

Enhancing robusta coffee quality through natural fermentation to resemble the aroma and flavor of arabica

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ABSTRACT

This research aims to enhance the flavor and aroma of robusta coffee through fermentation processes, aiming to achieve characteristics similar to arabica coffee. The methods employed in this study involve five treatments, each repeated three times. The treatments include: KP = non-fermented coffee, NA = natural anaerobic, KW = wine, FW = full wash, and KH = honey. The experimental design applied is a completely randomized design without factorial arrangement. The observed parameters include caffeine content, pH, cupping score, and Fourier Transform Infrared Spectroscopy (FTIR). The results indicate a decrease in caffeine content, and pH in robusta coffee subjected to fermentation processes, and increased cupping scores. FTIR analysis also demonstrated an increase in absorbance values at wave numbers associated with functional groups related to caffeine, aroma, flavor, and texture of the coffee. Thus, it can be concluded that fermented robusta coffee approaches the characteristics of arabica coffee grade based on standards for caffeine content, pH, and cupping score.

Key words: Aroma; cupping score; fermentation; FTIR; robusta coffee.

1 INTRODUCTION

Coffee is one of the most sought-after agricultural commodities worldwide and has been consumed for over 1,000 years. Coffee drinks are the most widely consumed beverage globally, with more than 2.4 billion cups consumed daily (Davis et al., 2019; Pancsira, 2022). Procida et al. (2020) explain that there are two well-known coffee varieties: arabica and robusta. The National Coffee Association (2020) indicates that arabica coffee is preferred in international markets to robusta coffee. Zainuri et al. (2023) add that the international market's preference for arabica coffee is due to its lower caffeine content and pH, as well as its slightly acidic flavor. In contrast, robusta coffee has higher caffeine content and pH, with a taste that tends to be bitter. Olechno et al. (2021) reveal that robusta coffee contains a higher caffeine level than arabica coffee, with caffeine content ranging from approximately 1.60% to 2.4% for robusta and 0.9% to 1.20% for arabica.

In 2022, Indonesia's coffee production reached 794.8 thousand tons, with South Sumatra being the largest coffee-producing province in the country, contributing 198 thousand tons or approximately 24.99% of the national total (Badan Pusat Statistik, 2023). To enhance the competitiveness of robusta coffee in international markets, two scientific approaches can be applied: cultivation and processing methods for coffee beans.

The processing methods of coffee beans significantly influence the flavor, aroma, and functional properties of coffee, in addition to the variety. Ferreira et al. (2023) explain

that coffee processing through fermentation methods has been implemented to develop new sensory profiles and enhance final scores in coffees processed using different methods, with the primary goal of achieving a better market position and increasing appreciation for the final product. Fmalinda et al. (2019) reveal that processing with fermentation using civet feces inoculum can improve the quality of arabica coffee beans. Kim et al. (2024) describe that robusta coffee processed through fermentation using *L. plantarum* bacteria can reduce caffeine levels from 6763.14 ppm to 6132.26 ppm.

The success of coffee processing through fermentation methods to produce high-quality coffee equivalent to arabica grade is influenced by several key factors. These factors include fermentation techniques, moisture levels and drying processes, fermentation duration, post-harvest handling, and environmental conditions. In South Sumatra Province, various natural fermentation methods are applied in the processing of robusta coffee beans, such as natural anaerobic, honey, wine, and full wash. Each of these methods has unique principles in processes such as the use of pulpers, fermentation duration, fermentation techniques, and drying procedures. The application of these methods results in coffee with flavors and aromas that appeal to consumers. However, scientific research on coffee produced from these methods remains limited, particularly regarding their effects on changes in caffeine levels, pH, cupping score evaluations, and FTIR analysis to identify compound changes in coffee related to flavor and aroma.

2 MATERIAL AND METHODS

2.1 Equipment and Materials

The equipment used includes a pH meter, UV-Vis spectrophotometer, cupping bowls, spoons, scales, thermometer, timer, and FTIR spectrometer (Fourier Transform Infrared Spectroscopy). The materials used are ripe robusta coffee beans sourced from Tanjung Menang Village, Pagaralam City, standard caffeine, chloroform (CHCl_3), calcium carbonate (CaCO_3), 96% ethanol, and potassium bromide (KBr).

2.2 Experimental design

The experimental design in this study employs a completely randomized block design without factorial arrangement, featuring five treatments, each replicated three times. The treatments consist of KP = non-fermented coffee, NA = natural anaerobic, KH = honey, FW = full wash, and WK = wine. The parameters observed include: 1) pH (Association of Official Analytical Chemists - AOAC, 2005), 2) caffeine content (SNI 01-3542-2004), 3) cupping score (cupping test score based on the criteria from the Specialty Coffee Association of America (SCAA), and 4) FTIR testing (Ribeiro da Cunha; Fonseca; Calado, 2020). The data collected will be analyzed using analysis of variance through the SAS for Windows 9 program, and treatments that show significant effects will be further tested using the honest significant difference (HSD) test at a significance level of 5%.

2.3 Methodology

The coffee processing methods in this research are divided into two types: non-fermented coffee and fermented coffee. The non-fermented coffee process is carried out using traditional methods commonly employed by local communities. The detailed procedure for processing coffee is as follows:

- Ripe robusta coffee cherries with a sugar content of 30%, measured using a refractometer, are harvested;
- The coffee cherries are sorted randomly, and then soaked in water with a total dissolved solid (TDS) of 300 mg/liter and a pH of 7. The cherries that sink are collected and drained;
- The cherries are dried under sunlight on raised platforms covered with plastic until the moisture content reaches 12.5%;
- The dried coffee cherries are rested in sacks for one week, followed by hulling to remove the outer skin using a huller, resulting in green coffee beans;
- The green beans are roasted to a medium to dark level and then ground to an 80 mesh size;
- The ground robusta coffee is ready for analysis.

The coffee processing methods using fermentation include natural anaerobic, wine, full wash, and honey processes,

consisting of several stages: harvesting, random sorting, peeling of coffee cherries, fermentation, drying, resting, hulling of dried coffee cherries, roasting, and packaging. The differences among the four fermentation methods lie in the stages of peeling the ripe coffee cherries, fermentation, and drying, while the other stages remain the same as in non-fermented coffee processing. The detailed procedure for fermentation processing is as follows:

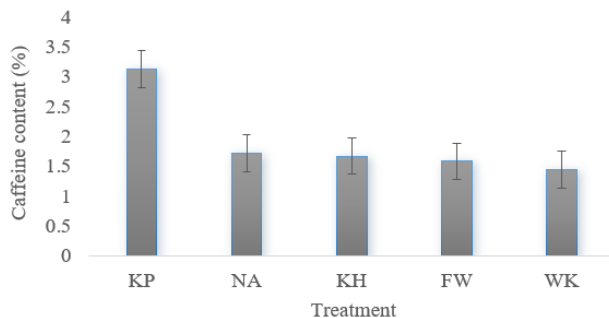
- Ripe robusta coffee cherries with a sugar content of 30%, measured using a refractometer, are harvested;
- The cherries are sorted randomly, and then soaked in water with a Total Dissolved Solid (TDS) of 300 mg/liter and a pH of 7. The cherries that sink are collected and drained;
- The natural anaerobic fermentation of coffee: the coffee cherries are placed in a sealed HDPE plastic drum equipped with an S-Shape Double Bubble Airlock to reduce the oxygen levels in the drum to achieve a vacuum condition. The fermentation process lasts for 24 hours at a temperature ranging from 21 to 26°C. For wine fermentation of coffee: The coffee cherries are placed in a tightly sealed HDPE plastic drum equipped with an S-Shape Double Bubble Airlock to reduce the oxygen levels in the drum, achieving a vacuum condition. The fermentation of the coffee cherries is conducted over a period of 28 days at a temperature ranging from 21 to 26°C. Every 7 days, the coffee cherries are dried under sunlight for 3 to 4 hours. For full wash fermentation of coffee: The drained coffee cherries are hulled using a pulper. Subsequently, the fermentation process is conducted by soaking the coffee cherries in water for 36 hours, during which the water is changed every 10 hours. For honey fermentation of coffee: The drained coffee cherries are hulled using a pulper. Following this, the fermentation process is carried out by placing the coffee cherries in a tightly sealed HDPE plastic drum equipped with an S-Shape Double Bubble Airlock to reduce the oxygen levels in the drum, achieving a vacuum condition. The fermentation process lasts for 24 hours at a temperature ranging from 21 to 26°C;
- The coffee beans that have undergone the fermentation process are dried by sun exposure. This process is carried out using raised platforms covered with plastic at a temperature of 50°C and a relative humidity (RH) of 32%. Drying continues until the moisture content of the coffee beans reaches 12.5%. For honey fermentation of coffee: The drying process is conducted in two phases. In the first phase, the coffee cherries are dried under sunlight for three days. During this process, the cherries are covered with opaque plastic and are not turned. The second phase of drying is carried out in the same manner as the drying process for other fermented coffee beans;
- The dried coffee cherries are stored in sacks for one week, after which a huller is used to remove the

skin of the coffee cherries, resulting in green coffee beans;

- f) The green coffee beans are roasted to a medium to dark level and then ground to a particle size of 80 mesh; and
- g) The ground robusta coffee is ready for analysis.

3 RESULTS

The caffeine content of non-fermented and fermented robusta coffee produced in this study ranges from 1.44% to 3.13%. The detailed caffeine levels in the coffee are presented in **Figure 1**.



Discription:

KP = non-fermented coffee FW = fullwash
 NA = Natural anaerob WK= wine
 KH = Honey

Figure 1: The caffeine content of non-fermented and fermented robusta coffee (natural anaerobic, full wash, honey, and wine).

The analysis of variance (ANOVA) indicates that the fermentation process of robusta coffee has a significant effect on the resulting caffeine content. The results of the 5% Honest Significant Difference (HSD) test show the impact of the fermentation process on the caffeine content and pH of robusta coffee, as presented in **Table 1**.

Table 1: The results of the Honest Significant Difference (HSD) test at a 5% for the effect of fermentation process on caffeine content and pH of robusta coffee.

Treatment	Caffeine content (%)	pH
Non-fermented coffee (KP)	3.14+0.006a	5.44+0.02a
Natural anaerob (NA)	1.72+0.017b	5.13+0.02b
Honey (KH)	1.68+0.013c	5.03+0.01c
Fullwash (FW)	1.58+0.01d	5.12+0.01b
Wine (WK)	1.44+0.006e	4.97+0.02d

Description: Numbers followed by the same letter in the same column indicate no significant difference.

The pH values of fermented and non-fermented robusta coffee produced in this study range from 4.95 to 5.46. The detailed pH levels of the coffee are presented in **Figure 2**.

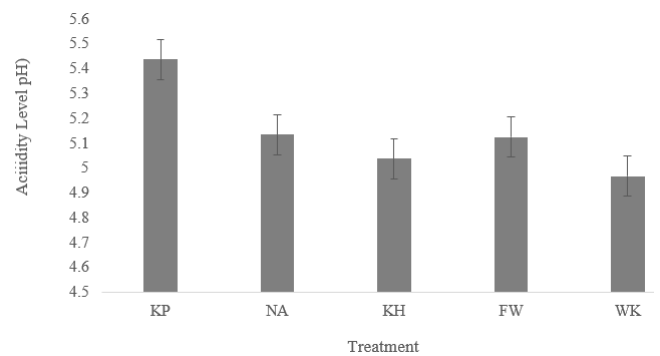


Figure 2: The pH of non-fermented and fermented robusta coffee (natural anaerobic, full wash, honey, and wine).

The assessment of the cupping score for the quality of robusta coffee flavor is derived from the average sensory evaluations of fragrance/aroma, flavor, aftertaste, body, uniformity, balance, clean cup, and overall quality for each treatment. The average cupping scores obtained are presented in **Table 2**.

Table 2: Average cupping Scores of fermented and non-fermented robusta coffee.

Attributes	Cupping score test coffee				
	Non-fermented robusta coffee	Fermented robusta coffee			
		Natural Anaerob (NA)	Honey (HY)	Fullwash (FW)	Wine (WK)
Aroma	7.15	8.13	7.88	7.85	8.00
Flavor	7.05	8.25	7.88	7.75	8.00
After taste	7.00	8.25	7.88	7.85	7.25
Acidity	7.00	8.25	7.94	7.70	8.00
Body	7.15	8.00	7.88	7.90	7.50
Uniformity	10.00	10.00	10.00	10.00	10.00
Balance	7.00	8.19	7.81	7.85	8.00
Clean Cup	8.00	10.00	10	10.00	10.00
Sweetness	7.15	8.19	7.88	7.90	8.25
Overall	7.00	8.13	7.94	7.85	8.00
Defect	0.00	0.00	0.00	0.00	0.00
Final score	74.50	85.39	83.09	82.65	83.00

4 DISCUSSION

Fourier transform infrared spectroscopy (FTIR) testing is highly useful for comparing robusta coffee produced through fermentation with that of non-fermented coffee, as it provides a specific overview of the changes in chemical bonds and flavor compounds that occur during the fermentation process. FTIR also detects changes in the intensity of functional groups associated with aroma by analyzing the infrared spectra generated from coffee samples. The FTIR spectra obtained from this study can be seen in **Figure 3**.

The results of the post-hoc test (Table 1) indicate that the caffeine content in fermented robusta coffee is lower compared to non-fermented robusta coffee. It is known that coffee beans contain proteins, which are key components alongside caffeine. Caffeine can bind to active sites or other regions on proteins through non-covalent interactions such as hydrogen bonds, van der Waals forces, and electrostatic

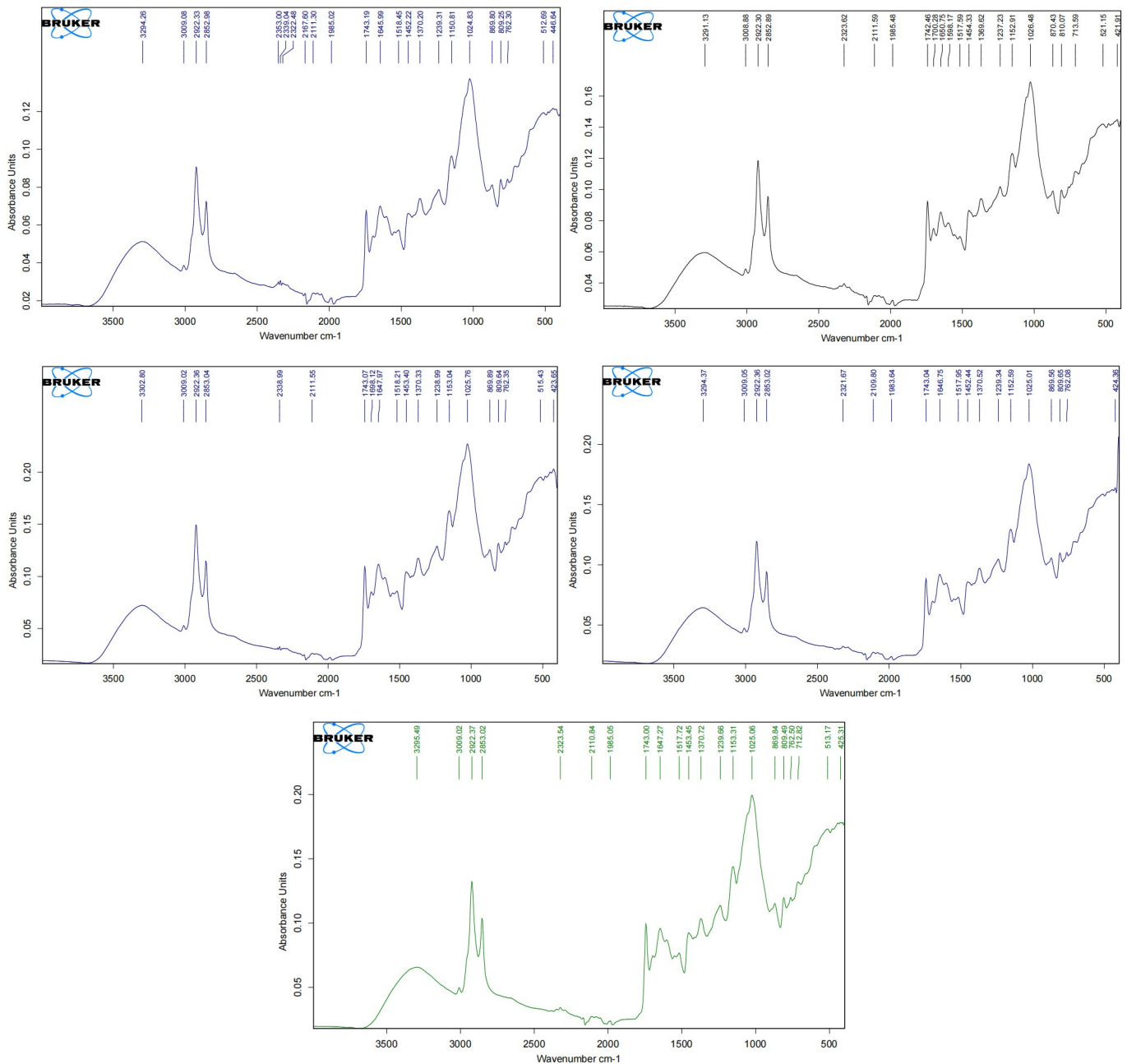


Figure 3: FTIR results for non-fermented coffee and fermented coffee (natural anaerobic, full wash, honey, and wine).

interactions. These bonds allow caffeine to tightly attach to the protein structure, making it difficult to release. During the fermentation process, the mucilage covering the coffee beans, which consists of 80% pectin and 20% sugars, is utilized by microbes such as lactic acid bacteria and molds (e.g., *Aspergillus niger*) as nutrients for their activity and growth, resulting in the production of protease enzymes. Protease enzymes function to hydrolyze proteins into smaller peptides and amino acids, potentially causing conformational changes in the proteins. When proteins undergo conformational changes, the bonds between the protein and caffeine may also be disrupted, allowing caffeine to be released and potentially enhancing the organoleptic quality of the resulting coffee. Bressani et al. (2021) revealed that the fermentation process can significantly reduce catechin levels in green coffee beans to a range of 3.84 – 7.52 mg/g compared to pre-fermentation levels of 9.01 – 3.84 mg/g. According to Purwoko et al. (2023), microbial fermentation activities involving *Lactobacillus casei*, *Leuconostoc mesenteroides*, *Rhizopus oryzae*, and *Saccharomyces cerevisiae* can effectively reduce caffeine content in robusta beans.

The results presented in Table 1 also show that the caffeine content in wine-fermented coffee is the lowest. Robusta coffee processed using the wine method requires the longest fermentation time compared to other methods, lasting 28 days. This extended fermentation period allows for more mucilage on the coffee beans to be hydrolyzed by microbes, which produce protease enzymes. It is known that these enzymes can hydrolyze proteins that interfere with the stability of the bonds between proteins and caffeine in coffee beans, ultimately leading to a reduction in caffeine content. Fermentation time significantly influences the sensory description of coffee beverages, with notes of honey, brown sugar, and almond dominating up to 48 hours. For coffee fermented for 72 and 96 hours, the flavor notes described include fruity and grape flavors. The chemical composition is primarily affected by fermentation time. Borem et al. (2024) explain that fermentation duration has a significant impact on the sensory description and chemical composition, particularly caffeine levels, in coffee beverages.

In addition to the fermentation process and duration, the difference in caffeine content in robusta coffee is also influenced by whether the coffee cherries are depulped or left intact before fermentation. Table 1 shows that natural anaerobic coffee contains a higher caffeine level compared to honey-processed coffee. This is attributed to the fact that although both methods utilize the same fermentation time of 24 hours, they differ in the depulping of the cherries; natural anaerobic coffee is not depulped, while honey-processed coffee is. The depulping of coffee cherries exposes the mucilage of the coffee beans, facilitating easier access for microorganisms to the substrate of the coffee beans, which leads to a more effective

degradation process and thus enhances the effectiveness of caffeine reduction.

Analysis of variance indicates that the fermentation treatments have a significant effect on the pH values of robusta coffee. The results of the 5% honest significant difference (HSD) test (Table 1) reveal that the pH values of fermented coffee (natural anaerobic, honey, full wash, and wine) are lower compared to non-fermented coffee. Furthermore, as fermentation time increases, the pH value decreases, with lower pH values observed in depulped coffee cherries (honey) before fermentation compared to intact cherries (natural anaerobic) when both undergo the same fermentation duration of 24 hours. Coffee fermentation involves microorganisms such as lactic acid bacteria (LAB) and fungi that play a role in breaking down compounds within the coffee beans. These microbes utilize available substrates such as sugars and pectin, producing organic acids as by-products. During fermentation, microorganisms convert complex compounds into various organic acids, including lactic acid and acetic acid. This process leads to an increase in hydrogen ion (H^+) concentration in the solution, contributing to the reduction in pH of the coffee. The fermentation duration of robusta coffee has a direct relationship with the pH value of the coffee. As the fermentation time increases, the pH of robusta coffee decreases due to the accumulation of organic acids and an increase in hydrogen ion (H^+) concentration. Therefore, controlling fermentation time is crucial in determining the quality and flavor profile of robusta coffee.

Kim et al. (2024) revealed that during the fermentation process using lactic acid bacteria, there is an increase in total acid concentration compared to non-fermented coffee extracts. Polania Rivera et al. (2024) explained that during coffee fermentation, acid production is observed through a decrease in pH, which is associated with the fermentation of glucose and fructose present in the fruit, resulting in organic acids such as citrate, malate, tartrate, acetate, lactate, phosphate, and succinate. Vaz, De Menezes, and De Santana (2023) added that arabica coffee processed through fermentation experiences a decrease in pH over time; however, significant reductions are more influenced by higher temperatures, starting from around pH 5 and dropping below 4 under extreme conditions. Kulieva et al. (2024) described that fermentation processes conducted on Typika, Caturra, and Katimor coffees for 16 hours resulted in pH reductions from 5.60, 5.43, and 5.57 to 4.77, 4.60, and 4.67, respectively.

Based on the data presented in Table 1, there is a positive relationship between caffeine content and pH in fermented robusta coffee. As the fermentation time increases, the caffeine content decreases, and the pH value also declines. In other words, as the caffeine content decreases, the acidity of the coffee becomes more pronounced.

Based on the cupping score values presented in Table 2, it is evident that all treatments of fermented robusta coffee

achieved cupping scores above 80, while non-fermented robusta coffee scored below 80, specifically at 74.50. According to the Coffee Association of America (Specialty Coffee Association, 2015), the classification of coffee quality based on cupping scores is as follows: cupping score < 75 (off grade); cupping score 75-80 (fine commercial coffee); cupping score > 80 (specialty coffee); and cupping score > 84 (Cup of Excellence Coffee). Based on Specialty Coffee Association (2015), it can be concluded that naturally fermented anaerobic coffee falls into the category of Cup of Excellence Coffee, indicating that it possesses the highest flavor profile. In contrast, honey, full wash, and other fermented coffees are classified as specialty coffee, while non-fermented robusta coffee is categorized as off-grade, indicating that it has very low flavor quality.

According to Mahingsapun et al. (2022), coffee fermentation plays a crucial role in developing the aroma and flavor of high-quality coffee beans. During fermentation, microbial activity dissolves the pulp material surrounding the beans, resulting in various metabolic end products that diffuse into the beans, thereby enhancing the cupping score. Salvio et al. (2023) noted that the highest scores and attributes described in high-quality coffee, such as sweetness, acidity, and aftertaste, are associated with coffee fermented for 96 hours using *Saccharomyces cerevisiae* CCMA 0543. This yeast is responsible for maintaining the sensory quality of the coffee even after being stored for six months. Research by Aditiawati, Astuti and Kriswanto (2020) indicated that arabica coffee beans fermented with isolates of *Bacillus bacteria* for 4-8 hours could increase total polyphenol content and improve the complexity of flavor and overall coffee quality (cupping score > 84).

The FTIR test results, as shown in Figure 3, indicate that there are six absorbance peaks at specific wave numbers across all coffee samples, both fermented and non-fermented, demonstrating a similar spectral pattern that is difficult to distinguish. The wave numbers of interest are as follows: First, 1024.83-1026.48 cm^{-1} , which indicates glycosidic functional groups. Second, 1150.481-1153.31 cm^{-1} corresponds to carbohydrate functional groups. These first and second-wave numbers play a role in the formation of aroma and texture in coffee. According to Sahachairungrueng et al. (2022), absorption around 1200-1000 cm^{-1} indicates C-O-C vibrations, which are relevant to glycosidic structures. The third peak at 2922.33-2922.37 cm^{-1} represents C-H functional group vibrations indicating the presence of caffeine. Triawan et al. (2022) noted that the absorbance peak around 2934.16 cm^{-1} signifies the presence of C-H bonds in coffee. The fourth peak at 2852.98-2853.04 cm^{-1} is associated with hydroxyl and methylene functional groups that influence coffee aroma. Coates (2000) observed that the characteristic band for the methyl group (CH_3) appears at a wave number of 2869.9 cm^{-1} , indicating symmetric vibrations of the methyl group. The fifth

peak at 1645.99-1650.47 cm^{-1} corresponds to aromatic acid groups that correlate with the characteristic aroma of coffee. Mafazi, Jaliz and Yusibani (2024) indicated that the wave number range of 1650-1600 cm^{-1} shows caffeine absorption, which is an essential component of coffee aroma.

The sixth peak at 1742.46-1743.19 cm^{-1} is associated with the C=O functional group in robusta coffee, referring to the presence of carbonyl groups that play a significant role in the chemical characteristics and aroma of coffee. Coates (2000) explain that the FTIR test results for robusta coffee show that the wave number range of 1724-1739 cm^{-1} corresponds to aldehyde groups, while the wave number range of 1740-1755 cm^{-1} indicates aliphatic ester groups; both of these wave numbers contribute to the flavor and aroma of robusta coffee.

The FTIR analysis results indicate an increase in absorbance values at the six previously mentioned wave numbers. The wave number 1024.83-1026.48 cm^{-1} , which is involved in the formation of aroma and texture in coffee, showed an increase in absorbance from 0.14 (non-fermented coffee) to 0.18 (natural anaerobic), 0.22 (full wash), 0.19 (honey), and 0.21 (wine). This indicates an enhancement of glycosidic and carbohydrate functional groups during fermentation, resulting in improved aroma and texture of the coffee. Similar increases were observed at the wave numbers 1150.481-1153.31 cm^{-1} ; 2922.33-2922.37 cm^{-1} ; 2852.98-2853.04 cm^{-1} ; 1645.99-1650.47 cm^{-1} ; and 1742.46-1743.19 cm^{-1} , as presented in Figure 3. The increase in absorbance values from the FTIR test reflects positive changes in the chemical composition of fermented robusta coffee, contributing to an enhanced cupping score. This indicates that the fermentation process not only alters the chemical properties of coffee but also improves its sensory quality, resulting in a higher-quality final product.

The caffeine content of robusta coffee processed using fermentation methods, particularly full wash and wine methods, was found to be 1.58% and 1.44%, respectively, meeting the specialty coffee standards for arabica coffee, which range from 1.2% to 1.5%. The pH values of brewed coffee and cupping scores for fermented robusta coffee fall into the specialty coffee category (arabica), with pH values ranging from 5.16 to 5.23 and cupping scores above 80, respectively.

5 CONCLUSION

The natural fermentation process has proven effective in enhancing the quality of robusta coffee by altering its chemical composition and enriching its flavor and aroma profiles, thereby approaching the quality traditionally associated with arabica coffee. With this approach, robusta coffee can offer a more complex and appealing flavor experience, positioning it as a potential competitor in the premium coffee market and providing an alternative for coffee enthusiasts seeking a more varied tasting experience.

6 AUTHORS' CONTRIBUTION

Conceptual Idea: Santoso, B.; Methodology Design: Rahmawati, L.; Syafutri, M.I.; Data Collection: Nurhaliza, M.; Data Analysis and Interpretation: Wijaya, A.; Priyanto, G.; Writing and Editing: Hermanto.

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