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Differentiation of Arabica Coffee from Several Regions and Roasting Condition by Detecting Released Gases using Electronic Food Nose

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Abstract

This study was aimed to identify the differentiation of Arabica coffee from West Java, East Java, West Nusa Tenggara and Bali using an electronic food nose. The analysis was conducted based on variations in temperature and roasting time to evaluate the effect of these parameters on coffee aroma characteristics. This research used an electronic nose device to detect volatile compounds quickly and accurately. The electronic nose was equipped with MQ-3, MQ-8, MQ-135, and MQ-136 sensors, able to detect alcohol, hexane, hydrogen, carbon dioxide, and hydrogen sulfide gas. Arabica coffee from various parts of Indonesia was roasted on three levels (light, medium, and dark). The results showed that variations in roasting temperature (220, 230, and 240 °C) and time (10, 13, and 17 min) significantly affected the volatile compounds' profile. The temperature and roasting time correlated proportionally to the hexane gas, CO_2, and alcohol produced. Conversely, the lower the temperature and the faster the roasting process, the higher H_2S gas was produced. Based on this, using an electronic nose effectively distinguishes the aroma characteristics of coffee based on differences in temperature and roasting time. This research contributes to helping improve the quality of Indonesian arabica coffee by understanding how temperature variation and roasting time length can be used to optimize the coffee production process and improve the coffee quality produced.

Keywords: Arabica coffee, volatile compounds, electronic nose, roasting temperature, roasting time, coffee aroma

INTRODUCTION

As one of the most widely traded and consumed commodities worldwide, coffee holds significant economic and cultural importance. Indonesia is the fourth largest coffee-producing countries in the world. According to data from the Central Bureau of Statistics (2023), Indonesia's coffee production in 2022 reached 794.8 thousand tons, reflecting a 1.1% increase from the previous year. Indonesia primarily produces three types of coffee: Arabica, Robusta, and Liberica. Among these, Arabica coffee is the most highly valued internationally, followed by Robusta and Liberica (Anggraini, 2024). Arabica coffee is known for its diverse flavor profile, higher acidity, and lower caffeine content compared to Robusta and Liberica (Asiah *et al.*, 2022). Flavor and aroma play a crucial role in coffee's sensory appeal, with its distinctive fragrance and slightly bitter taste contributing to an enjoyable drinking experience.

Indonesian Arabica coffee encompasses a diverse range of varieties cultivated across different regions, each exhibiting unique characteristics influenced by environmental factors, cultivation techniques, and post-harvest processing. Sebatubun & Pujiarini (2018) noted that Indonesia cultivates multiple coffee varieties, each differing in color, shape, and texture. Consequently, these factors contributed to high competitiveness of Indonesian Arabica coffee in the international market.

Roasting is one of the most critical stages in coffee processing, as it plays a key role in developing the coffee's flavor and aroma. Roasting triggers chemical transformations in the beans, leading to the formation of key volatile compounds that define coffee's characteristic taste and fragrance (Sutarsi *et al.*, 2016). Coffee roasting is generally categorized into three levels: light, medium, and dark, each distinguished by differences in roasting temperature and duration. According to Perangin-angin and Winarno (2024), roasting temperatures typically range from 60 °C to 250 °C, with roasting times varying based on the roasting system and machine type, usually lasting between 15 to 30 minutes. The roasting process significantly influences both the physical attributes and volatile compound composition of coffee beans. Fauzi *et al.* (2016) stated that roasting levels affect the color of coffee beans as well as the volatile compounds produced.

Traditionally, aroma detection relies on the human sense of smell. However, the human olfactory system is inherently subjective and can be influenced by physical conditions. Gas Chromatography-Mass Spectrometry (GC-MS) is a widely used tool for detecting volatile compounds, but it has several limitations, including long analysis times, high costs, and lack of portability (Wu *et al.*, 2024). Given these challenges, a simpler and more cost-effective alternative is the electronic nose (E-nose). Furthermore, E-nose offers highly relatable results to another analysis such as sensory, due to its design that mimics the human olfactory sense.

An electronic nose functions similarly to the human sense of smell, using an array of gas sensors to detect volatile compounds (Karakaya *et al.*, 2020). This tool offers several advantages, including affordability, ease of use, rapid analysis, high sensitivity, and portability (Sarno *et al.*, 2020). The E-nose has been successfully employed to differentiate products based on type, processing techniques, maturity level, and microbiological contamination (Swiglo & Chmielewski, 2017). It has also been used to detect meat and pork adulteration (Sarno *et al.*, 2020) and assess mango quality (Rahman *et al.*, 2024). In this study, an E-nose is used to distinguish coffee based on roasting level and origin. Its application enhances the differentiation of Arabica coffee varieties in Indonesia, providing valuable insights into how roasting conditions and regional factors influence coffee characteristics.

MATERIALS AND METHODS

Materials

The green bean used in this study was Arabica coffee obtained from 4 regions (Table 1) and processed by the full-washed method. This research utilizes an E-nose equipped with MQ-3, MQ-8, MQ-135, and MQ-136 sensors. The device measures 21 × 21 × 25 cm and operates with an electrical input of AC 220V, which is converted to

Table 1. The origin and processing method of Arabica coffee

Type of coffee	Origin of coffee place	Altitude	Processing method
West Java	Megamendung village, Megamendung sub-district, Bogor Regency	1.200 m a.s.l	Full Washed
Ijen (East Java)	Blawan village, Sempol sub-district, Bondowoso district	1200-1350 m a.s.l.	Full Washed
Mataram (West Nusa Tenggara)	Sajang village, Sembalun sub-district, East Lombok district	800 m a.s.l.	Full Washed
Bali	Landih village, Kintamani sub-district, Bangli district	1.200-1.700 m a.s.l.	Full Washed

DC 5V 10A. The system includes an Arduino Mega 2560, a 9 × 9 cm 12V fan, and a laptop. The software used for data processing is eFNose V.3, developed using the Visual Basic.NET programming language.

The Arabica coffee used in this study is processed using the full-washed method. This process involves washing the peeled coffee beans, soaking them in a water tank for approximately 18 hours for fermentation, and then drying them until the moisture content is reduced to less than 12% (Sunarharum *et al.*, 2018).

Sample Preparation

The coffee beans (West Java, Ijen, Mataram, and Bali) were sorted and roasted at three variations of roasting levels, namely light (220 °C for 10 minutes), medium (230 °C for 13 minutes), and dark (240 °C for 17 minutes). After roasting, the coffee beans were ground using a grinder machine to produce coffee powder with a particle size of 60 mesh. A 6 g sample of the ground coffee was then placed into a 20 mL vial for further analysis.

E-nose Aanalysis

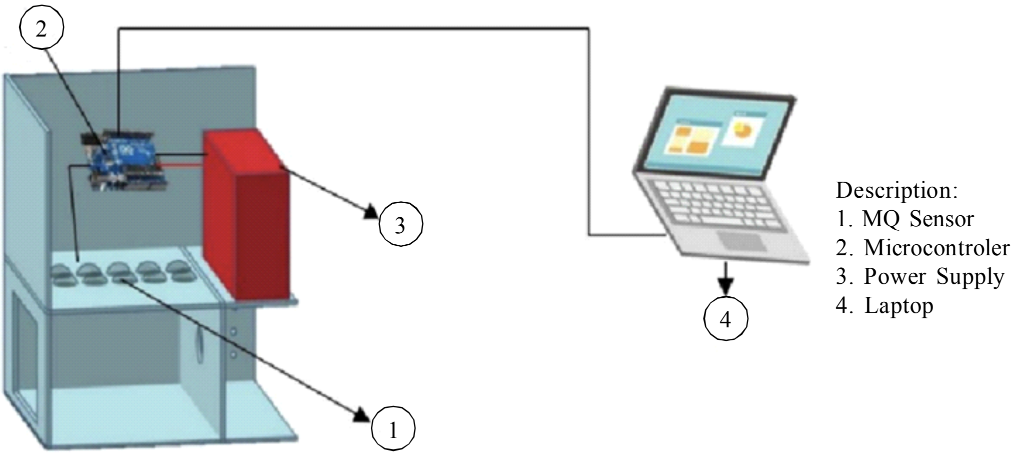
The roasted coffee was then aroma-identified using an electronic nose (E-nose) device. The E-nose tool design can be seen in Figure 1.

The sensor room contains MQ-3, MQ-8, MQ-135, and MQ-136 sensors and a power supply. The four sensors are connected to an Arduino mega 2560 and a laptop, and the process is completed with e-Food Nose V.3 data processing software. The sensor list and the gas detected can be seen in Table 2. The electronic nose device is designed as a block measuring 21 × 21 × 25 cm and consists of two compartments: the sample chamber and the sensor chamber. The sample chamber holds the sample during aroma testing and includes an exhaust fan that removes residual gases after testing.

The device is equipped with four sensors connected to an Arduino Mega 2560 and a laptop, with data processing managed by eF-Nose V.3 software. According to Tan *et al.* (2019), an electronic nose system typically consists of an array of gas sensors, reaction chambers, valves, air pumps for sampling and cleaning, control units, and data acquisition systems. Additionally, the E-nose features a data acquisition system for signal processing and software that utilizes multivariate data processing techniques to recognize and classify food based on its characteristic odor (Dymerski *et al.*, 2011, in Swiglo & Chmielewski, 2017).

Statistical Analysis

The average test result data were analyzed using Principal Component Analysis (PCA), a multivariate data analysis method,



Description:
1. MQ Sensor
2. Microcontroler
3. Power Supply
4. Laptop

Figure 1. Electronic nose tool design

Table 2. List of sensors and gases detected

Sensors	Type of gas detected
MQ-3	Alcohol, Hexane,
MQ-8	Hydrogen (H_2)
MQ-135	Carbon dioxide (CO_2),
MQ-136	Hydrogen sulfide (H_2S)

with SIMCA Series 14 software (Sartorius AG, Germany).

RESULTS AND DISSCUSION

Coffee Aroma

The characteristics of Arabica coffee's volatile compounds are influenced by several factors, including altitude, environmental conditions, and the roasting process. According to Maryuna *et al.* (2022), Arabica coffee thrives at altitudes above 1,000 meters above sea level. Higher altitudes generally produce higher-quality coffee due to favorable environmental conditions, such as cooler temperatures and higher rainfall. These factors influence the metabolic processes of coffee plants, ultimately affecting the volatile compounds responsible for coffee's aroma and flavor (Cahyadi *et al.*, 2021).

Volatile compounds in Arabica coffee are released during the roasting process, which is the most critical stage in coffee bean processing. Roasting plays a key role in developing coffee's characteristic aroma and flavor profile. During roasting, a distinctive aroma and flavor are produced through the Maillard reaction, which occurs between carbonyl groups and amino acids. The Maillard reaction is a non-enzymatic browning process that generates complex high-molecular-weight compounds, along with several volatile compounds that contribute to coffee's unique sensory characteristics. Figure 2 presents the average Arabica coffee aroma test results using an electronic nose.

Coffee aroma detection is conducted using an E-nose equipped with MQ-3, MQ-8, MQ-135, and MQ-136 sensors. According to the Hanwei Electronics Gas Sensor Datasheet (2014), these sensors have the following detection capabilities: MQ-3: Detects alcohol, hexane, benzene, CH_2, LPG, and CO gases; MQ-8: Detects hydrogen (H_2), LPG, CH_2, CO, and alcohol gases; MQ-135: Detects carbon dioxide (CO_2), NH_2, NO_2, alcohol, benzene, and smoke; MQ-136: Detects hydrogen sulfide (H_2S), CO, and NH_2 gases. Due to differences in sensor sensitivity, the detected aroma profile varies depending on the volatile compounds present. A diagram illustrating the results of Arabica coffee aroma detection using the E-nose, based on variations in roasting temperature and time, is shown in Figure 2.

The analysis revealed that H_2 gas values decreased as the roasting level progressed. The H_2 gas content in Arabica coffee at light, medium, and dark roasting levels was 167.37 parts per million (ppm), 163.48 ppm, and 160.68 ppm, respectively. For Arabica Kintamani Bali, the values were 152.68 ppm, 149.36 ppm, and 145.76 ppm, while for Mataram Arabica coffee, they were 191.62 ppm, 172.78 ppm, and 169.22 ppm. Similarly, West Java Arabica exhibited H_2 gas values of 182.94 ppm, 166.8 ppm, and 149.51 ppm at the corresponding roasting levels.

The decrease in H_2 gas during roasting can be attributed to thermal processes that break down volatile compounds containing hydrogen, such as phenols and chlorogenic acid. As roasting temperature and duration increase, these compounds undergo more extensive decomposition. Herawati *et al.* (2018) explained that roasting alters the bioactive characteristics of coffee by increasing solute components, reducing chlorogenic acid and total phenol content, and enhancing melanoidin compounds. This is further supported by Divis *et al.* (2019) and Kamiyama *et al.* (2015), who found that prolonged roasting

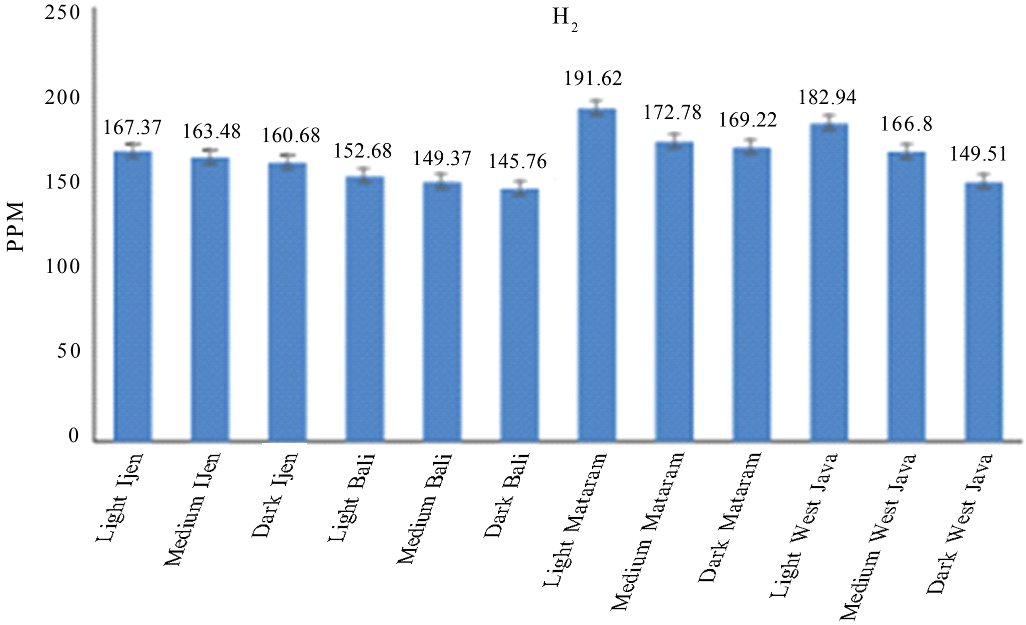


Figure 2. H_2 gas concentration in Arabica Ijen, Bali, Mataram, and West Java coffee based on different roasting levels using electronic nose (E-nose)

at high temperatures leads to the degradation of chlorogenic and caffeic acids. During roasting, chlorogenic acid—the primary phenolic fraction in coffee beans—is hydrolyzed into various aromatic metabolites, including salicylic acid (Król *et al.*, 2020).

The altitude at which Arabica coffee is grown also affects H_2 gas production. Research data indicate that Arabica coffee from Ijen (1,200–1,350 m asl.), Bali (1,200–1,700 m asl.), and West Java (1,200 m asl.) exhibits lower H_2 gas values compared to Arabica coffee from Mataram (800 m asl.). These results suggest that higher-altitude coffee produces less H_2 gas, likely due to the increased presence of complex precursor compounds, such as chlorogenic acid, in coffee grown at higher elevations. According to Mintesnot & Dechassa (2018), coffee cultivated in high-altitude regions contains higher concentrations of chlorogenic acid. The cooler temperatures at these elevations slow down the ripening process, allowing for the accumulation of secondary metabolites, including chlorogenic acid. Consequently, when high-altitude Arabica coffee is roasted, it releases less hydrogen gas. The composition of these biochemical compounds is influenced by environmental factors, including altitude and genotype (Cheng *et al.*, 2016).

As shown in Figure 3, the hexane concentration in Arabica coffee increases as the roasting level progresses. The hexane gas concentrations obtained from Ijen Arabica coffee at light, medium, and dark roasting levels were 312.41 ppm, 324.54 ppm, and 530.7 ppm, respectively. For Kintamani Bali Arabica, the values were 288.33 ppm, 524.01 ppm, and 532.68 ppm, while for Mataram Arabica, they were 228.16 ppm, 424.9 ppm, and 582.24 ppm. West Java Arabica exhibited hexane concentrations of 510.68 ppm, 770 ppm, and 1,275.4 ppm at the corresponding roasting levels.

Based on these data, it is evident that higher roasting temperatures and longer roasting durations result in increased hexane gas production. Hexane is a hydrocarbon compound classified within the alkane group (Fransiska *et al.*, 2021). Certain alkane compounds, such as 6,10,14-trimethyl-dodecane, 4-methyl-hexadecane, and tetradecane, contribute to coffee's aroma, imparting waxy, fresh oily, and jasmine-like notes (Dias *et al.*, 2025). These compounds are primarily formed due to lipid degradation in coffee beans during roasting, a process that intensifies with prolonged roasting times and elevated temperatures.

Williamson & Hatzakis (2019) explained that during roasting, coffee beans undergo morphological changes, leading to oleosome damage and lipid migration to the surface. Additionally, Hu *et al.* (2020) used scanning electron microscopy (SEM) to observe pore-like oil droplets along the edges of medium-roasted coffee beans, with a noticeable increase in oily substances on the surface of dark-roasted coffee beans. This phenomenon occurs because higher roasting temperatures increase the kinetic energy of lipid molecules, weakening chemical bonds and leading to the formation of simpler compounds, including hexane.

Differences in growing location and altitude also influence hexane gas concentrations. Study results indicate that Arabica coffee from high-altitude regions, such as West Java (1,200 meters above sea level, m asl.), Bali (1,200–1,700 m asl.), and Ijen (1,200–1,350 m asl.), tends to produce higher hexane concentrations at the dark roast level compared to Arabica coffee from Mataram (800 m asl.).

According to Supriadi *et al.* (2015), higher-altitude regions are characterized by lower air temperatures, higher rainfall, and more fertile soil. These conditions slow coffee plant growth, allowing the beans to develop a complex chemical composition. Slower-growing coffee beans typically contain a

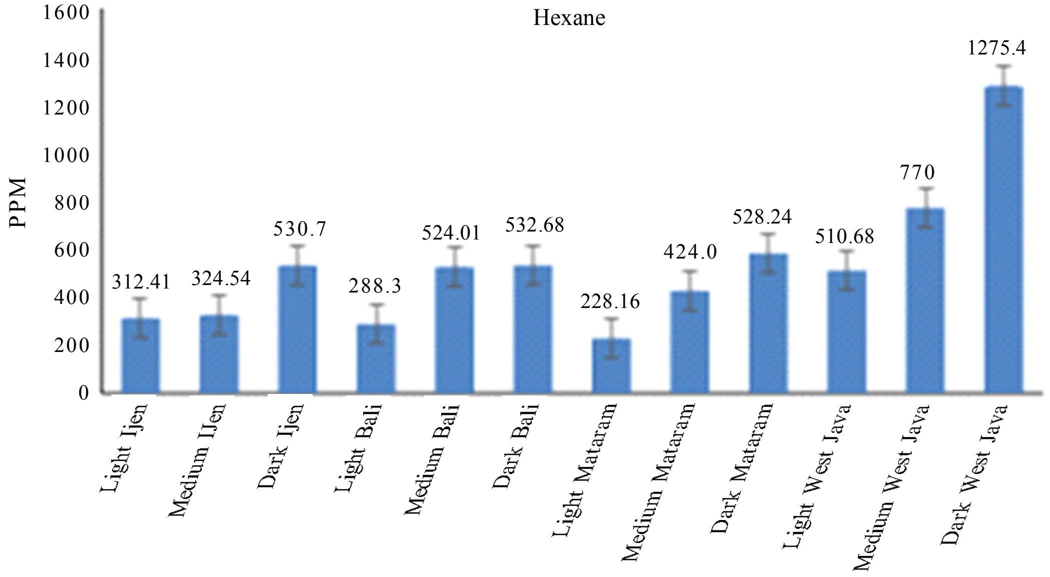


Figure 3. Hexane gas concentration in Arabica Ijen, Bali, Mataram, and West Java coffee based on different roasting levels using electronic nose

richer profile of volatile compounds and fewer simple hydrocarbons such as alkanes. As a result, Arabica coffee grown at higher altitudes generally produces higher hexane concentrations than coffee cultivated at lower elevations.

As shown in Figure 4, the CO_2 concentration in Arabica coffee increases as the roasting level progresses. The CO_2 gas concentrations obtained from Ijen Arabica coffee at light, medium, and dark roasting levels were 821.78 ppm, 1,080.52 ppm, and 1,118.45 ppm, respectively. For Balinese Kintamani Arabica, the values were 863.57 ppm, 891.49 ppm, and 911.67 ppm, while for Mataram Arabica, they were 887.89 ppm, 930.64 ppm, and 1,034.74 ppm. West Java Arabica exhibited CO_2 concentrations of 802.77 ppm, 1,074.62 ppm, and 1,533.51 ppm at the corresponding roasting levels.

The data indicate that higher roasting temperatures and longer roasting times result in increased CO_2 production in Arabica coffee. A significant rise in CO_2 levels was observed in Ijen, Mataram, and West Java Arabica coffee samples, particularly at the dark roast level. This suggests that longer and hotter roasting intensifies CO_2 release.

Arabica coffee beans naturally contain various organic compounds that contribute to their distinctive taste and aroma during roasting. According to Ciptadi and Nasution (1985) and Kaswindi *et al.* (2017), CO_2 formation occurs due to oxidation processes, which also contribute to coffee's characteristic aroma. During roasting, gases—primarily CO_2—accumulate within the pores of coffee bean cells, causing them to expand and swell.

The altitude at which Arabica coffee is grown also influences CO_2 concentration. Although the study results did not show significant differences, coffee samples from Ijen (1,200–1,350 m asl.), Bali (1,200–1,700 m asl.), and West Java (1,200 m asl.) at the dark roast level exhibited CO_2 concentrations exceeding 1,000 ppm. This may be due to the environmental conditions at higher elevations

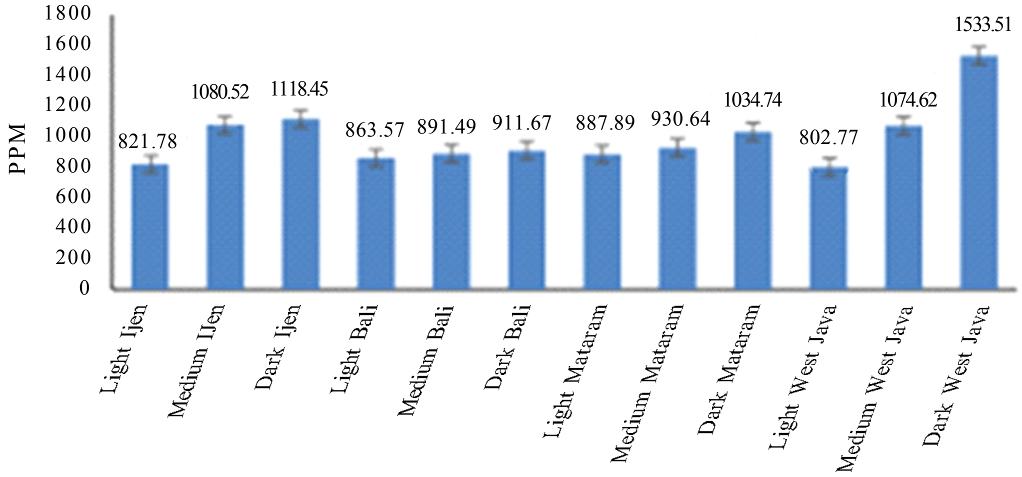


Figure 4. CO_2 gas concentration in Arabica Ijen, Bali, Mataram, and West Java coffee based on different roasting levels using electronic nose

(above 1,200 m asl.), where lower temperatures and atmospheric pressure slow plant metabolism, leading to a greater accumulation of precursor compounds (Tolessa *et al.,* 2017).

Additionally, higher roasting temperatures and longer roasting times further increase CO_2 production. According to Diviš *et al.* (2019), roasting coffee at medium and dark roast levels promotes the formation of various organic acids, particularly acetic and formic acids. These volatile compounds contain CO_2 and contribute to the acidic, bitter, and vinegar-like aromas characteristic of roasted coffee (Galarza & Figueroa, 2022).

Figure 5 presents the average test results of the electronic nose using the MQ-3 sensor to detect alcohol gas. The bar chart indicates that alcohol concentration in Arabica coffee increases as the roasting level progresses.

The data demonstrate that longer roasting durations and higher roasting temperatures lead to increased alcohol gas production. This is due to the intensification of the Maillard reaction and carbohydrate decomposition, which results in the formation of higher alcohol compound levels.

According to Sari *et al.* (2023), the primary reactions responsible for alcohol compound formation in coffee include thermal degradation and Maillard reactions. During thermal degradation, complex components in raw coffee beans break down into simpler compounds, including alcohol. The Maillard reaction, which involves the interaction between amino acids and sugars, further contributes to alcohol formation, producing sweet, fruity, floral, and tropical/exotic aromas.

The altitude at which Arabica coffee is grown significantly influences alcohol gas concentration. Research shows that Arabica coffee from Ijen (1,200–1,350 m asl.), Bali (1,200–1,700 m asl.), and West Java (1,200 m asl.) exhibits higher alcohol gas levels compared to Arabica from Mataram (800 m asl.). This suggests that coffee grown above 1,000 m produces more alcohol gas than coffee cultivated at lower altitudes.

Arabica coffee cultivated at higher altitudes tends to have higher levels of organic

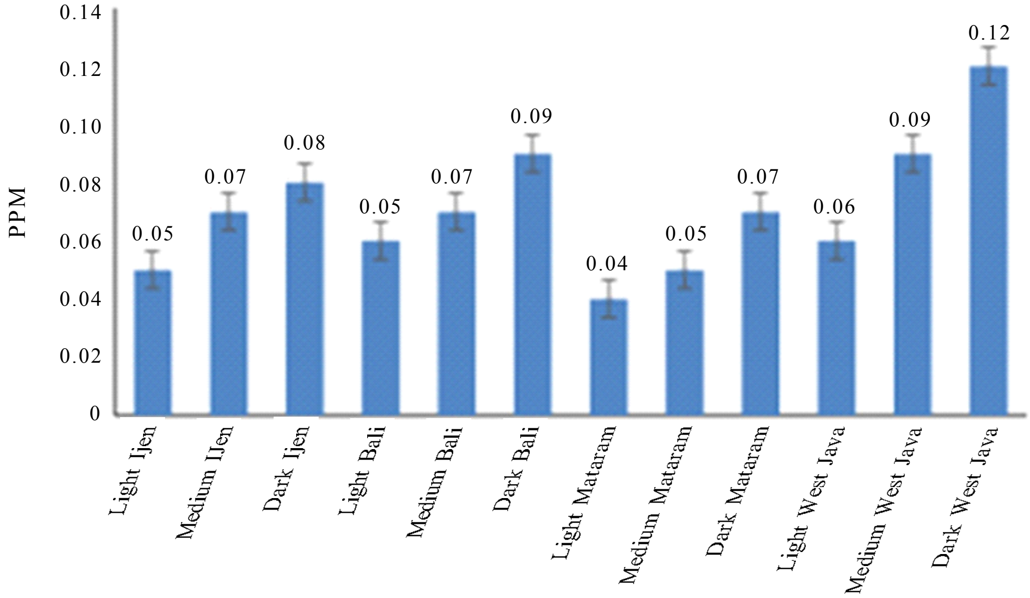


Figure 5. Alcohol gas concentration in Arabica Ijen, Bali, Mataram, and West Java coffee based on different roasting levels using electronic nose

acids and polysaccharides due to slower metabolism. Purba *et al.* (2020) noted that lower temperatures extend the coffee bean maturation period, allowing a greater accumulation of chemical compounds. In contrast, Arabica coffee from Mataram (800 m asl.), grown in warmer conditions, undergoes faster metabolism, reducing the accumulation of precursor compounds necessary for alcohol formation.

According to Tolessa *et al.* (2017), cooler temperatures at higher elevations slow the ripening process, giving beans more time to absorb nutrients and develop complex volatile compounds, including alcohol-related compounds. This results in a richer chemical profile and more intricate aroma compared to coffee grown at lower altitudes.

Furthermore, Urugo *et al.* (2024) found that Arabica coffee grown at higher elevations, where temperatures are lower and rainfall and humidity are higher, is dominated by volatile alcohol compounds such as 1-hexanol, 1-octan-3-ol, and benzyl alcohol. These compounds contribute to floral, fruity, and green aromas, further enhancing the coffee's sensory profile.

Figure 6 shows the average test results of electronic food nose based on MQ-136 sensor to detect H_2S gas. Based on the bar chart, the results of H_2S gas data on Arabica coffee decrease as the roasting level progresses. The following are the results of H_2S gas data obtained from Ijen Arabica coffee in order of 25.63 ppm; 22.44 ppm; and 16.7 ppm, Kintamani Bali Arabica of 18.98 ppm; 17.76 ppm; and 13.25 ppm, Mataram Arabica of 26.47 ppm; 22.85 ppm; and 17.3 ppm, West Java Arabica 24.42 ppm; 23.22 ppm; and 19.33 ppm. Based on the data obtained, it can be explained that the longer the time and the higher the roasting temperature, the lower the H_2S gas produced. H_2S gas is classified as an acid gas (Fatimura *et al.*, 2018). Based on the data obtained, it can be explained that the longer the time and the higher the roasting temperature, the lower the H_2S gas produced. According to

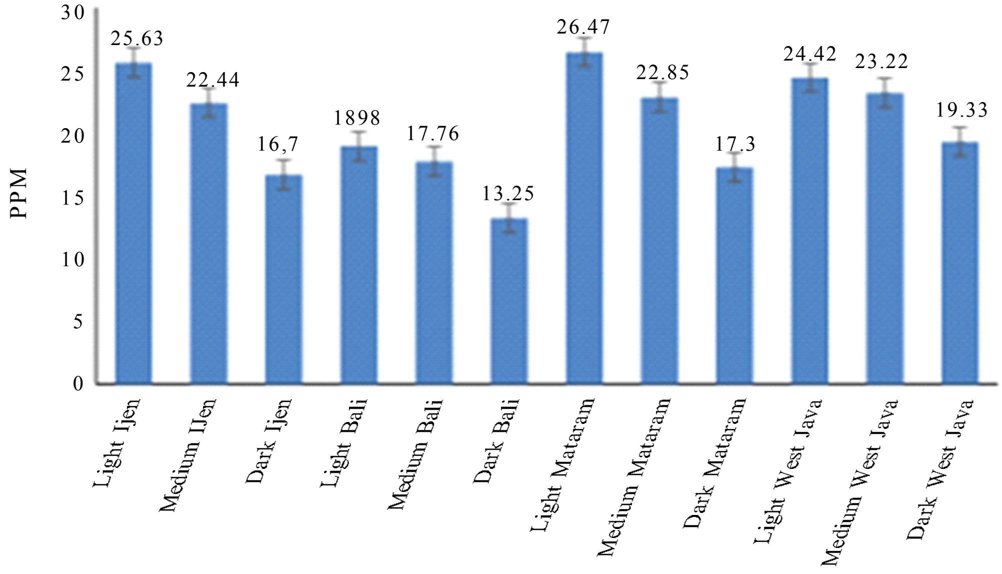


Figure 6. H_2S gas concentration in Arabica Ijen, Bali, Mataram, and West Java coffee based on different roasting levels using E-nose

Pamungkas *et al.* (2021), this can occur because there is a decrease in total acid due to aliphatic acid compounds decomposed into carbon dioxide (CO_2) gas along with the increase in temperature and length of the roasting process. Lorensia *et al.* (2023) stated that the higher the roasting temperature, the lower the acidity level of coffee. The duration of roasting time also affects the acidity level of coffee, although the effect is not very significant. However, the research of Lorensia *et al.* (2023) showed that the longer the duration of roasting time, the lower the acidity of the coffee.

The concentration of H_2S gas in Arabica coffee is influenced by the altitude at which it is grown. Coffee cultivated at lower altitudes, such as in Mataram (800 meters above sea level, m asl.) and West Java (1,200 m asl.), has higher H_2S levels compared to coffee from Ijen (1,200–1,350 m asl.) and Bali (1,200–1,700 m asl.). This is because coffee grown at lower elevations tends to grow faster, leading to a higher accumulation of sulfur-containing amino acids (methionine and cysteine), which later decompose into H_2S during roasting.

Although the initial H_2S levels are high, they decrease over time and with increasing roasting temperature, as the compound is volatile and reacts with other substances. Sulfur compounds in coffee, such as 2-furfurylthiol, contribute to its characteristic roasty, smoky, and burnt-sugar aroma.

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) is a multivariate statistical method that linearly reshapes a set of original variables into fewer, uncorrelated variables. The resulting variables can represent information from the original variables more efficiently (Radiarta *et al.*, 2013 in Wangge, 2021). The main goal is to explain as much of the original data variance as possible with a few principal components called factors. The Bi-Plot diagram of PCA of Arabica Coffee Volatile Components can be seen in Figure 7.

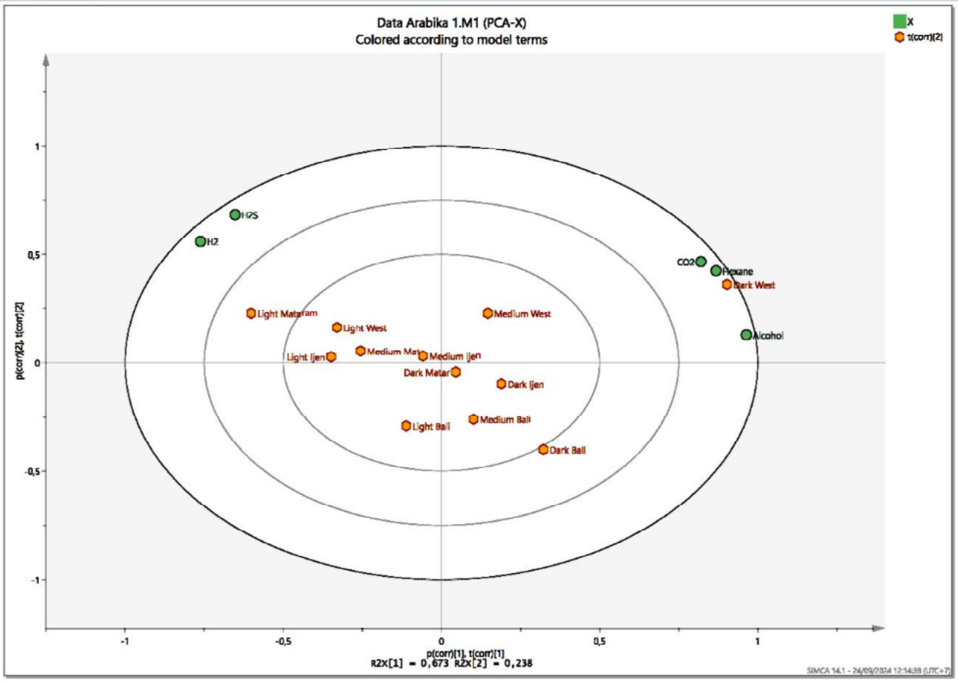


Figure 7. PCA Bi-Plot diagram of volatile components of Arabica Coffee Ijen, Kintamani Bali, Mataram, and West Java based on different roasting levels

The Bi-Plot graph shows that Arabica coffee from West Java dark, Bali dark, and Ijen dark has high levels of hexane, CO_2, and alcohol gases. The hexane content is influenced by the altitude at which the coffee is grown, with coffee grown below 1,200 m asl. tending to have lower hexane levels due to faster metabolism.

The highest alcohol concentration is found in Arabica coffee from West Java dark, Bali dark, and Ijen dark. The longer and hotter the roasting process, the more alcohol gases are produced, particularly furfuryl alcohol acetate, which gives caramel and smoky aromas. Arabica coffee grown above 1,200 m asl. tends to have higher alcohol content due to slower ripening, allowing the formation of complex compounds such as 1-hexanol and benzyl alcohol.

CO_2 gas is also produced in greater amounts with longer roasting. Coffee grown above 1,200 m asl. contains more precursor compounds, leading to higher CO_2 production during roasting. Meanwhile, Arabica coffee from Mataram light contains higher levels of H_2S and H_2 gases, which contribute to sharp, acidic, and slightly fruity aromas. Coffee grown at lower altitudes produces more of these gases due to faster growth, which increases nitrogen and sulfur content—key precursors for H_2 and H_2S during roasting. In conclusion, altitude and roasting levels significantly affect the gas composition in Arabica coffee.

CONCLUSION

Arabica coffee samples from West Java (dark roast), Bali (dark roast), and Ijen (dark roast) exhibit high levels of hexane, CO_2, and alcohol gases, while Arabica coffee from Mataram tends to have lower hexane concentrations.

Alcohol and CO_2 concentration increases with roasting temperature and duration and is also influenced by an altitude. It means that gas variations can be used as markers to differentiate coffee based on its origin and roasting level. This study demonstrates that the Electronic Food Nose (eF-Nose) effectively distinguishes Arabica coffee from Ijen, Mataram, West Java, and Bali across different roasting levels—light, medium, and dark. The variations in H_2 , hexane, CO_2 , alcohol, and H_2S concentrations in samples with different roasting intensities serve as key indicators for identifying differences in coffee origin and roasting conditions.

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