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The Effect of Roasting Degrees and Brewing Techniques on the Physicochemical and Sensory Characteristics of Anaerobically Fermented Liberica Coffee (*Coffea liberica*)

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Abstract

Liberica coffee from Banyuwangi, Indonesia, is distinguished by its unique flavor and high antioxidant content but is often considered inferior to Robusta and Arabica. This study investigated the effects of roasting degrees and brewing methods on the physicochemical and sensory properties of anaerobically fermented Liberica coffee. Coffee beans were roasted at light and medium levels and brewed using V60, French Press, and Vietnam Drip methods. The results indicated that the roasting degree significantly influenced the pH, antioxidant activity, and total dissolved solids (TDS) of the brewed coffee. Light roasting enhanced fruity and acidic notes, particularly a jackfruit-like aroma, while medium roasting pronounced stronger chocolate, roasted, and caramel flavors. Sensory analysis confirmed that roasting had a greater impact on flavor than brewing methods. HS-SPME/GC-MS analysis identified 72 volatile compounds, demonstrating that medium roasting yielded a higher concentration of furans, pyrazines, and ketones, as the most dominant compounds. These findings emphasize the importance of carefully selecting roasting and brewing techniques to optimize the chemical and sensory qualities of Liberica coffee. By refining these methods, Banyuwangi Liberica coffee can be positioned as a distinctive and appealing choice in the global coffee market.

Keywords: Brewing, Liberica coffee, Roasting, Sensory profile, Volatile

Introduction

Coffee is one of the world's most widely consumed beverages, cherished for its complex flavor profiles, aromatic qualities, and stimulating properties. Liberica coffee (*Coffea liberica*) has gained attention due to its unique attributes and adaptability to various growing conditions, particularly in Banyuwangi, Indonesia. Research indicates that Liberica coffee is well-suited to thrive in diverse agroecological settings, which is crucial given the increasing challenges posed by climate change on traditional coffee crops [1]. Although Liberica coffee has lower productivity compared to Arabica and Robusta, it holds great potential for development due to its distinctive characteristics [2]. It exhibits a jackfruit-like aroma as a key distinguishing feature [2,3]. Despite its unique profile, the flavor quality of Liberica coffee is still considered lower compared to Arabica coffee.

The low-quality perception of Liberica coffee is thought to arise from several factors, including post-harvest processing practices. Effective post-harvest processing plays a significant role in enhancing the quality of coffee beans. Among these processing stages, fermentation and roasting stand out as the most critical phases in shaping coffee flavor compounds [2]. Fermentation significantly influences the characteristics of roasted coffee beans, with yeast fermentation enhancing the chemical profile, organic acid content, and sensory attributes such as sweet caramel, dried fruit, vanilla, and hazelnut-like flavors. The impact varies by coffee cultivar, highlighting the importance of selecting suitable fermentation methods and starter cultures to optimize coffee quality [4]. Notably, the practice of anaerobic fermentation has gained traction for its potential to preserve bioactive compounds, particularly antioxidants [5]. Experimental anaerobic fermentation processes have primarily been applied to Arabica coffee, aiming to improve its sensory attributes with distinct fruity, woody, and caramel notes [6,7]. Such innovations have the potential to improve the quality of Liberica coffee.

Roasting is also a pivotal stage in coffee processing that significantly influences the sensory quality of the final product due to thermal processes and the Maillard reaction [8]. The quality of roasted coffee beans is influenced by a multitude of factors, including roasting temperature, time, method, and the intrinsic properties of the beans themselves [9-11]. Understanding these factors is essential for optimizing the roasting process to achieve desirable sensory qualities in the final product. Research indicates that roasting can be divided into 2 main phases, such as drying, which occurs at temperatures below 160 °C, and roasting, which takes place between 160 and 260 °C. During the roasting phase, complex chemical reactions, including the Maillard reaction, occur, leading to the formation of various volatile compounds that contribute to the coffee's flavor and aroma [12]. The duration of the roasting process also plays a critical role in determining the final quality of the coffee. Longer roasting times can lead to the degradation of desirable compounds, while shorter times may not allow for the full development of flavors [13]. Among the 3 commonly recognized roasting levels, light and medium roasts are considered particularly suited for anaerobically fermented coffee. According to the previous report, light-to-light-medium roast brews yield a flavor profile characterized by fruity, acidic, and citrusy notes [14]. The roasting level is also recognized to significantly affect the chemical composition and sensory attributes of coffee, with light roasting preserving higher phenolic and flavonoid content, as well as fruity and caramelized aroma compounds, while dark roasting enhances smoky and burnt notes, reduces acrylamide and organic acids [10].

The final quality of coffee is also influenced by other factors such as brewing technique, time, and temperature as well as the ratio of coffee to water [3]. Manual brewing methods, chosen for their simplicity and ease of use, have been favored for consistently producing enjoyable brews. V60, French Press, and Vietnam Drip are among the most commonly used techniques, each highlighting different sensory attributes of the coffee. Recent studies indicate that V60 enhances acidity and fruity notes, French Press provides a full-bodied brew, and Vietnam Drip intensifies caramelized and roasted flavors [3,15,16].

In this study, we highlighted the effects of roasting degrees (light and medium) and manual brewing methods (V60, Vietnam Drip, French Press) on the physicochemical and sensory characteristics of anaerobically fermented Liberica coffee. This investigation aims to unveil the potential of these methods in enhancing the sensory quality of Liberica coffee processed through modified anaerobic fermentation. By refining roasting and brewing techniques, this study contributes to optimizing the unique sensory attributes of Liberica coffee, which may enhance its global appeal.

Materials and methods

Materials

Liberica coffee samples from Kopendukuh, Kalipuro, Banyuwangi, Indonesia, and belonged to the Liberica variety. These samples underwent anaerobic fermentation preceded by pulping. The materials used for analysis included 2,2-diphenyl-1-picrylhydrazyl (DPPH) powder, petroleum ether (PE) solvent, methanol, ethanol, deionized water, distilled water, and caffeine powder.

Methods

Coffee beans preparation

Liberica coffee cherries originated from the Kopendukuh coffee plantation in Kalipuro, Banyuwangi, Indonesia. The coffee cherries were first carefully sorted and subjected to pulping. Subsequently, the coffee cherries were processed using the full-wash method and underwent anaerobic fermentation with the addition of carbonated water in a 2:1 ratio for 5 days. After fermentation, the coffee cherries were thoroughly washed and then sun-dried for 14 days. Once dried, the coffee cherries were de-hulled and further sorted, making them ready for the roasting process.

Roasting and grinding of coffee beans

The sorted green coffee beans were roasted using a W1A Giesen coffee roaster, The Netherlands (drum speed: 55 Hz; airflow: 110 Pa; temperature 175 °C; turning point: 1 min 30 s) with a capacity of 600 - 700 g per batch. Roasting temperature at 210 °C. Roasting time approx. 8 min for light roasting and approx. 10 min for medium roasting. Following the roasting process, the roasted coffee was placed in aluminum foil packaging equipped with a valve and allowed to rest for approximately one week. The resting process aids in degassing the roasted coffee beans. After the resting period, the coffee beans were ground using a grinder machine. The particle size of the coffee grounds was adjusted according to the brewing method under the Specialty Coffee Association of America (SCAA) standards. For the V60 brewing method, the coffee particle size ranged from medium to fine, for the Vietnam Drip method, it ranged from medium, and for the French Press method, it ranged from medium to coarse.

Brewing method

Coffee brewing was carried out using the method reported by the previous study, the ratio of water to coffee grounds was approximately 1:15 [17].

V60 brewing method

Twelve g of medium-to-fine roasted coffee grounds were weighed, and 150 mL of hot water within the temperature range of 75 - 93 °C was prepared alongside a V60 filter. Subsequently, the V60 filter was rinsed with hot water. The roasted coffee grounds were then placed into the dripper, and hot water was poured in a clockwise direction until the volume reached 30 mL. A 2nd pour of 50 mL was executed, and it was patiently waited until approximately half of the remaining water in the dripper had drained. The final pour was then performed, adding water until the total volume reached 150 mL.

Vietnam drip brewing method

Subsequently, the dripper was thoroughly rinsed with water. Ten g of medium ground roasted coffee were carefully placed into the dripper, and poured with 30 mL hot water (85 - 90 °C) for 30 s, marking the onset of the blooming phase. Following the initial pour, the final pour was executed, adding water until the total volume reached 150 mL, at which point the coffee ceased to drip.

French press brewing method

One hundred twenty mL hot water within the temperature range of 85 - 90 °C was prepared. Subsequently, the French Press device was rinsed thoroughly with water. The 14 g medium to coarse roasted coffee grounds were then carefully placed into the glass chamber, and hot water was poured until it reached a volume of 30 mL, followed by a 30-second resting period, marking the initiation of the blooming stage. A 2nd pour was performed over a 60-second duration, followed by a 20-second resting period to ensure complete water absorption into the coffee. A final pour lasting 20 s was carried out to complete the brewing process.

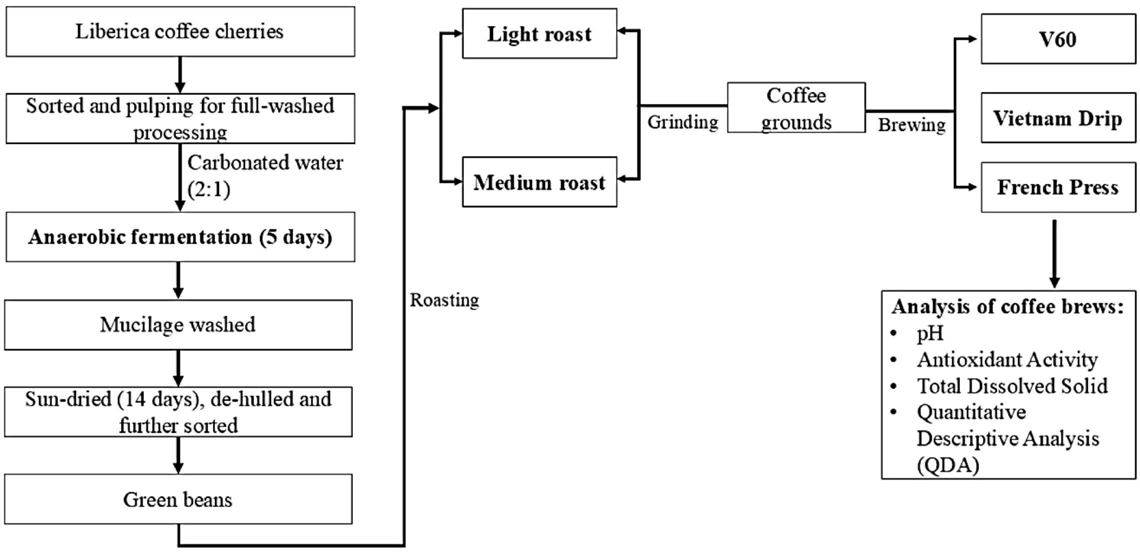

Figure 1 Flow chart of coffee bean preparation, roasting and grinding of coffee beans, and brewing method.

Quantitative descriptive analysis (QDA)

QDA was conducted based on the modification of the previous report [18]. This sensory test carried out has obtained ethical review permission No.691/KEPK-POLKESMA/2023.

Panelist selection and training

The panel consisted of 6 male and 2 female panelists aged between 22 to 45 years. They were selected based on their ability to evaluate coffee attributes effectively based on matching tests, difference tests, and threshold tests. Before testing, a Focus Group Discussion (FGD) was conducted to develop the panelists' perceptions of coffee attributes and to align their sensory vocabulary. Panelists then underwent training sessions to enhance their sensory skills in identifying and quantifying coffee attributes. The process was reiterated until a consensus was reached among the panel.

Sensory evaluation

Ten mL samples of brewed coffee, each labeled with a unique 3-digit code, were presented randomly to the panelists. They assessed the intensity of aroma and flavor attributes of the brewed coffee samples using a testing form that included sensory attributes, each with a 15 cm unstructured line scale with a vertical line located 1.5 cm from each end. To ensure consistency and minimize potential bias, the testing procedure was repeated 3 times for each sample. The data collected from the panelists' evaluations were tabulated and the sensory attributes' intensity was presented in a spider web diagram, allowing for a visual comparison of the intensity of each sensory attribute for the brewed coffee samples.

HS-SPME/GC-MS analysis

A solid-phase microextraction (SPME) method was employed to extract volatile compounds from the roasted Liberica coffee beans. Five g of the sample were placed into a 20 mL SPME vial, and 0.6 µL of trimethyl pyridine (0.0001 %, v/v) was added as an internal standard. The extraction was conducted using a DVB/CAR/PDMS (divinylbenzene/carboxen/polydimethylsiloxane) SPME fiber (2 cm) at 60 °C for 20 min to optimize the extraction of volatiles.

The analysis was performed using a GC-MS system consisting of a gas chromatograph (GC Agilent 7890A) coupled to a mass spectrometer (MS Agilent 5975C XL EI/CI). The injector temperature was set to 250 °C in spitless mode, with helium as the carrier gas at a flow rate of 1 mL/min. The oven temperature program began at 40 °C (held for 1 min), increased at a rate of 4 °C/min to 150 °C (with no hold), and then further increased at 30 °C/min to a final temperature of 230 °C, held for 15 min. Separation was achieved using a DB-Wax column (30 m×250 µm×0.25 µm), and the interface temperature was maintained at 250 °C. The mass spectrometer was operated with a scan range of 29

- 550 amu, with the MS source and quad temperatures set to 230 and 150 °C, respectively. Compound identification was performed using the NIST14 library. This setup ensured accurate detection and profiling of the volatile compounds in the samples.

Statistical analysis

Statistical analysis was conducted using Minitab 19 software. To identify significant differences in each parameter, Analysis of Variance (ANOVA) was applied with a significance level of α = 0.05. For factors showing significant effects, Fisher's post hoc tests were performed with a 95 % confidence interval. Additionally, sensory evaluation was analyzed descriptively using XLSTAT software.

Results and discussion

Effect of roasting degrees and brewing techniques on the physicochemical characteristics of anaerobically fermented liberica coffee brew

Based on **Table 1**, it can be concluded that the roasting degree and the nested brewing technique within the roasting degree significantly influenced the pH values of anaerobic fermentation Liberica coffee brews (α = 0.05). The pH values rose as the roasting degrees increased. As reported, the pH was commonly correlated with the composition of various acids, such as formic and acetic acids during roasting in the coffee matrix [19]. However, the impact of roasting on pH is not merely a consequence of acid formation, it is also influenced by the loss of other key compounds. One significant aspect is the degradation of chlorogenic acids (CGA), which are known to contribute to the acidity and overall flavor profile of coffee. Chlorogenic acids are sensitive to heat, and their degradation begins at relatively low temperatures during the roasting process. Studies have shown that as the roasting temperature increases, chlorogenic acids are thermally degraded into other compounds, such as caffeic acid and quinic acid [20]. This degradation of chlorogenic acids during roasting diminishes the acidity, which is particularly intense in darker roasts [10]. This finding was supported by the previous research**,** higher roast degrees result in coffee brews with lower pH and total titratable acidity (TA) compared to light and medium roasts, which exhibit higher acidity and lower pH values [21]. Additionally, this degradation process is essential for understanding the sensory characteristics of coffee.

Table 1 Physicochemical properties of Liberica coffee on different roasting degrees and brewing methods.

Roasting degree	Brewing method	pH	TDS	IC_{50}
Light	Vietnam drip	5.26 ± 0.02^{a}	1.50 ± 0.10^{a}	67.34 ± 14.81^{a}
	French press	5.26 ± 0.02^{a}	1.27 ± 0.31^{a}	74.86 ± 8.71^{a}
	V60	5.26 ± 0.03^{a}	1.37 ± 0.15^{a}	75.70 ± 4.37^{a}
Medium	Vietnam drip	5.61 ± 0.05^{b}	1.73 ± 0.25^{b}	87.34 ± 4.77^{b}
	French press	5.31 ± 0.02^{a}	1.47 ± 0.25^{b}	97.90 ± 8.97^{b}
	V60	5.29 ± 0.06^{a}	1.90 ± 0.17^{b}	73.62 ± 9.27^{b}

*Data are presented as means ± standard deviation (n = 3). The different letter indicates significant differences between samples (Fisher LSD, α = 0.05).

The pH levels of coffee brewed using different methods, such as Vietnam Drip, V60, and French Press showed varied values (**Table 1**). Notably, Vietnam Drip coffee tends to have a higher pH compared to the other 2 methods, which can be attributed to differences in extraction dynamics and the resulting chemical composition of the brews. This method involves a slower drip process, which allows for a gradual extraction of flavors. The medium ground size used in Vietnam Drip impacts the flow rate and extraction efficiency, similar to the French Press, but with a different flavor profile due to the specific brewing technique and contact between water and coffee grounds [17]. In contrast, the V60 methods utilize finer grind size, which promotes a more efficient extraction of acidic compounds, leading to a brew that often exhibits higher acidity levels and lower pH. This result was aligned with the previous studies [3,21].

The investigation into the effects of roasting degree and brewing techniques on TDS in Liberica coffee revealed significant insights about these variables. Research showed that the medium roast exhibits a higher level of TDS compared to the light roast (**Table 1**), which can be attributed to the chemical transformations that occur during the roasting process. Roasting coffee beans leads to the development of various soluble compounds, including sugars and organic acids, which contribute to the overall TDS of the brew [19]. Additionally, the caramelization of sugars during roasting also contributes to the sweetness and body of the coffee, further increasing TDS levels [22].

In contrast, the brewing techniques employed, such as V60, French Press, and Vietnam Drip, have been shown to have less impact on TDS (**Table 1**). This suggests that while brewing methods can influence the extraction of certain compounds, the roasting degree is more critical in determining TDS levels. However, In Vietnam Drip and V60 brewing techniques, the brewed coffee produced high TDS values. The dripping brewing system can yield higher TDS values compared to the immersion brewing system, such as the French Press, due to the circulating water in the dripping system versus the static water in the immersion system [23]. In general, the range of TDS values in this study was slightly higher compared to the previous report which suggested that the ideal TDS content falls within the range of 1.15 - 1.35 %. The high TDS values in the coffee brews could be attributed to excessively long extraction times, leading to over-extraction [24].

The roasting degrees significantly affected antioxidant activity in anaerobic fermented Liberica coffee brews ($\alpha = 0.05$) as shown in **Table 1**. Light roast coffee brewed with the V60 technique exhibited the highest antioxidant activity, while medium roast coffee brewed with the French Press technique had the lowest antioxidant activity. The decrease in antioxidant activity with increasing roast degree could be due to the degradation of antioxidant compounds. Excessive roasting degrees cause the degradation of phenolic compounds and has an impact on reducing their antioxidant capacity [25]. However, antioxidant activities were more influenced by roasting processes than brewing techniques. This result was supported by a previous report that conducted a comprehensive investigation into the effect of different brewing methods on the antioxidant capacity of coffee. The result showed that while both roasting and coffee variety significantly modulated various metabolites and antioxidant levels, the brewing method itself did not lead to substantial differences in antioxidant activity across the samples tested [26].

Effect of roasting degrees and brewing technique on the sensory profile of anaerobically fermented liberica coffee brew

A group of 8 panelists (6 men and 2 women) who successfully passed the selection process were joined in a FGD to evaluate the sensory attributes found in Liberica coffee brew. Twenty sensory attributes were obtained on Liberica coffee consisting of odor, flavor, taste, aftertaste, and mouthfeel of coffee brewed as shown in **Table 2**.

The descriptive sensory evaluation of anaerobically fermented Liberica coffee brews demonstrated a distinct sensory characteristic influenced by both roasting degree and brewing techniques (**Figure 2**). Light-roasted coffee generally exhibited more fermentation-derived fruit and acidic characteristics such as jackfruit-like aroma and flavor, and also a sour taste. This aligns with previous research indicating that lighter roasts maintain fruit-forward attributes and higher acidity [19]. Particularly in the V60 and Vietnam Drip techniques, reflecting a stronger fermented aroma and flavor than others. In addition, the French Press allowed a lighter note of brewed coffee. On the other hand, medium-roasted coffee showed a high intensity of roasted, smoky, and caramelized flavors, with the Vietnam Drip techniques enhancing these deeper and richer notes due to extended extraction. The results suggest that medium roasts were more intended for consumers who prefer bolder and more robust flavor profiles. This variation in sensory outcomes highlights the potential of Liberica coffee and the importance of optimizing roasting and brewing techniques to target different flavor preferences.

Table 2 List of attributes in Liberica coffee brews based on light and medium roast.

Sensory attribute		**Description**
Aroma	Jackfruit	Aroma correlated with jackfruit
	Spicy	Spicy and herbal aroma
	Chocolate	Strong chocolate aroma
Flavor	Smoky	Flavor correlated with burnt smoke
	Roasted	Flavor of roasted coffee beans
	Chocolate	Rich chocolate flavor
	Caramel	Sweet caramel-like flavor
	Spicy	Spicy, herbal flavor
	Jackfruit-like	Flavor resembling jackfruit
	Dried fruit-like	Flavor or of dried fruits, like raisins
	Fermented	Flavor resembling wine fermentation
	Black tea	Flavor resembling black tea
	Earthy	Flavor resembling damp earth
Taste	Sweetness	Sweet taste derived from sugar solution
	Bitter	Bitterness from caffeine solution
	Sourness	The sour taste from a citric acid solution
Aftertaste	Bitter	Lingering bitter in the mouth
	Sweet	Lingering sweet taste in the mouth
	Astringent	Lingering astringency in the mouth
Mouthfeel	Body	The thickness or viscosity of the coffee perceived by the tongue

In general, the highest intensity of sensory attributes was found in the medium roast coffee samples brewed using the Vietnam Drip, while the samples with the lowest intensity of attributes were the light roast coffee brewed using the French Press technique. Several dominant attributes were observed in the Vietnam Drip brewing technique, including caramel and smoky aroma, smoky and roasted flavor in medium roast coffee, caramel and dried fruit flavor in light roast coffee, and bitter taste in both light and medium roasted coffee. Additionally, in the V60 brewing technique, dominant attributes included caramel and smoky aroma, smoky, roasted, and chocolate flavor, bitter taste and aftertaste, and body in medium roast coffee, as well as caramel aroma and body in light roast coffee. Furthermore, in the French Press brewing technique, dominant attributes included chocolate and smoky aroma, chocolate taste, bitter taste and aftertaste in medium roast coffee, and caramel and dried fruit aroma, caramel taste, and sweet taste in light roast coffee. This result supports a previous report that brewing techniques play a pivotal role in extracting these sensory attributes.

The brewing process of coffee is a series complex interplay of physical and chemical changes that significantly affect the flavor, aroma, and overall quality of the beverage. The primary goal of brewing coffee is to extract soluble compounds from the coffee grounds into the water. This extraction process is influenced by several factors, including water temperature, brewing time, grind size, and the brewing method employed [19,25]. During brewing, several chemical reactions occur that alter the composition of the coffee. For example, chlorogenic acids, which are abundant in coffee, can degrade during the brewing process, affecting the acidity and bitterness of the final beverage [27]. The interaction of these acids with other compounds can also lead to the formation of new flavor compounds, enhancing the complexity of the coffee's flavor profile [26]. Understanding these mechanisms allows for better control over coffee quality and the creation of unique flavor profiles suitable to consumer preferences.

In the context of the brewing techniques, the V60, Vietnam Drip, and French Press methods use distinct extraction principles, influencing coffee's flavor profile and sensory attributes. The water used was similar for all of the samples. The V60, a pour-over technique, offers precise control, yielding a clean, bright cup by filtering out oils and fine particles [3,15,28]. The French Press, using full immersion brewing, extracts more oils and sediments, producing a fuller-bodied coffee [16]. Vietnam Drip, similar to the V60, employs gravity but with a coarser grind and longer brewing time, affecting [3]. The particle size of the coffee grounds affects the extraction kinetics. Finer grinds increase the surface area, allowing for quicker extraction, while coarser grinds may require longer brewing times to achieve optimal flavor extraction. Finer grinds, as in the V60, accelerate extraction but risk bitterness, while coarser grinds, like in the French Press, require longer steeping [16,29]. Water temperature (75 - 93 °C for V60, 85 - 90 °C for Vietnam Drip and French Press) affects solubility, influencing bitterness and acidity [30]. Higher temperatures generally enhance the extraction of soluble solids, including caffeine and certain acids, which can lead to a more robust flavor profile [19]. However, excessive heat can also result in over-extraction, leading to bitterness and undesirable flavors. Despite varying extraction dynamics, statistical analysis revealed that different brewing techniques did not significantly influence the sensory perceptions of trained panelists when coffee was tasted at room temperature. This could imply that the unique characteristics imparted by each brewing method are subtle enough that they do not drastically alter the overall sensory experience when the coffee was cooled.

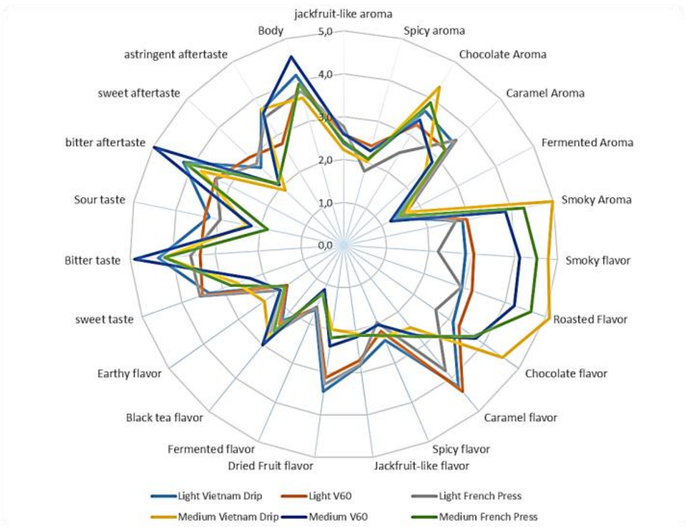

Figure 2 Sensory profile of anaerobically fermented Liberica coffee brews under varying roasting degrees and brewing techniques.

However, 13 distinct attributes exhibited significant differences ($\alpha = 0.05$) across various roasting degrees (**Figure 2**). These attributes included chocolate aroma, caramel aroma, smoky aroma, smoky flavor, roasty flavor, chocolate flavor, caramel flavor, jackfruit-like flavor, dried-fruit flavor, earthy flavor, sweetness, sourness, and body. Coffee roasting is a crucial process that transforms green beans into a flavorful product through complex chemical reactions. This transformation involves many chemical changes in the coffee beans, mainly involving the Maillard reaction and caramelization which are responsible for the formation of the final flavor [13]. The Maillard reaction, one of the most significant reactions occurring during coffee roasting involves the interaction between amino acids and reducing sugars. The extent of this reaction is influenced by the roasting temperature and time, with higher temperatures accelerating the reaction and leading to more complex flavors. In addition to the Maillard reaction, caramelization of sugars occurs during roasting, further contributing to the flavor profile of coffee. This process involves the thermal decomposition of sugars at high temperatures, resulting in the formation of various aromatic compounds that enhance sweetness and flavor complexity [31]. Chlorogenic acids (CGAs), which contribute to acidity, degrade during roasting, especially in darker roasts, increasing bitterness. The breakdown of CGAs leads to the formation of caffeic and quinic acids, altering flavor perception [32]. Volatile compounds such as aldehydes, ketones, and pyrazines, formed through the Maillard reaction and amino acid degradation, contribute to coffee's aroma, with distinct profiles depending on roasting conditions. Roasting duration also affects flavor; longer times enhance caramelization but may increase bitterness and reduce volatile compounds [13]. Balancing time and temperature is crucial for optimal sensory attributes. Understanding these mechanisms helps optimize coffee quality and meet consumer preferences. Future research should explore the interplay between roasting parameters and chemical transformations to refine flavor development further.

Based on the result of our study, Liberica coffee roasted in medium degree showed a higher intensity of chocolate aroma (**Figure 3**). The formation of chocolate aroma in coffee brews is commonly influenced by the presence of pyrazine compounds, particularly 2,3-dimethyl pyrazine. This compound is a key contributor to the chocolate aroma, which is most intense in medium-roast coffee. The roasting process plays a crucial role in the development of these pyrazine compounds, as it involves the degradation of carbohydrate compounds, leading to the formation of various volatile compounds, including pyrazines [33]. The development of chocolate flavor is following its similar aroma. It is commonly perceived due to the formation of pyrazine group compounds, particularly 2,6- dimethylpyrazine [34].

Other aromas that were perceived differently by panelists on brewed coffee from different roasting degrees were caramel aroma and flavor. These sensory characteristics in coffee are primarily produced by a group of volatile compounds, including furan (2-furan methanol), aldehyde (5-methylfurfural), and ketone (furaneol) [35]. Research indicates that furan compounds are generated from the reaction between sugars and amino acids during roasting, which can significantly enhance the caramel aroma [12]. Interestingly, our studies have shown that the intensity of caramel aroma and flavor was higher in light roast coffee compared to medium roast coffee (**Figure 3**). This sensory characteristic is commonly correlated with its chemical composition.

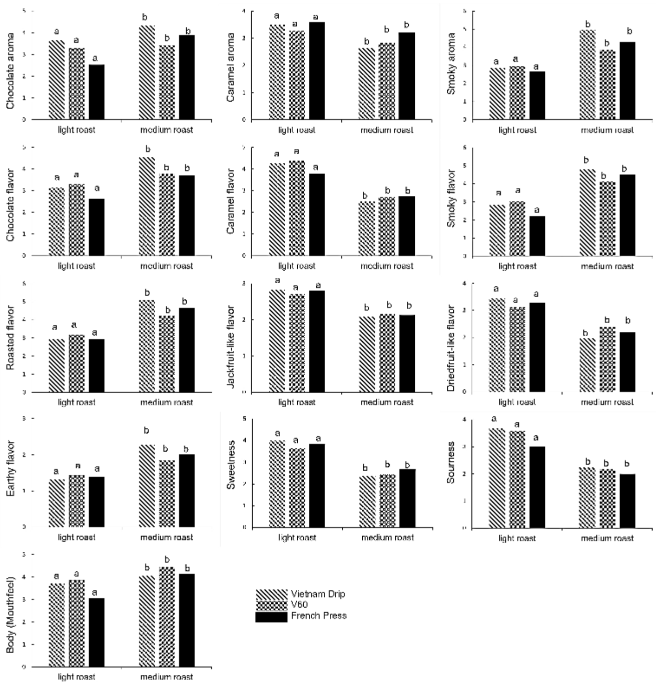

Figure 3 Sensory attributes under different roasting degrees and brewing techniques. (Different letters indicate significant differences).

Based on our findings, it was known that the intensity of smoky aroma and flavor in brewed coffee is positively correlated with the degree of roasting. As the roasting intensity increased, the intensity of these smoky attributes was higher detected (**Figure 3**). This relationship was well-documented in the literature. Smoky characteristics in brewed coffee are primarily due to the formation of phenolic compounds such as guaiacol and vinyl-guaiacol during the roasting process. The degradation of chlorogenic acids during roasting contributes to the formation of phenolic compounds, which are intended for the development of smoky flavors [35]. This aligns with previous findings which report that higher roasting intensities lead to an increase in the intensity of various aroma and flavor compounds, including those associated with smoky characteristics [36].

Our research indicates that the intensity of roasted flavors is affected by the degree of roasting, with medium-roast coffee exhibiting the highest intensity of this flavor. The formation of roasted flavor attributes in coffee is significantly influenced by pyrazine compounds, particularly 2,5-dimethyl pyrazine [33]. The previous report showed that as the degree of roasting increases, the intensity of the roasted attributes becomes more pronounced, correlating with the formation of pyrazine compounds derived from Maillard reactions during roasting. Volatile compounds such as 2,5-dimethyl pyrazine and 2,6-dimethyl pyrazine are crucial for the development of roasted flavor characteristics in coffee [37]. Furthermore, a variety of pyrazine compounds in roasted coffee, including 2,5-dimethyl pyrazine, which was identified as discriminant molecules for differentiating roasting levels among samples of the same origin [38].

The jackfruit-like flavor is one of the distinctive attributes of Liberica coffee that has been widely recognized by coffee enthusiasts. This attribute is primarily attributed to the presence of ester compounds, notably ethyl-3-methylbutyrate, which are formed during the fermentation of coffee beans. During fermentation, various biochemical reactions occur that produce esters, which contribute to the fruity and floral notes in coffee [36]. Our data in **Figure 3** showed that this flavor characteristic is significantly intense in light roasts compared to medium roasts ($\alpha = 0.05$). It can be due to the thermal degradation of these esters during the roasting process. Research indicates that the intensity of jackfruit-like flavor diminishes as the roasting level increases, as higher temperatures lead to the breakdown of these volatile compounds [3,39]. Furthermore, the masking effect of complex flavors in higher roasting degrees also plays a role in the sensory experience of coffee. As the roast level increases, complex and bold flavors are more pronounced, overshadowing the subtler notes that are characteristic of lighter roasts [40]. The lighter roasts preserve more of the original flavor compounds compared to darker roasts [34].

In addition, our findings have revealed that an anaerobically Liberica coffee brew has a hint of dried fruit-like flavor. The formation of a dried fruit-like flavor in coffee is significantly influenced by the presence of ketone compounds. Research indicates that the presence of specific ketones, such as 4-(4-hydroxyphenyl)-2-butanone, is crucial for developing the desired fruity flavors in roasted coffee. This compound is formed from the degradation of phenolic compounds during roasting, which is a critical phase where the temperature and duration of roasting significantly affect the final flavor profile [8]. In our study, the lighter roasting degree generated a higher intensity of this flavor (**Figure 3**). The prolonged roasting leads to the degradation of certain compounds while promoting the formation of others, such as phenolic compounds and various aromatic constituents through Maillard and Strecker reactions [13].

The higher temperature of roasting impacts the lower intensity of earthy flavor in Liberica coffee brew. This result was also supported by previous report, which indicated an inverse relationship between roasting level and the perception of earthy sensory attributes. Their study suggests that as the roasting temperature increases, the concentration of certain flavor compounds, including earthy notes, diminishes, leading to a reduced perception of these flavors in darker roasts [41]. The earthy flavor of coffee is primarily attributed to the presence of pyrazine compounds, such as ethyl pyrazines and ethenyl alkyl pyrazines, which are formed during the roasting process [42]. The degradation of pyrazine compounds during roasting is a critical factor influencing the intensity of earthy flavors. As roasting progresses, certain pyrazines initially increase in concentration but subsequently degrade at higher temperatures, resulting in a complex interplay of flavor compounds [43].

The sensory characteristics of Liberica coffee brewed, particularly sweetness and sourness, were also significantly influenced by the roasting degrees (**Figure 3**). Sweetness in coffee is primarily derived from compounds formed during the caramelization process, which occurs as a result of the Maillard reaction during roasting. The highest intensity of sweetness is found in light roast coffee brews, attributed to the presence of furans, 2-furancarboxaldehyde (or furfural), and 5-methyl-2-furancarboxaldehyde, which are produced early in the roasting process [44]. These compounds are formed from the thermal degradation of carbohydrates, a key aspect of caramelization. Furthermore, as roasting progresses, the concentration of sweetness-forming compounds tends to decrease, particularly at higher temperatures, which can lead to a reduction in perceived sweetness [12]. Conversely, the sour taste in coffee is largely attributed to chlorogenic acid. Their research indicates that increasing the roast level correlates with a decrease in the intensity of sourness in the brew. Specifically, they found that chlorogenic acid levels can decrease significantly at the medium roast level, which directly impacts the sour flavor profile of the coffee [2]. Moreover, the roast level plays a significant role in the overall flavor profile, including sourness. Their findings indicate that lighter roasts tend to retain more acidic and sour notes compared to darker roasts, which are characterized by a more subdued acidity and a shift toward bitter and roasted flavors [45].

Mouthfeel is a crucial sensory characteristic that significantly influences the enjoyment of coffee. In the case of Liberica coffee, our study indicates that the brewing technique does not produce significant variations in mouthfeel among panelists. This finding suggests that the brewing method may have a limited impact on the tactile sensations experienced when consuming Liberica coffee, contrasting with the effects of roasting degrees on the coffee's body (**Figure 3**). Research has shown that medium-roasted Liberica coffee tends to produce a brew with a fuller body and stronger intensity compared to light-roasted variants. The higher intensity and body of medium-roasted coffee can be largely attributed to the presence of non-dissolved compounds such as lipids. These lipids play a crucial role in enhancing the mouthfeel and richness of the brew. The lipid fraction in coffee beans constitutes about 7 - 17 % of their composition, with variations depending on the botanical origin, whereas Arabica beans contain approximately 5 % more lipids than Robusta [46]. Moreover, the roasting process itself alters the chemical composition of coffee, leading to the release of various bioactive compounds. The roasting process affects not only the antioxidant activity of coffee but also the extraction of flavor compounds, which can include lipids and other non-dissolved materials that enhance the body of the brew. The degradation of certain compounds during roasting, such as chlorogenic acids, can also lead to the formation of new compounds that contribute to the overall flavor profile and mouthfeel of the coffee [12].

In general, the roasting process of coffee beans is pivotal in determining the sensory attributes of the final brew, with significant variations observed across different roasting degrees. Understanding these dynamics is essential for optimizing roasting techniques to enhance the sensory qualities of brewed coffee, ultimately improving consumer satisfaction.

Effect of roasting degrees on the volatile compounds of anaerobically fermented liberica coffee

The roasting process of coffee significantly influences its physicochemical properties and sensory attributes, primarily through the generation and transformation of volatile compounds. Therefore, the roasted coffee beans in light and medium roast were analyzed to evaluate the composition of compounds that affected the overall characteristics of roasted coffee. In our study, the volatile compounds were evaluated based on headspace extraction. Many studies have reported various chemical compositions in coffee under various roasting conditions. Based on the HS-SPME/GC-MS analysis there were 274 compounds identified from 2 different roasted degrees, of which 72 compounds were included after validation. These compounds were categorized into 17 distinct groups (**Table 3**). The dominant groups included furans, pyrazines, and ketones, which are known to contribute to the aroma and flavor profile of roasted coffee. The roasting conditions play a crucial role in the formation of these volatile compounds. As the roasting temperature increases, various chemical reactions such as the Maillard reaction and caramelization occur, leading to the production of a wide range of aroma and flavor precursors from carbohydrates, proteins, chlorogenic acids, and trigonelline that were present in the green coffee beans [47,48].

GC MS analysis revealed that furans were the most abundant group in the anaerobically fermented Liberica coffee after the roasting process. This compound group plays a crucial role in defining the aroma and flavor profile of roasted coffee. As shown in **Table 3**, several furan compounds have been identified, with medium roast coffee exhibiting significantly higher concentrations compared to light roast. Two-furan methanol with bready sensory characteristics was identified as the highest volatile compound in roasted coffee through all the samples (135.96 ppb) [11]. Other dominant furans compounds were 5-methyl-furfural which is associated with caramel and nutty aromas, and furfural which contributed to a bready and creamy flavor [11,48]. These compounds are known to contribute bready, creamy, and caramel flavor characteristics, enhancing the overall sensory experience of coffee by imparting chocolatey and caramel flavor [37,47]. As the roasting temperature increases, the concentration of these furan compounds also rises, indicating a direct relationship between roasting conditions and the development of flavor [44].

The formation of furan compounds during the roasting process is primarily attributed to the Maillard reaction, which occurs when reducing sugars react with amino acids under heat. Furans were commonly generated from the degradation of sugar during the roasting process [11]. Although the furans group mostly contributed to the development of caramel aroma and flavor, our data showed that the intensity of caramel was pronounced higher in light roast coffee samples that have a lower concentration of furans (**Figure 3**). This phenomenon can be attributed to the limited chemical transformations that occur during light roasting, allowing certain compounds to remain prominent. The Maillard reaction not only produces furans but also a variety of other volatile compounds that contribute to the complex flavor profile of roasted coffee [47,48]. The interplay of these furan compounds with other volatile and non-volatile substances formed during roasting enhances the complexity of the coffee's aroma. As the roasting temperature increases, the diversity of Maillard reaction products increases, potentially leading to a masking effect where the intensity of caramel aroma diminishes due to interactions among various compounds [41,49]. The lighter roasts provided a more intense caramel profile due to fewer competing compounds that may mask these aromas.

Table 3 Volatile compounds of anaerobically fermented Liberica coffee under different roasting degrees by using HS-SPME/GC-MS.

No	RT (min)	Compound	CAS number	Light roast (ppb)	Medium roast (ppb)	Classification	References
1	1.66	Acetaldehyde	75-07-0	2.06	8.46	Aldehydes	[33,42]
2	2.44	Methyl formate	107-31-3	0.89	3.76	Esters	[13]
3	3.35	2,3-Butanedione	431-03-8	0.48	2.30	Ketones	[11,37,42]
4	4.37	Toluene	108-88-3	0.00	0.76	Aromatic Compounds	[13,36]
5	4.76	2,3-Pentanedione	600-14-6	0.97	2.52	Ketones	[11,13,37,42]
6	5.14	Hexanal	66-25-1	0.06	0.52	Aldehydes	[11,38]
7	5.58	Undecane	1120-21-4	0.16	0.86	Linear Alkanes	[38]
8	7.69	Pyridines	110-86-1	6.00	38.83	Pyridines	[11,31,36-38,42]
9	8.03	D-Limonene	5989-27-5	0.04	0.16	Terpenes	[38,42,50]
10	8.22	Dodecane	112-40-3	0.25	1.15	Linear Alkanes	[13,38]
11	8.43	Pyrazine	290-37-9	0.70	3.01	Pyrazines	[37,51]

No	RT (min)	Compound	CAS number	Light roast (ppb)	Medium roast (ppb)	Classification	References
12	9.24	2-(methoxymethyl)-furans	13679-46-4	0.13	0.91	Furans	[37]
13	9.56	Thiazoles	288-47-1	0.05	0.31	Thiazoles	[36,52]
14	10.06	methyl-Pyrazine	109-08-0	10.78	33.98	Pyrazines	[37]
15	10.54	4-Methylthiazoles	693-95-8	0.13	0.49	Thiazoles	[52]
16	11.02	3-Hydroxy-2-butanone (Acetoin)	116-09-6	7.93	21.55	ketones	[33]
17	11.82	Pyrazine, 2,5-dimethyl-	123-32-0	6.97	17.90	Pyrazines	[37,42]
18	12.03	Pyrazine, 2,6-dimethyl-	108-50-9	6.87	19.49	Pyrazines	[37]
19	12.16	Pyrazine, ethyl-	13925-00-3	3.27	8.80	Pyrazines	[37]
20	12.34	4-Hydroxy-3-hexanone	4984-85-4	0.40	1.67	Ketones	[13]
21	12.56	Pyrazine, 2,3-dimethyl-	5910-89-4	1.89	5.85	Pyrazines	[42]
22	13.29	1-Hydroxy-2-butanone	5077-67-8	0.57	1.81	Ketones	[37]
23	13.82	Pyrazine, 2-ethyl-6-methyl-	13925-03-6	6.05	27.83	Pyrazines	[37]
24	14.01	Pyrazine, 2-ethyl-5-methyl-	13360-64-0	3.79	9.40	Pyrazines	[37]
25	14.31	Tetradecane	629-59-4	0.73	2.90	Terpenes	[38]
26	14.39	Pyrazine, 2-ethyl-3-methyl-	15707-23-0	1.50	1.75	Pyrazines	[37]
27	14.48	Pyrazine, trimethyl-	14667-55-1	2.50	7.53	Pyrazines	[37]
28	15.30	Pyrazine, ethenyl-	4177-16-6	0.13	0.58	Pyrazines	[37]
29	15.45	Acetic acid	64-19-7	18.85	61.53	Carbonic Acids	[11,37,38]
30	15.73	Pyrazine, 3-ethyl-2,5-dimethyl-	13360-65-1	7.19	20.91	Pyrazines	[37]
31	16.09	Furfural	72321	21.03	70.72	Furans	[11,37,38,42,44,47,51]
32	16.61	Pyrazine, tetramethyl-	1124-11-4	0.19	0.77	Pyrazines	[37]
33	16.90	Pyrazine, 2-ethenyl-6-methyl-	13925-09-2	0.62	1.61	Pyrazines	[37]
34	17.15	Furfuryl formate	13493-97-5	1.34	6.82	Esters	[33,37,52]
35	17.31	2-AcetylFurans	1192-62-7	4.66	17.79	Furans	[11]
36	17.66	Pyrrole	109-97-7	0.17	0.78	Pyrroles	[11,37,38,42,44,47,52]
37	17.73	Benzaldehyde	100-52-7	0.33	1.10	Aldehydes	[11,37,38]
38	18.31	2-Butanone, 1-(acetyloxy)-	1575-57-1	1.23	1.26	Ketones	[37]
39	18.43	2-Furanmethanol acetate	623-17-6	7.50	45.86	Esters	[13,33,52]
40	18.48	Propanoic acid	65627	0.32	0.68	Carbonic Acids	[37]
41	18.66	2,3-Butanediol	513-85-9	0.08	0.73	Alcohols	[38]
42	19.41	5-methyl-Furfural	620-02-0	18.69	76.13	Furans	[11,36,37]

No	RT (min)	Compound	CAS number	Light roast (ppb)	Medium roast (ppb)	Classification	References
43	19.68	2-Acetyl-5-methylFurans	1193-79-9	0.12	0.97	Furans	[11,13,37,52]
44	19.97	2,2'-Bifuran	5905-00-0	0.3318	1.32	Furans	[33]
45	20.18	2-Acetylpyridine	1122-62-9	0.4958	1.6334	Pyridine	[33]
46	20.21	Furfuryl propionate	623-19-8	0.47	3.51	Esters	[11,13]
47	20.58	2-Acetyl-5-methylFurans	1193-79-9	0.40	2.40	Furans	[11,13,36,37]
49	20.68	2-Formyl-1-methyl pyrrole	1192-58-1	1.18	5.61	Pyrroles	[11]
50	20.77	Butyrolactone	96-48-0	0.46	1.50	Ketones	[11,37]
48	20.83	4-Hydroxybutanoic acid	591-81-1	1.73	10.44	Carbonic Acids	[33]
51	22.17	2-Furansmethanol	98-00-0	36.24	135.97	Furans	[11,13,37,48]
52	22.25	3-Acetyl-1-methyl pyrrole	932-62-7	0.35	2.14	Pyrroles	[37]
53	22.33	Isovaleric acid	503-74-2	18.20	47.43	Carbonic Acids	[38]
54	22.71	2-Thiophenecarboxaldehyde	72382	0.40	1.45	Aldehydes	[37]
55	22.84	6-Methyl-2-acetyl pyrazine	22047-26-3	1.49	5.11	Pyrazines	[33]
56	23.50	Pyrazinamide	98-96-4	1.81	7.06	Pyrazine	[13]
57	24.31	2(5H)-Furansone	497-23-4	0.47	1.56	Furans	[37]
58	24.94	Methyl salicylate	119-36-8	1.74	10.23	Esters	[36]
59	25.92	Ethyl salicylate	118-61-6	1.13	6.35	Esters	[36]
60	26.50	1-Furfurylpyrrole	1438-94-4	1.09	6.18	Pyrroles	[33]
61	27.34	2-methoxy-Phenols (guaiacol)	69519	1.12	5.62	Phenol	[33,37]
62	28.33	2-Cyclopenten-1-one, 3-ethyl-2-hydroxy-	21835-01-8	0.69	4.20	Ketones	[37]
63	28.48	3-Buten-2-one, 4-(2-Furansyl)-	623-15-4	0.08	0.82	Ketones	[37]
65	28.72	Phenylethyl alcohol	58783	0.29	2.26	Alcohols	[37,38]
66	29.56	Maltol	118-71-8	1.64	13.67	Pyranone	[13,33,37,52]
64	29.63	2-Acetylpyrrole	1072-83-9	1.90	9.53	Pyrroles	[33]
67	29.79	Furfuryl ether	4437-22-3	0.32	3.54	Furans	[11]
68	30.01	Phenols	108-95-2	0.38	3.28	Phenol	[13,33,36,37]
69	30.32	Furanseol	3658-77-3	0.78	1.91	Furans	[37]
70	33.05	Indole (Benzopyrrole)	120-72-9	0.07	0.59	Pyrroles	[36]
71	33.12	Benzoic acid	65-85-0	0.11	0.43	Carbonic Acids	[50]
72	44.36	Caffeine	57924	0.19	0.71	Alkaloids	[38,42,44]

This was also relevant for the generation of sweetness in roasted coffee. In general, its formation is correlated with the presence of furans, as well as by other non-volatile components that contribute to this sweetness. As the roasting mode increases various types of compounds are produced, one of which is caffeine, which has a bitter hint. Thus, the sweet intensity in medium roast is covered by the more dominant bitter taste. Furthermore, the higher concentration of furans in medium-dark roasted coffee correlated with the higher intensity of bold sensory characteristics such as chocolate attributes [11,36].

Other dominant groups that were found in roasted Liberica coffee samples were pyrazines. These compounds were found in higher concentrations at medium roasting degrees compared to other roasting levels (**Table 3**). Data showed that methyl-pyrazine; 2,5-dimethyl-Pyrazine; 2,6-dimethyl-Pyrazine; 2-ethyl-6-methyl-Pyrazine; and 3-ethyl-2,5-dimethyl-Pyrazine had the highest concentration of other pyrazine classes in medium roast coffee. Pyrazines, which are formed primarily through Maillard reactions during the roasting process, contribute substantially to the sensory attributes of coffee and contribute to the generating of roasted and nutty flavors that are highly valued by consumers [44]. These compounds are commonly present in varying concentrations depending on the roasting conditions. The presence of these pyrazines is essential for creating the characteristic roasted attributes of coffee and smoky flavors, which are often associated with darker roasts [36,37]. Moreover, the sensory evaluation of coffee has shown that the intensity of roasted flavors, including those derived from pyrazines, increases with the roasting level. This is particularly evident in medium roasts, often described as rich and complex, with a combination of chocolate, caramel, and nutty notes, largely attributed to the higher concentration of pyrazines and other volatile compounds formed during the roasting process. This volatile compound composition data was aligned with the results of the sensory evaluation. The higher the degree of roasting, the higher the concentration of pyrazine compounds. This has an impact on increasing the intensity of chocolate, roasted, and earthy attributes which are widely reported to be related to the presence of pyrazine compounds. Specific pyrazines, such as 2-methyl pyrazine and 2,6-dimethyl pyrazine, are particularly associated with the roasted flavor profile, reinforcing the idea that increased roasting intensity correlates with heightened sensory attributes [33,37].

In the context of roasted coffee, aldehydes and ketones were also significant volatile compounds that contribute to the overall flavor profile. Our findings showed that the concentration of these compounds is generally higher in medium-roasted samples compared to light roasts (**Table 3**). Ketones are particularly noted for imparting sweet, buttery, and creamy characteristics to coffee, while aldehydes are associated with fruity and floral odors [11,37,47]. For instance, specific ketones such as 1-acetyloxy-2-butanone and 2,3-butanedione have been identified as contributing to the buttery and caramel-like aromas that enhance the sensory experience of coffee [44]. Moreover, aldehydes such as hexanal and benzaldehyde and other related compounds are formed through the thermal degradation of carbohydrates and can contribute to the overall fruity and green notes in coffee [11,38]. As the roasting temperature increases, the concentration of both ketones and aldehydes tends to rise, indicating that higher roasting levels can enhance the development of these flavor compounds. This relationship underscores the importance of controlling roasting parameters to achieve the desired sensory attributes in the final coffee product.

The presence of ester compounds in roasted coffee was also impactful to the generation of coffee flavor, particularly in contributing to fruity sensory attributes. In our analysis, we found that medium-roasted coffee samples exhibited higher concentrations of esters, especially for 2-furfuryl acetate, ethylene acetate, and furfuryl formate. These esters are known to enhance the fruity notes in coffee [13,37]. However, this finding appears to contradict the sensory evaluation data. This fruity flavor is commonly derived from the presence of an ester compound. However, the result showed that light roast coffee that has a lower concentration of esters indicated a higher intensity of jackfruit-like and dried fruit-like flavor. The contradictory result between the chemical composition and sensory evaluation can be attributed to several factors. While esters are typically associated with fruity attributes, the overall sensory experience of coffee is influenced by a complex interplay of various volatile compounds, including aldehydes, ketones, and other aromatic substances. For instance, light roasts are often characterized by a sweeter profile with more pronounced fruity and floral notes, which may overshadow the contributions of esters [37]. This is consistent with findings that suggest lighter roasts tend to retain more of the original fruit characteristics of the coffee beans, while medium and dark roasts may alter these flavors due to the degradation of certain volatile compounds during roasting [39]. Moreover, the sensory attributes of roasted coffee are not only determined by the presence of esters. This suggests that while medium roasts may contain higher concentrations of esters, the sensory evaluation may reflect a more nuanced interaction of compounds that favors the lighter roasts for fruity characteristics.

The sensory profile of coffee was also influenced by the presence of nitrogen-containing compounds such as pyridines and pyrroles, which contribute unique characteristics of coffee brewed. The concentrations of these compounds can vary significantly depending on the roasting conditions. In our report, they are found in lower concentrations compared to pyrazines. Furthermore, as the roasting degree increased, the concentration of these compounds also increased (**Table 3**). Pyridines are known for imparting sour, resinous, roasted, and burnt notes, while pyrroles can add a roasted and smoky aroma [11,37]. The balance of these compounds is crucial for achieving a well-rounded sensory profile that appeals to coffee consumers.

In addition to nitrogen-containing compounds, terpenes also play a vital role in enhancing the complexity of coffee's aroma. Terpenes are often associated with fresh and citrus notes such as limonene, which can complement the earthy and roasted flavors contributed by pyridines and pyrroles. These terpenes can enrich the sensory profile of coffee, adding layers of complexity that appeal to consumers. Our findings also indicated that the total alcohol content varied between roasting levels, with medium roast exhibiting a higher concentration of alcohol (**Table 3**). The most abundant alcohol in the coffee sample was maltol which has been reported to contribute to sweet, caramel notes [37]. Phenols are also essential for enhancing the sensory attributes of coffee, as it has pungent and phenolic characteristics that contribute to coffee's complexity and richness in flavor [36].

Among the various acids present, acetic acid is one of the most abundant and plays a significant role in contributing to the sourness of coffee. Research indicates that acetic acid is characterized by a strong pungent, acidic, and sour flavor [11,13,37]. Other acids, such as Propanoic acid and Isovaleric acid, also contribute to the overall sourness, but their higher concentrations do not always correlate with an increase in perceived sourness intensity. Acetic acid, along with other acids, contributes to the sourness, but the perception of this sourness is not solely dependent on acid concentration. Interestingly, medium roasts, which typically have a higher concentration of acids, exhibit a lower intensity of sourness compared to light roasts (**Table 3**). This phenomenon can be attributed to the complex interactions between various flavor compounds developed during roasting. For instance, while medium roasts may contain more acids, the balance of other flavor compounds can lead to a diminished perception of sourness [41]. Conversely, light roasts tend to retain more of the original fruit characteristics of the coffee beans, resulting in a stronger detection of sourness that aligns with an increase in sweetness [41,53].

These various volatile compounds play a crucial role in shaping the overall flavor complexity of Liberica coffee. Additionally, they are suspected to be indirectly associated with umami perception, alongside their contributions to sweetness, bitterness, and acidity. However, their precise role in enhancing umami sensations remains unclear. Umami taste is primarily linked to amino acids such as glutamic acid and nucleotides like inosine monophosphate (IMP) [54,55]. Since non-volatile analysis was not conducted in our study, the presence of umami-active compounds in Liberica coffee remains unknown. The interaction between umami and other flavor compounds is complex. Roasting conditions have been reported significantly increase umami taste, suggesting that the generation of savory flavors during roasting may be linked to the formation of certain volatile compounds [56]. This indicates that while volatile compounds like furans, pyrazines, and aldehydes do not directly impart umami, they could enhance its perception when combined with taste-active compounds. Additionally, peptides and amino acids, which can be released during roasting and brewing, could further influence umami perception.

Further research is needed to explore the relationship between volatile and non-volatile compounds in coffee and to determine how roasting and brewing conditions can optimize its savory aspects.

Conclusions

Anaerobically fermented Liberica coffee (*Coffea liberica*), brewed using V60, French Press, and Vietnamese Drip techniques at light and medium roasting degrees, exhibited diverse physicochemical and sensory characteristics. Roasting degree played a more dominant role than brewing technique in influencing pH, TDS, antioxidant activity, and the sensory profile. Thirteen out of 20 sensory attributes showed significantly different intensities based on roasting degrees, with medium roast pronounced greater complexity in sensory attributes. A total of 75 volatile compounds in roasted coffee were tentatively identified using HS-SPME/GC-MS analysis, primarily from furans, pyrazines, ketones, and aldehydes groups, which significantly contribute to the sensory characteristics of brewed coffee. The concentration of volatile compounds increased with higher roasting degrees, enhancing the aroma and flavor complexity of the coffee. To enhance the quality of Liberica coffee, future research should explore optimized anaerobic fermentation conditions, such as controlled temperature, fermentation duration, and microbial inoculation, to further refine flavor development. Advanced analytical techniques like targeted metabolomics and sensory-driven profiling could further elucidate key flavor precursors and their transformations during processing. Furthermore, a consumer acceptance studies across diverse market segments would help proposed Liberica coffee profiles to specific preferences, potentially increasing its global market appeal and positioning it as a high-value specialty coffee.

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References

[1] DW Lachenmeier, P Weller, A Farah, MCA Lagman, M Fabian, MDD Castillo and S Schwarz. Shaping the future of coffee: Climate resilience, Liberica's rise, and by-product innovation—Highlights from the International Coffee Convention 2023 (ICC2023). *Foods* 2024; **13(6)**, 832.

[2] NA Wibowo, W Mangunwardoyo, TJ Santoso and Yasman. Effect of fermentation on sensory quality of Liberica coffee beans inoculated with bacteria from saliva *Arctictis binturong* Raffles, 1821. *Biodiversitas* 2021; **22(9)**, 3922-3928.

[3] DR Azizah, WB Sunarharum, T Mahatmanto, AA Kartika and L Hakim. Exploring the impact of various manual brewing techniques on the physicochemical and sensory characteristics of brewed coffee. *In*: Proceedings of the 1st International Conference on Tropical Agroforestry in Indonesia, Malang, Indonesia. 2024.

[4] D Athinuwat, A Klomchit, K Phonwong, R Nachalaem, P Thammakulkrajang and S Brooks. Assessing the impact of yeast fermentation in dry processing on coffee quality from *Coffea arabica* cv. Caltimor, *C. arabica* cv. Bourbon, and *C. canephora* cv. Robusta. *Trends in Sciences* 2024; **21(10)**, 8132.

[5] M Várady, J Boržíková and P Popelka. Effect of processing method (natural, washed, honey, fermentation, maceration) on the availability of heavy metals in specialty coffee. *Heliyon* 2024; **10(3)**, e25563.

[6] TS Pereira, NN Batista, LPS Pimenta, SJ Martinez, LS Ribeiro, JAO Naves and RF Schwan. Self-induced anaerobiosis coffee fermentation: Impact on microbial communities, chemical composition, and sensory quality of coffee. *Food Microbiology* 2022; **103**, 103962.

[7] LCF Silva, PVR Pereira, MADD Cruz, GXR Costa, RAR Rocha, PLL Bertarini, LRD Amaral, MS Gomes and LD Santos. Enhancing sensory quality of coffee: The impact of fermentation techniques on *Coffea arabica* cv. Catiguá MG2. *Foods* 2024; **13(5)**, 653.

[8] D Herawati, MO Loisanjaya, RH Kamal, DR Adawiyah and N Andarwulan. Profile of bioactive compounds, aromas, and cup quality of Excelsa coffee (*Coffea liberica* var. *dewevrei*) prepared from diverse postharvest processes. *International Journal of Food Science* 2022; **2022**, 2365603.

[9] A Analianasari, D Berliana and S Shintawati. Defects of coffee beans with different postharvest processes and roasting temperatures on volatile compounds of coffee beans from coffee small-scale industries of West Lampung Indonesia. *Trends in Sciences* 2024; **21(7)**, 7695.

[10] I Laukaleja, Z Kruma and I Cinkmanis. Impact of the roast level on chemical composition of coffee from Colombia. *Proceedings of the Latvian Academy of Sciences. Section B: Natural, Exact, and Applied Sciences* 2022; **76(1)**, 145-151.

[11] T Dippong, M Dan, MH Kovacs, ED Kovacs, EA Levei and O Cadar. Analysis of volatile compounds, composition, and thermal roasting intensity. *Foods* 2022; **11(19)**, 3146.

[12] WB Setianto, H Yohanes, G Atmaji, M Susanto, EP Astin and Lanjar. The effect of fluidized bed roaster temperature on the roasted coffee beans antioxidant activity and its sensory evaluation. *IOP Conference Series: Earth and Environmental Science* 2023; **1246**, 12005.

[13] W Choe, JH Woo, M Hong, H Jang, P Deepa and S Kim. Determination of aromatic profiles of coffee beans according to different roasting times by SPME/GC-MS analysis. *Journal of Applied Pharmaceutical Science* 2023; **13(10)**, 157-171.

[14] I Laukaleja and Z Kruma. Influence of the roasting process on bioactive compounds and aroma profile in specialty coffee: A review. *In*: Proceedings of the 13th Baltic Conference on Food Science and Technology, Jelgava, Latvia. 2019, p. 7-12.

[15] AS Santanatoglia, G Caprioli, M Cespi, D Ciarlantini, L Cognigni, L Fioretti, F Maggi, AM Mustafa, F Nzekoue and S Vittori. A comprehensive comparative study among the newly developed Pure Brew method and classical ones for filter coffee production. *LWT* 2023; **175**, 114471.

[16] B Lapčíková, L Lapčík, P Barták, T Valenta and K Dokládalová. Effect of extraction methods on aroma profile, antioxidant activity, and sensory acceptability of specialty coffee brews. *Foods* 2023; **12(22)**, 4125.

[17] R Fadhil, D Nurba and E Sukmawati. Sensory assessment of Gayo Arabica coffee taste based on various varieties and manual brewing devices. *Coffee Science* 2021; **16**, e161918.

[18] S Cortés-Diéguez, C Otero-Cerviño, H Rodeiro-Mougán and JA Feijóo-Mateo. Quantitative descriptive analysis of traditional herbal and coffee liqueurs made with grape marc spirit (orujo). *Foods* 2020; **9(6)**, 753.

[19] NZ Rao, M Fuller and MD Grim. Physiochemical characteristics of hot and cold brew coffee chemistry: The effects of roast level and brewing temperature on compound extraction. *Foods* 2020; **9(7)**, 902.

[20] H Jeong, S Yoon, SM Jo, SJ Hong, YJ Kim, JK Kim and EC Shin. Chemical sensory investigation in green and roasted beans *Coffea arabica* L. (cv. Yellow Bourbon) by various brewing methods using electronic sensors. *Journal of Food Science* 2023; **88(3)**, 1033-1047.

[21] LDO Silva, CP Rosado, FDS Ferreira, J Melengati, S Terra and AJ Teodoro. The effect of brewing method and different roasting degree on physicochemical characteristics, total phenolic content and antioxidant activity of Amazonian Robusta coffee (*Coffea canephora*). *Revista de Gestão Social e Ambiental* 2024; **18(9)**, e06197.

[22] NH Zakaria, K Whanmek, S Thangsiri, W Chathiran, W Srichamnong, U Suttisansanee and C Santivarangkna. Optimization of cold brew coffee using central composite design and its properties compared with hot brew coffee. *Foods* 2023; **12(12)**, 2412.

[23] G Angelonia, L Guerrini, P Masella, M Bellumori, S Daluiso, A Parenti and M Innocenti. What kind of coffee do you drink? An investigation on effects of eight different extraction methods. *Food Research International* 2019; **116**, 1327-1335.

[24] WB Sunarharum and M Farhan. Effect of manual brewing techniques on the sensory profiles of Arabica coffees (Aceh Gayo *wine process* and Bali Kintamani *honey process*). *In*: Proceedings of the International Conference on Agriculture, Environment and Food Security, Medan, Indonesia. 2020.

[25] L Pan, Y Xiao, F Jiang, T Jiang, J Zhu, W Tang, X Liu, Y Zhou and L Yu. Comparison of characterization of cold brew and hot brew coffee prepared at various roasting degrees. *Journal of Food Processing and Preservation* 2023; **2023(1)**, 3175570.

[26] PV Nerurkar, J Yokoyama, K Ichimura, S Kutscher, J Wong, HC Bittenbender and Y Deng. Medium roasting and brewing methods differentially modulate global metabolites, lipids, biogenic amines, minerals, and antioxidant capacity of Hawai‘i-grown coffee (*Coffea arabica*). *Metabolites* 2023; **13(3)**, 412.

[27] S Yildirim, I Gok, E Demir and O Tokusoglu. Use of electrochemical techniques for determining the effect of brewing techniques (espresso, Turkish and filter coffee) and roasting levels on total antioxidant capacity of coffee beverage. *Journal of Food Processing and Preservation* 2022. https://doi.org/10.1111/jfpp.16626.

[28] WB Sunarharum, R Ahmad and E Primadiani. Effect of different manual brewing techniques to the sensory profile of the Indonesian Arabica and Robusta ‘natural coffees’. *In*: Proceedings of the International Conference on Green Agro-industry and Bioeconomy, Malang, Indonesia. 2020.

[29] M Várady, J Tauchen, P Klouček and P Popelka. Effects of total dissolved solids, extraction yield, grinding, and method of preparation on antioxidant activity in fermented specialty coffee. *Fermentation* 2022; **8(8)**, 375.

[30] WD Ristenpart, AR Cotter and JX Guinard. Impact of beverage temperature on consumer preferences for black coffee. *Scientific Reports* 2022; **12(1)**, 20621.

[31] MC Pham, NY Dinh and PH Le. Coffee volatile compounds. *International Journal of Food Science and Nutrition* 2023; **8(3)**, 50-57.

[32] S Awwad, R Issa, L Alnsour, D Albals and I Al-Momani. Quantification of caffeine and chlorogenic acid in green and roasted coffee samples using HPLC-DAD and evaluation of the effect of degree of roasting on their levels. *Molecules* 2021; **26(24)**, 7503.

[33] P Zakidou, F Plati, A Matsakidou, EM Varka, G Blekas and A Paraskevopoulou. Single origin coffee aroma: From optimized flavor protocols and coffee customization to instrumental volatile characterization and chemometrics. *Molecules* 2021; **26(15)**, 4609.

[34] DR Seninde and IVE Chambers. Coffee flavor: A review. *Beverages* 2020; **6(3)**, 44.

[35] H Wu, P Lu, Z Liu, J Sharifi-Rad and HAR Suleria. Impact of roasting on the phenolic and volatile compounds in coffee beans. *Food Science and Nutrition* 2022; **10**, 2408-2425.

[36] SC Frost, P Walker, CM Orians and A Robbat. The chemistry of green and roasted coffee by selectable 1D/2D gas chromatography mass spectrometry with spectral deconvolution. *Molecules* 2022; **27(16)**, 5328.

[37] H Zhai, W Dong, Y Tang, R Hu, X Yu and X Chen. Characterization of the volatile flavour compounds in Yunnan Arabica coffee prepared by different primary processing methods using HS-SPME/GC-MS and HS-GC-IMS. *LWT* 2024; **192**, 115717.

[38] F Vezzulli, M Lambri and T Bertuzzi. Volatile compounds in green and roasted Arabica specialty coffee: Discrimination of origins, post-harvesting processes, and roasting level. *Foods* 2023; **12(3)**, 489.

[39] M Bolka and S Emire. Effects of coffee roasting technologies on cup quality and bioactive compounds of specialty coffee beans. *Food Science and Nutrition* 2020; **8(11)**, 6120-6130.

[40] WB Sunarharum, T Mahatmanto, DY Ali, YP Prananto, N Efrat, NE Asih and NG Mirillia. Sensory and physicochemical characteristics of two common roast defects in Robusta coffee. *International Journal of Advanced Science Engineering and Information Technology* 2022; **12(1)**, 394-402.

[41] A Pinsuwan, S Suwonsichon, P Chompreeda and W Prinyawiwatkul. Sensory drivers of consumer acceptance, purchase intent and emotions toward brewed black coffee. *Foods* 2022; **11(2)**, 180.

[42] WB Sunarharum, DJ Williams and HE Smyth. Complexity of coffee flavor: A compositional and sensory perspective. *Food Research International* 2014; **62**, 315-325.

[43] Y Zou, M Gaida, FA Franchina, PH Stefanuto and JF Focant. Distinguishing between decaffeinated and regular coffee by HS-SPME-GC×GC-TOFMS, chemometrics, and machine learning. *Molecules* 2022; **27(6)**, 1806.

[44] N Chindapan, C Puangngoen and S Devahastin. Profiles of volatile compounds and sensory characteristics of Robusta coffee beans roasted by hot air and superheated steam. *International*

Journal of Food Science and Technology 2021; **56(8)**, 3814-3825.

[45] SE Yeager, ME Batali, LX Lim, J Liang, J Han, AN Thompson, JX Guinard and WD Ristenpart. Roast level and brew temperature significantly affect the color of brewed coffee. *Journal of Food Science* 2022; **87(4)**, 1837-1850.

[46] N Stanek, M Zarębska, Ł Biłos, K Barabosz, E Nowakowska-Bogdan, I Semeniuk, J Błaszkiewicz, R Kulesza, R Matejuk and K Szkutnik. Influence of coffee brewing methods on the chromatographic and spectroscopic profiles, antioxidant and sensory properties. *Scientific Reports* 2021; **11**, 21377.

[47] DAL Meireles, ASB Valdez, M Boroski, SC Augusto and AT Toci. Effects of pollination on the composition of volatile compounds in *Coffea arabica* L. *Journal of the Science of Food and Agriculture* 2022; **102(11)**, 4955-4960.

[48] R Rusinek, JB Dobrzański, A Oniszczuk, M Gawrysiak-Witulska, A Siger, H Karami, AA Ptaszyńska, A Żytek, K Kapela and M Gancarz. How to identify roast defects in coffee beans based on the volatile compound profile. *Molecules* 2022; **27(23)**, 8530.

[49] M Latief, Muhaimin, Heriyanti, IL Tarigan and Sutrisno. Determination antioxidant activity of *Coffea arabica*, *Coffea canephora*, *Coffea liberica* and sunscreens cream formulation for sun protection factor (SPF). *Pharmacognosy Journal* 2022; **14(2)**, 335-342.

[50] E Alamri, M Rozan and H Bayomy. A study of chemical composition, antioxidants, and volatile compounds in roasted Arabic coffee. *Saudi Journal of Biological Sciences* 2022; **29(5)**, 3133-3139.

[51] CDC Couto, DWH Chávez, EMM Oliveira, O Freitas-Silva and S Casal. SPME-GC-MS untargeted metabolomics approach to identify potential volatile compounds as markers for fraud detection in roasted and ground coffee. *Food Chemistry* 2024; **446**, 138862.

[52] AM Obando and JG Figueroa. Effect of roasting level on the development of key aroma-active compounds in coffee. *Molecules* 2024; **29(19)**, 4723.

[53] L Anokye-Bempah, T Styczynski, NDAT Fernandes, J Gervay-Hague, WD Ristenpart and IR Donis-González. The effect of roast profiles on the dynamics of titratable acidity during coffee roasting. *Scientific Reports* 2024; **14**, 8237.

[54] J Zhao, J Lin, J Yan, C Zhang, T Wang and B Gan. Evaluation of the nutritional value, umami taste, and volatile organic compounds of *Hypsizygus marmoreus* by simulated salivary digestion *in vitro*. *Current Research in Food Science* 2023; **7**, 100591.

[55] F Yang, H Meng, A Fu, Y Liu and S Bi. Quantification- and structural-taste intensity of umami peptides from *Agrocybe aegerita* through quantitative structure-activity relationship. *Food Chemistry* 2024; **455**, 139919.

[56] Y Lee and KG Lee. Effects of pan- and air fryer-roasting on volatile and umami compounds and antioxidant activity of dried laver (*Porphyra dentata*). *Food Chemistry* 2024; **458**, 140289.