

Hybrid Carbonic Maceration Techniques for Enhancing Arabica Coffee Flavor Profiles

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ABSTRACT

This study examined the application of carbonic maceration fermentation with natural inoculants to enhance the flavor profile of Indonesian coffee, develop unique fruity flavor characteristics, and promote both global market competitiveness and the economic sustainability of local farmers. Four fermentation treatments were applied: F1 (control: no inoculant, 29°C, 3 days), F2 (pineapple, yeast, and sugar inoculant; 29°C, 4 days), F3 (banana, jasmine flower, and yeast inoculant; 29°C, 2 days), and F4 (pineapple, yeast, sugar, and rose flower inoculant; 29°C, 3 days). Sensory evaluation was performed by nine trained panelists in accordance with the guidelines of the Specialty Coffee Association of America (SCAA). Sample F2 achieved the highest score (85.50), excelling in sweetness, clean cup, body, acidity, flavor, aroma, and aftertaste. Its aroma profile included distinctive notes of fruit, dried fruit, over-ripe fruit, banana, tamarind, and raisin. All samples met the criteria for specialty coffee (score ≥ 80), with the exception of F1, which received a score of 79.00. This study confirmed that carbonic maceration fermentation with natural inoculants improves coffee sensory scores, creates opportunities for flavor diversification, and enhances the quality and global competitiveness of Indonesian coffee.

Key words: Cupping; fermentation of carbonic maceration; inoculant; international competitiveness; specialty coffee.

1 INTRODUCTION

Coffee is one of the plantation commodities that plays a strategic role in the global economy, especially in producing countries such as Indonesia (Andrade et al., 2022). According to data from the International Coffee Organization - ICO (2023), global coffee consumption experienced a significant increase in 2021/2022, rising by 4.2% to reach 175.6 million 60-kg bags annually. As one of the world's largest coffee exporters, Indonesia has an advantage in the diversity of coffee flavors produced from various regions, such as Gayo, Toraja, and Java. However, competition in the global market demands improvements in coffee quality, particularly in terms of flavor and aroma, to meet international consumer preferences. One of the key factors determining these characteristics is the post-harvest processing method, particularly fermentation (Lee et al., 2015).

From harvest to storage, the production of green beans directly influences the flavors of coffee (Agresti et al., 2008). Three types of coffee beans are produced: wet hulled or thoroughly washed, pulped natural, and dried natural. The purpose of these procedures is to eliminate the mucilage and lower the beans' moisture content (Poltronieri; Rossi, 2016). To achieve the appropriate tastes, proteolysis, lipolysis, formation of volatiles such as aldehydes and ketones, free fatty acids, and acidity in the final product, it may entail controlled fermentation. Specialty coffee is quickly emerging from the many coffee processing methods.

Fermentation is a crucial step in coffee processing, as it influences the formation of volatile compounds that

contribute to flavor and aroma. Traditionally, fermentation is performed naturally; however, this approach often results in inconsistent quality due to limited control over key process variables. To address this, advancements in fermentation technology are essential for improving the consistency and quality of the final product (Bertrand et al., 2012). This can be achieved by harnessing microorganisms from the environment and using inoculants (Jitjaroen et al., 2023a; Zhang et al., 2019). Recent innovations, such as the use of microorganisms as starter cultures, enzyme treatments (Poltronieri; Rossi, 2016), and the carbonic maceration process (Gudi, 2017), are paving the way for more controlled and effective fermentation practices.

One innovation that has garnered attention is the Carbonic Maceration (CM) method, which was originally used in the wine industry. This method involves fermenting fruit in an anaerobic environment rich in carbon dioxide (CO₂). In the context of coffee, CM allows fermentation to occur within the coffee bean tissue, resulting in a unique and complex flavor profile. This process also provides better control over fermentation, reduces the risk of microbial contamination, and enriches volatile compounds such as esters and alcohols responsible for fruity and floral aromas (Selmar et al., 2008). A winemaking method called carbonic maceration takes advantage of intact grape berries' capacity to adapt to an oxygen-deficient medium that is enhanced by carbon dioxide. The change from a respiratory to a fermentative anaerobic metabolism occurs practically immediately within

each berry, reflecting this adaptability. Whole coffee cherries are fermented in a carbon dioxide-filled vacuum-sealed atmosphere. Coffee's sensory, chemical, and microbiological profiles are altered by the carbonic maceration, which also encourages several biochemical interactions (Brioschi et al., 2021). The coffee cherries started fermenting without oxygen or yeast after absorbing carbon dioxide gasses, which broke down the carbohydrates and made the berries more acidic. To produce distinct flavors in the cup, a variety of processes occur inside the coffee cherries. Coffee cherries can be separated from their beans in a variety of ways, including by washing or by natural means. The trademark of the carbonic process is the production of more fruity flavors, including bubblegum, banana, strawberry, raspberry, and cherry. The value of coffee beans on the global market has significantly increased due to the use of this approach in numerous nations (Gudi, 2017).

Previous studies have shown that the Carbonic Maceration (CM) method can enhance the complexity and flavor quality of specialty coffee. The semi-carbonic maceration fermentation method offers several advantages, including accelerating anaerobic fermentation, promoting more uniform fermentation, and maintaining consistent temperature and pH levels (Budi et al., 2022). However, the application of this method remains limited, particularly in Indonesia, which has significant potential to adopt this technology. Therefore, this study aims to explore the application of fermentation technology using the Carbonic Maceration method in an effort to improve the flavor quality of Indonesian coffee through various treatments, which can effectively support the sensory aspects used in the fermentation process. This research is also expected to provide a tangible contribution to enhancing the competitiveness of Indonesian coffee in the international market while supporting the economic sustainability of local coffee farmers.

2 MATERIAL AND METHODS

2.1 Fermentation condition

The red coffee fruit used in this study is of the Line S.795 variety, sourced from the PT Sulotco Jaya Abadi plantation in Tanah Toraja, situated at an altitude of 1,800 meters above sea level. The Arabica coffee fruits were harvested at full maturity, followed by a sorting process to remove defective fruits and impurities, including wood twigs, leaves, and other foreign materials. The sorting procedure ensured that only the red coffee fruits remained. These fruits were then fermented using the carbonic maceration technique in fermentation containers made from 10 kg-capacity water gallons. The fermentation tubes were equipped with a temperature sensor and connected to an Arduino system for monitoring fermentation time. CO₂ cylinders, sourced from a gas company in Makassar,

were injected into the fermenter reactor tank to facilitate the carbonic maceration process (Ariefandie et al., 2023).

The CO₂ injection process is designed to reduce both the acidity and caffeine content of the coffee. A gas pressure indicator is used during fermentation to maintain a stable pressure range of 50–100 millibars. While some processors introduce CO₂ daily throughout fermentation, this study applied it only once, on the first day. The following treatments were applied: Sample F1 (control) at 29°C, without inoculants, following a natural drying process; Sample F2 at 29°C with a 4-day fermentation period and the addition of inoculants (pineapple, yeast, and sugar); Sample F3 at 29°C with a 2-day fermentation period and the addition of inoculants (banana, jasmine flower, and yeast); Sample F4 at 29°C with a 3-day fermentation period and the addition of pineapple, yeast, sugar, and rose flower. The coffee cherries were placed in fermentation tubes, each containing a specific inoculant mixture based on the treatment, and submerged in water to fully cover the cherries. After fermentation, the cherries were sun-dried until the moisture content reached 18–20%, then hulled to remove the fruit skin. The green coffee beans were then sun-dried until the moisture content dropped to approximately 12% (Pereira, 2021).

2.2 Roasted preparation

Samples of coffee were made in compliance with SCAA guidelines (2012). A Probat roaster machine of the BR22 model was used to roast 150 g of coffee. (Baggenstoss et al., 2008; Illy; Viani, 2005; Owen, 2009; Schenker et al., 2002; Sivetz; Desrosier, 1979; Yeretian et al., 2002; Reta et al., 2017; Reta et al., 2020). The roasting temperature was 150°C for 25 minutes. The roasted coffee was then ground for the test sample in 10 seconds using a Latina grinder machine with a 7.8 mesh size. To guarantee the samples' freshness, tests were conducted right away and took no more than 30 minutes (Sivetz; Desrosier, 1979; Reta et al., 2017; Reta et al., 2020).

2.3 Sensory Test Analysis Procedures (SCAA Method)

The SCAA standard (2015) was followed when doing the sensory analysis. Samples of roasted coffee were kept for a full day before being milled. The water used in this cup-test had dissolved solids of 125 to 175 ppm and was odorless and clean. A porcelain dish filled with 150 mL of hot water was used to brew the 10 g coffee samples. The water was poured straight onto the ground coffee samples in bowls after being boiled at 95 to 99 degrees Celsius. This sensory test was conducted by nine panelists from the Indonesian Coffee and Cocoa Research Institute's Sensory Laboratory, three of whom were women and six of whom were men, ages 37 to 55.

Samples were drawn at random using three replications of nine descriptors. Aroma, acidity, aftertaste, body, flavor, clean cups, mouthfeel, and overall flavor profiles were all used to assess the quality of the brewed coffee. According to Ribeiro et al. (2011), another technique assessed the entire flavor profiles' quality and strength concurrently using a scoring scale ranging from 1 to 5. According to SCAA (2015), the flavor profile scores were separated into four groups: Average (5.00–5.75), Good (6.00–6.75), Very good (7.00–7.75), Excellent (8.00–8.75), and Outstanding (9.00–9.75).

2.4 Data analysis

Compusense software was used for data collection, and the data analysis was performed using analysis of variance (ANOVA), specifically the Duncan test, to determine statistical significance. ANOVA was conducted in SPSS at a 5% significance level. Sensory analysis was employed to evaluate the relationship between temperature, fermentation duration, and flavor profile descriptions. A spiderweb chart was utilized to visualize participants' perceptions of the coffee flavor profile scores for each sample.

3 RESULT

The Arduino-based digital system developed in this study for coffee cherry fermentation using the carbonic maceration technique effectively controls the fermentation temperature. The temperature inside the fermentation chamber starts at approximately 25°C and gradually rises to the target fermentation temperature of 29°C. During the process, various inoculants were applied, and fermentation durations were adjusted to reduce the acidity and caffeine content of the coffee cherries (Geromel et al., 2008). The system also aimed to enhance the aromatic profile of the coffee beans, offering real-time monitoring and control of temperature, pH, and pressure within the fermentation chamber.

Maintaining a stable temperature of 29°C within the fermentation chamber allows the inoculants mixed with the coffee cherries to impart distinct flavors and aromas specific to each inoculant. These results demonstrate that Carbonic Maceration, facilitated by injecting CO₂ at 29°C, effectively supports the fermentation process. However, further experiments with different temperatures and fermentation times are required to determine the optimal conditions for coffee fermentation using this method.

According to the results of the cup test, the coffee beans produced from the fermentation trials in this study may generally be categorized as specialty coffee beans due to their overall quality. According to the standards outlined in the Specialty Coffee Association of America (SCAA) handbook, coffee samples with scores between 80 and 84 are categorized as high-quality beans of coffee, while samples

with scores between 85 and 89 are categorized as specialty coffee beans.

The results of this study show that coffee cherry fermentation using the digital-based Carbonic Maceration technique with Arduino control can consistently produce high-quality coffee beans. Furthermore, these results also indicate that this technology produces coffee beans with higher cup scores compared to fermentation using microbes isolated from civet intestines, as reported by several researchers (Towaha; Rubiyo, 2016; Hadipernata; Nugraha, 2017). The results reported by these researchers show that the coffee beans produced in their studies (artificial civet coffee) received cup scores of less than 80. It is also noteworthy that the cup score of civet coffee tested by Towaha and Rubiyo (2016) as a benchmark only achieved a cup score of 79.25, and the civet coffee sample used by Hadipernata and Nugraha (2017) received a cup score of 84.875. Therefore, the cup score (Figure 1) of the coffee beans produced using the technology developed in this study provides a higher cup score compared to both authentic and artificial civet coffee cup scores reported by the researchers mentioned above.

The results of the testing on all characteristics assessed by the SCAA panelists showed that the samples tested achieved “very good” to “excellent” cupping scores in all aspects. It is important to note that the cupping score scale used by the judges at the Indonesian Coffee and Cocoa Research Center is based on the SCAA scale. The quality descriptors used by the judges are as follows: scores of 6 - 6.75 are categorized as Good, 7 - 7.75 as Very Good, 8 - 8.75 as Excellent, and 9 - 9.75 as Outstanding.

The cupping test results showed that Sample 1 received an “excellent” score in 6 aspects and a “very good” score in 4 aspects, while Sample 2 received an “excellent” score in 4 aspects and a “very good” score in 6 aspects. Sample 3 received a “very good” score in 6 aspects and an “excellent” score in 4 aspects. Based on the final scores of each sample, all coffee beans produced from this technology can be classified as specialty coffee (final score > 80). According to the SCAA panelists, two samples can be classified as “Very Good” (final score = 85), and two samples can be classified as “Very Good” (final score > 80). These results demonstrate that coffee cherry fermentation with the help of digital-based carbonic maceration with Arduino control can consistently produce high-quality coffee beans.

The panelists qualitatively described the control treatment as a sample F1: nutty, caramel, sugar cone, and chocolate; F2 as fruity, dried fruit, over ripe fruit, banana, tamarin and raisin; F3 as chocolaty, spicy-clove like; F4: Brown sugar, flowery-coffee blossom-honeyed, herbal. The results obtained in this study indicate that the temperature used during fermentation (29°C) is suitable for the growth of yeast and bacteria involved in the fermentation process.



Figure 1: Result of cup testing score of F1, F2, F3, and F4.

4 DISCUSSION

The results obtained in this study indicate that the temperature used during fermentation (29°C) is suitable for the growth of yeast and bacteria involved in the fermentation process. The fermentation duration of approximately 72 hours at 29°C is sufficient to thoroughly degrade the mucilage and produce coffee beans that can brew coffee with a pleasant taste and aroma. In addition to the positive effects of the temperature used in this experiment on the growth and activity of yeast and bacteria, there may also be an effect of the electric field on the structure of the coffee beans, which facilitates diffusion and chemical interactions within the beans. The cupping test results, tested by the panelists, revealed attributes such as clean cup and sweetness, with the highest score (score 10.00) in all treatments (Figure 2), consistent with previous reports (Ribeiro et al., 2011).

Specialty coffee is defined by the SCAA as coffee beverages with a score of 80 or higher. The ultimate product

with extraordinary and careful attention to detail to maintain standards and perfection from beginning to end is referred to as specialty coffee (SCA, 2012). Every stage of the production process for these coffees is carried out with the utmost skill, including the growing environment, cultivation system, growth-promoting nutrients, coffee fruit variety selection, harvesting methods, fermentation, drying, storage, roasting (Reta et al., 2020; Dinnella Masi; Naes, 2013), and beverage preparation.

Based on the cupping test data, this indicates the interaction differences in flavor profiles from the carbonic maceration fermentation treatments with the addition of different inoculants to the sensory profile. Another factor influencing the fermentation process is the quantity and type of microbes present during fermentation (Brioschi et al., 2021), which relates to the sensory profile of the final product, as observed during wine fermentation (Lai et al., 2019). Coffee processed with SCM has a greater potential for active aroma attributes compared to dry-processed coffee (Jitjaroen; Chaisri; Panjai,

2023b). These complex and diverse factors directly correlate with the improvement of the sensory profile of coffee.

Coffee that is fermented via the carbonic maceration method also has distinctive scents. This happens because substances such as acids, alcohols, aldehydes, and esters are formed (Lee et al., 2023; Karynda; Jaya, 2023). These substances add unique scents of fresh fruit, flowers, and spices, which have a big impact on the product's final flavor and aroma character. The technique of carbonic maceration is characterized by the production of fruit scents such as banana, strawberry, raspberry, and cherry (Gudi, 2017). Additionally, this technique can intensify fruity and floral scents (Tong et al., 2023). According to the results of sensory tests, the F2 treatment had a strong fruity scent reminiscent of bananas. As a result, this technique has a lot of promise for improving coffee flavor profiles.

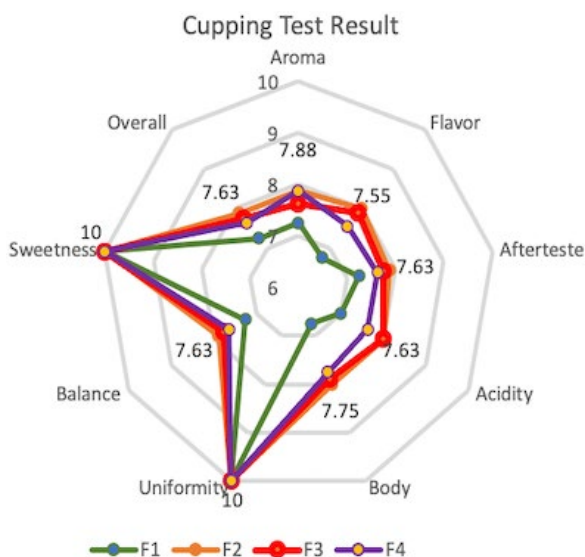


Figure 2: The cupping test results, tested by the panelists

5 CONCLUSIONS

The Arduino-controlled carbonic maceration fermentation with pineapple, yeast, and sugar (F2) produced the best coffee quality after 4 days at 29°C. It scored highest in aroma, flavor, and other sensory attributes, surpassing the control. All samples qualified as specialty coffee. This technique improves flavor consistency and quality while potentially lowering costs. The digital system ensures precise control and data collection, supporting further research and offering broader applications in the controlled fermentation of other agricultural products.

6 AUTHOR CONTRIBUTION

Conceptual Idea: Reta.; Zaimar.; Methodology design: Reta; Zaimar.; Data collection: Henny, P., Data analysis and interpretation: Reta.; Zaimar., and Writing and editing: Reta.; Zaimar.; Henny, P.

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8 REFERENCE

- AGRESTI, P. D. M. et al. Discrimination between defective and non-defective brazilian coffee beans by their volatile profile. **Food Chemistry**, 106(2):787-796, 2008.
- ANDRADE, C. et al. Bioactive compounds and antioxidant activity from spent coffee grounds as a powerful approach for its valorization. **Molecules**, 27(21):7504, 2022.
- ARIEFANDIE, N.; ZHU, F. Coffee bean processing: Emerging methods and their effects on chemical, biological and sensory properties. **Food Chemistry**, 412:135489, 2023.
- BAGGENSTOSS, J. et al. Coffee roasting and aroma formation: application of different time and temperature conditions. **Journal of Agricultural and Food Chemistry**, 56:5836-5846, 2008.
- BERTRAND, B. et al. Comparison of carbonic maceration and conventional fermentation techniques: Influence on coffee bean quality. **Food Research International**, 46(2):541-547, 2012.
- BRIOSCHI, J. D. et al. Microbial fermentation affects sensorial, chemical, and microbial profile of coffee under carbonic maceration. **Food Chemistry**, 342:128296, 2021.
- BUDI, H. et al. An aerobic coffee fermentation engineering with carbonic and semi-carbonic maceration methods. **Jurnal Pengembangan Potensi Laboratorium**, 1(2):79-85, 2022.
- DINNELLA, C.; MASI, T.; NAES, E. M. A new approach in tds data analysis: a case study on sweetened coffee. **Journal of Food Science**, 30(1):33-46, 2013.
- GEROMEL, C. et al. Effects of shade on the development and sugar metabolism of coffee (*Coffea arabica* L) fruits. **Plant Physiology and Biochemistry**, 46(5):569-579, 2008.
- GUDI, P. Carbonic maceration (a unique way of coffee processing). *Maceracion*, 1-4, 2017. <https://www.scribd.com/document/419276376/Maceracion>

- HADIPERNATA, M.; NUGRAHA, S. Processing technology of luwak coffee through bioreactor utilization. **IOP Conf Series: Earth and Environmental Science**, 102:012092, 2017
- INTERNATIONAL COFFEE ORGANIZATION - ICO. **Coffee statistics international coffee organization**. Trade statistics of total production of exporting countries. Access in: https://icocoffee.org/documents/cy2023-24/Coffee_Report_and_Outlook_December_2023_ICO.pdf Access in: May 15, 2025.
- ILLY, A.; VIANI, R. **Espresso coffee**: The science of quality (2nd ed.). London, uk: elsevier academic press, 2005. 256p.
- JITJAROEN, W. et al. Characterization of active-aroma wheel in contemporary coffee processes via gas chromatography: olfactometry, and sensory perspective. **Coffee Science**, 18:e182059, 2023a.
- JITJAROEN, W. et al. Aroma profile and cupping characteristics of coffee beans processed by semi-carbonic maceration process. **Coffee Science**, 18:e182119, 2023b.
- KARYNDA R. P. M.; JAYA, M. M. The potential of carbonic maceration fermentation technology for enhancing coffee flavor quality. **Prosiding Seminar Nasional Teknologi Pangan**, 121-129, 2023.
- LAI, Y.T. et al. Isolation and identification of aroma producing strain with esterification capacity from yellow water. **Plos One**, 2(14):e0211356, 2019.
- LEE, B. H. et al. Microbial diversity of anaerobic-fermented coffee and potential for inhibiting ochratoxin-produced aspergillus niger. **Foods**, 12(15):2967, 2023.
- LEE, L. W. et al. Coffee fermentation and flavor—an intricate and delicate relationship. **Food Chemistry**, 185:182-191, 2015.
- OWEN, T. **An updated pictorial guide to the roast process**. 2009. Available in: <https://www.sweetmarias.com/> Access in: May 15, 2025.
- POLTRONIERI, P.; ROSSI, F. Challenges in specialty coffee processing and quality assurance. **Challenges**, 7:01-19, 2016.
- PEREIRA, P. V. et al. Microbial diversity and chemical characteristics of *cofea canephora* grown in different environments and processed by dry method. **World Journal of Microbiology and Biotechnology**, 37(51):1-12, 2021.
- PEREIRA, T. S. et al. Self-induced anaerobiosis coffee fermentation: impact on microbial communities, chemical composition and sensory quality of coffee. **Food Microbiol**, 103:103962, 2022.
- RETA. et al. Reducing the acidity of arabica coffee beans by ohmic fermentation technology. **Food Research**, 1(5):157-160, 2017.
- RETA. et al. Fermentation of arabica coffee beans using ohmic heating technology in producing specialty coffee. **Pelita Perkebunan**, 36(3):226-235, 2020.
- RIBEIRO, F. C. et al. Storage of green coffee in hermetic packaging injected with CO₂. **Journal of Stored Products Research**, 47(4):341-348, 2011.
- SPECIALTY COFFEE ASSOCIATION - SCA. **Protocol and best practice**. 2012. Available in: <https://www.scaj.org/wp-content/uploads/2012/09/2012-CRC-RULES-AND-REGULATIONS-2012.05.07.pdf> Access in: May 15, 2025.
- SPECIALTY COFFEE ASSOCIATION OF AMERICA - SCAA. **SCAA protocols** - Cupping Specialty Coffee. SCAA, Santa Ana, 2015, 10p.
- SCHENKER, S. et al. Impact of roasting conditions on the formation of aroma compounds in coffee beans. **Journal of Food Science**, 67(1):60-66, 2002.
- SELMAR, D. et al. The storage of green coffee (cofea arabica): decrease of viability and changes of potential aroma precursors. **Annals of botany**, 101(1):31-38, 2008.
- SIVETZ, M.; DESROSIER, N. W. **Coffee technology**. Avi: westport, ct, Vol.17. p.716, 1979.
- TONG, W. et al. 2023. Influence of modified carbonic maceration technique on the chemical and sensory characteristics of Cabernet Sauvignon wines. **Food Chemistry**, 403:134341, 2023.
- TOWAHA, J.; RUBIYO. Physical quality of arabica green coffee beans and flavor characteristics of coffee produced from fermentation process using probiotic microbes isolated from luwak intestines (in bahasa). **TIDP Journal**, 3(2):61-70, 2016.
- ZHANG, S. J. et al. Influence of various processing parameters on the microbial community dynamics, metabolomic profiles, and cup quality during wet coffee processing. **Frontiers in Microbiology**, 10:2621, 2019.
- YERETZIAN, C. et al. From the green bean to the cup of coffee: investigating coffee roasting by on-line monitoring of volatiles. **European Food Research and Technology**, 214(2):92-104, 2002.