenced by the genetics factor, geographical origin, agricultural practice, and processing method [17,18]. Therefore, different chemical compositions resulted in different gas sensor responses.

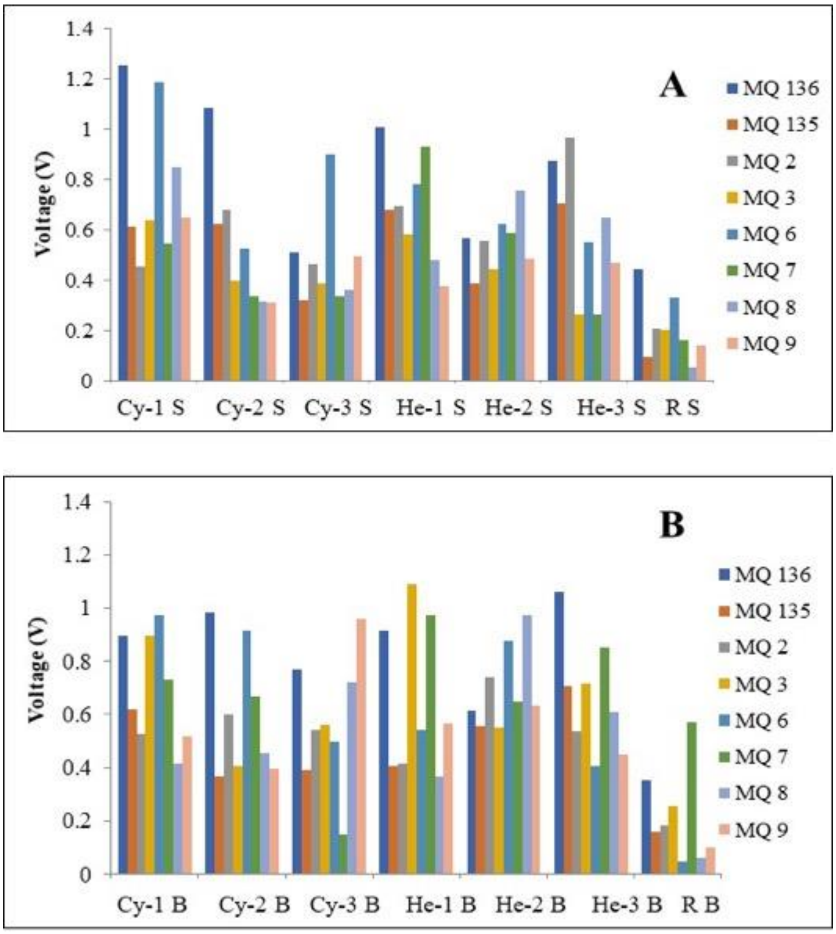


Figure 5. Response patterns characteristics of the gas sensor array in various chambers to (A) Robusta coffee Sidomulyo; (B) Robusta coffee Bangsalsari (S= Sidomulyo; B= Bangsalsari) (Cy-1= Cylindrical chamber 1; Cy-2= Cylindrical chamber 2; Cy-3= Cylindrical chamber 3; He-1= Hemisphere chamber 1; He-2= Hemisphere chamber 2; He-3= Hemisphere chamber 3; dan R= Ring chamber).

Various chamber design variations, the study investigated the ability of eight sensors in an array to distinguish between Robusta coffee aromas from different regions in Jember, Indonesia. The results showed that the sensors' response patterns differed for each sample, as determined by the potential difference between the coffee vapor signal and the baseline. Figure 5 illustrates the sensor response pattern characteristics to the aroma of Sidomulyo and Bangsalsari Robusta coffee.

The different chamber variations affected the response patterns in measuring the Robusta coffee aroma from Sidomulyo and Bangsalsari due to differences in the gas flow inside the chamber. The response pattern differences were attributed to the different responses of each sensor in the gas array sensor, which created a distinct pattern of the signal produced in different chamber variations and samples. Cy-1 and He-1 had the highest voltage values compared to other chamber variations because of the differences in inlet and outlet positions and the chamber volume. The inlet position Cy-1 and He-1 was lower than the outlet and opposite positions, resulting in more even gas distribution than Cy-2, Cy-3, He-2, and He-3. This even distribution led to more interaction between gases and the gas sensor surface, resulting in higher voltage values. Conversely, due to its smaller volume, the ring chamber had the lowest potential difference compared to chamber-1 and chamber-2 in the hemisphere and cylindrical design. The smaller chamber volume in the ring chamber caused more gases from the steam coffee to force out, leading to less interaction between gas and sensor surface.

Different signal responses of each sensor correlate with the specific gas detection, as mentioned in Table 1. Coffee aroma mainly comprises alcohols, aldehydes, esters, carbonic acids, thiols, sulfides, terpenes, phenols, and ketones [19,20].

**PCA Results**

The response pattern of the gas array sensor in various chamber variations was further analysed using the PCA method. This method compares characteristics of the response patterns in each chamber variation in detecting robusta coffee aroma from Sidomulyo and Bangsalsari—the PCA score plot to distinguish robusta coffee aroma presented in Figure 6.

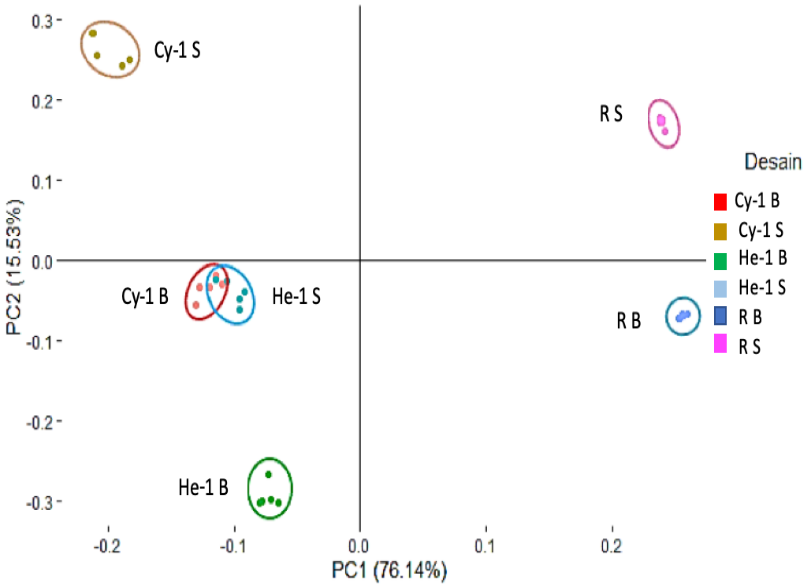


Figure 6. 2D PCA test result of Robusta coffee (Cy-1B= Cylindrical chamber 1-Bangsalsari; Cy-1S= Cylindrical chamber 1 Bangsalsari; He-1B= Hemisphere chamber 1 Bangsalsari; He-1S= Hemisphere chamber 1 Sidomulyo; RB= Ring chamber-Bangsalsari, dan RS= Ring chamber -Sidomulyo).

PCA method reduces the existing variables without losing the information contained in the original data [21,22]. PCA results can be differentiated based on the Euclidean distance, the distance used to measure the distance between two points in Euclidean space, which includes 2-dimensional, 3-dimensional, or even more to measure the degree of data similarity [23]. The higher Euclidean distance value indicates the sensor's ability to distinguish the aroma between Robusta Sidomulyo coffee and Robusta Bangsalsari coffee. In this study, the R-Studio software was used for analysis. The input data set to the R Studio software is obtained from the difference in coffee vapor pressure to water vapor (baseline) from each repetition and each chamber variation.

PCA analysis produces two main components, namely PC1 and PC2 (Figure 6). The resulting PC value of PC1 and PC2 were 76.14% and 15.53%, with a total accumulated value of 91.67% of the total data variance. Therefore, the cumulative proportion of the variance of the first and second principal components can explain the diversity of the data by 91.67%. According to Artigue & Smith (2019), the cumulative proportion value of the principal component variance should reach a minimum value of 80% to obtain a very good data diversity [24].

The Euclidean value for (Bangsalsari and Sidomulyo coffee aroma) from the Cy-1, He-1, and r chambers are 0.17, 0.17, and 0.11. the results indicated that sensors with various design chambers could distinguish the robusta coffee aroma from Bangsalsari and Sidomulyo. Based on the results from sensor response time, signal (potential difference), and PCA, as presented in Table 2, the He-1 chamber performs well, with a good response time, intensities and PCA results.

Table 2. Optimum parameters for cylinder model-1, hemisphere model-1, and ring chamber.

| *Chamber* | Parameters | | |
|---|---|---|---|
| | Sensor response time | Potential difference | PCA results |
| *Cy -1* | ∗ | ∗∗∗ | ∗∗∗ |
| *He -1* | ∗∗ | ∗∗ | ∗∗∗ |
| *Ring chamber* | ∗∗∗ | ∗ | ∗ |

(Note: ∗ = Deficient; ∗∗ = Good; ∗∗∗ = Very good)

**Gas Sensor Characteristics**

Table 3 shows the repeatability value (in %RSD) for hemisphere chambers (He-1, He-2, and He-3) ranging from 1.044% to 5.516%, while cylindrical chambers (Cy-1, Cy-2, and Cy-3) have a range of values from 0.96 to 5.41%, and the ring chamber ranging from 2.563 to 5.014%. The %RSD value tends to have an average measurement below 5%. These results indicate that the performance of the gas array sensor has good repeatability. The %RSD value that reaches more than 5% (<6%) is probably caused by the sensor humidity factor, which affects the measurement process.

The reproducibility characteristics of each sensor in each design as shown in Table 4. The He-2 %RSD ranged from 1.277-5.649%, while He-2 and 3 ranged from 1.691-6.105% and 1.945-7.101%. Meanwhile, cy -1 ranges from 7.45-19.79%, Cy-2 8.77-23.98%, Cy-3 6.36-21.10%, and the r-chamber has a %RSD value ranging from 9.217-17.577%. From these results, it can be said that He- 1, 2, and 3, Cy-1, and ring chambers produce %RSD values of less than 20%. According to the references, a %RSD value of less than 20% is considered a sensor with good performance [9,25]. These results indicate that the performance of the gas array sensor performed very well in detecting the aroma of Sidomulyo and Bangsalsari Robusta coffee. On the other hand, the %RSD in Cy-2 and Cy-3 ranged from 8.77-23.98% and 6.36%-23.10%, reached more than 20% (<24%). These results indicate that the sensor has poor performance. This is probably caused by the humidity sensor, sensor storage factor, or poor chamber design that affects the measurement process.

Table 3. RSD (%) array gas sensor repeatability of all chambers

| Coffee origin | Sensor | RSD (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | *Hemisphere* | | | *Cylindrical* | | | *Ring (R)* |
| | | *He-1* | *He-2* | *He-3* | *Cy-1* | *Cy-2* | *Cy-3* | |
| Sidomulyo | MQ-136 | 3.43 | 3.19 | 2.84 | 4.77 | 1.44 | 3.88 | 3.50 |
| | MQ-135 | 2.91 | 2.70 | 2.23 | 4.48 | 4.73 | 4.70 | 3.65 |
| | MQ-2 | 3.57 | 3.04 | 3.65 | 1.48 | 4.63 | 5.13 | 3.45 |
| | MQ-3 | 3.69 | 2.87 | 4.68 | 4.94 | 4.53 | 5.31 | 3.35 |
| | MQ-6 | 2.80 | 3.89 | 2.89 | 3.29 | 3.47 | 4.72 | 2.90 |
| | MQ-7 | 2.73 | 5.06 | 1.04 | 2.54 | 3.86 | 4.16 | 2.56 |
| | MQ-8 | 4.24 | 2.85 | 2.76 | 4.60 | 4.94 | 2.90 | 2.98 |
| | MQ-9 | 228 | 3.74 | 4.54 | 4.14 | 4.13 | 3.96 | 4.08 |
| Bangsalsari | MQ-136 | 3.76 | 2.32 | 2.82 | 4.70 | 3.11 | 5.00 | 3.19 |
| | MQ-135 | 3.92 | 3.77 | 2.71 | 1.11 | 3.27 | 3.74 | 4.47 |
| | MQ-2 | 5.52 | 4.47 | 3.22 | 4.95 | 5.41 | 5.41 | 4.17 |
| | MQ-3 | 3.06 | 2.11 | 3.63 | 2.11 | 4.62 | 4.62 | 3.64 |
| | MQ-6 | 4.55 | 3.21 | 3.79 | 0.96 | 2.16 | 2.16 | 4.48 |
| | MQ-7 | 1.42 | 2.01 | 2.37 | 3.08 | 4.91 | 4.91 | 2.82 |
| | MQ-8 | 3.44 | 5.07 | 3.45 | 4.18 | 5.09 | 5.09 | 5.01 |
| | MQ-9 | 2.62 | 3.24 | 3.77 | 4.92 | 1.99 | 1.99 | 4.59 |

**Table 4.** RSD (%) array gas sensor reproducibility of all chambers and all sensors

| Coffee origin | Sensor | RSD (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | *Hemisphere* | | | *Cylindrical* | | | *R* |
| | | *He-1* | *He-2* | *He-3* | *Cy-1* | *Cy-2* | *Cy-3* | |
| Sidomulyo | MQ-136 | 5.65 | 2.85 | 2.84 | 14.66 | 9.76 | 16.12 | 17.58 |
| | MQ-135 | 1.59 | 6.12 | 2.28 | 11.61 | 13.77 | 21.88 | 16.01 |
| | MQ-2 | 1.94 | 2.37 | 4.94 | 9.07 | 10.81 | 17.09 | 10.74 |
| | MQ-3 | 1.28 | 4.12 | 7.05 | 12.16 | 22.45 | 12.54 | 12.23 |
| | MQ-6 | 1.28 | 3.16 | 2.98 | 14.59 | 15.66 | 17.15 | 9.34 |
| | MQ-7 | 1.79 | 1.69 | 4.05 | 8.65 | 17.52 | 7.61 | 11.05 |
| | MQ-8 | 3.48 | 3.06 | 2.03 | 16.67 | 22.72 | 14.54 | 16.26 |
| | MQ-9 | 4.03 | 1.91 | 1.95 | 16.39 | 8.77 | 11.44 | 15.05 |
| Bangsalsari | MQ-136 | 1.81 | 2.62 | 4.27 | 7.45 | 17.40 | 13.36 | 13.78 |
| | MQ-135 | 2.43 | 2.68 | 3.06 | 12.13 | 15.97 | 20.11 | 16.14 |
| | MQ-2 | 5.27 | 4.41 | 6.39 | 16.43 | 13.82 | 18.00 | 16.73 |
| | MQ-3 | 2.54 | 1.94 | 3.07 | 11.76 | 15.02 | 6.43 | 12.14 |
| | MQ-6 | 1.93 | 5.63 | 3.63 | 7.30 | 15.54 | 14.83 | 15.83 |
| | MQ-7 | 1.45 | 3.84 | 7.10 | 15.36 | 11.88 | 23.10 | 13.21 |
| | MQ-8 | 3.29 | 6.09 | 3.45 | 19.79 | 14.04 | 8.93 | 9.22 |
| | MQ-9 | 2.78 | 2.21 | 6.12 | 16.97 | 23.98 | 6.36 | 15.29 |

## CONCLUSION

The results show that Hemisphere chamber model-1 (He-1) is the most effective design for detecting and distinguishing Robusta coffee aroma. He-1 performs a faster response time and higher signal intensity, which allows it to distinguish the characteristics of the sensor response pattern between different varieties/origins. Gas array sensors in all variations of hemisphere chambers and ring chambers have good performance (%RSD <20%), while cylindrical chambers 2 and 3 had poor performance, with RSD values above 20%. The finding suggests that the sensor chamber's design can significantly affect the sensor response pattern. These results can help develop more accurate and efficient gas sensor technology *for coffee aroma detection.*

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