Comprehensive Characterisation of the Robusta Coffee Postharvest Processes: Insight into Physicochemical, Volatile Compounds, and Sensory Preferences

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ABSTRACT

This study investigated how different postharvest processes, specifically wet, semi-wet, and hybrid methods, affect the physicochemical quality and aroma profile of Menoreh Robusta coffee. We mapped the volatile composition of roasted coffee beans using solid-phase microextraction coupled with gas chromatography-mass spectrometry (SPME-GCMS). All samples met the physical standards of the Indonesian National Standard for green beans and the Specialty Coffee Association, but their chemical compositions varied significantly. Principal component analysis (PCA) revealed distinct clustering, confirming that each processing imparts unique chemical signatures to the final product. The hybrid process proved superior in maintaining nutrient density, resulting in higher glucose, fructose, chlorogenic acid, caffeine, fat, protein, and crude fibre contents compared to the other methods. The wet process maximised antioxidant properties, evidenced by the lowest DPPH IC_{50} value (7.51 ppm) and the highest ABTS radical scavenging activity (88.32%), as well as the highest total flavonoid (181.22 mg QE/g) and phenolic (139.45 mg GAE/g) levels. Meanwhile, the semi-wet sample had the highest carbohydrate content (65.66%). Analysis of volatile compounds revealed a complex chemical matrix involving ketones, pyrazines, and esters, among others. Sensory assessments showed that although approximately 35% of flavour attributes were similar across treatments, the flavour profile was dominated by distinctive aromas of brown sugar, spices, coconut milk, chocolate, and rubber. All postharvest treatments

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yielded cupping scores exceeding 80, validating the classification of the Robusta Menoreh as a Fine Robusta regardless of the processing strategy used.

Keywords: Flavour characteristics, coffee Robusta, quality, postharvest processing, PCA, PLS-R, SPME-GCMS

INTRODUCTION

Indonesia is the world's fourth-largest coffee producer, with Robusta coffee being the primary source. According to national statistics, over 99% of Indonesian coffee comes from small-scale plantations (Indonesia Ministry of Agriculture, 2022). The Robusta coffee is often associated with a strong, bitter, and earthy flavour, leading to a perception that it is less desirable than Arabica (Liu et al., 2021), although this depends on culture and personal preference. Many consumers tend to prefer Arabica due to its more complex flavour profile (Velásquez & Banchón, 2023), underscoring the importance of improving postharvest handling for the Robusta. Flavour plays a central role in shaping quality perceptions and directly influences price formation and market value (Elhalis et al., 2023). By improving the Robusta's quality, there is clear potential to broaden consumer acceptance and strengthen its position in the coffee market.

The postharvest process produces green beans, which are a crucial foundation for coffee quality. At this stage, green beans carry various flavour precursors that will emerge during roasting (Leblanc, 2021) and determine the coffee's final sensory characteristics (Mulato, 2019). These precursor components include non-volatile compounds related to physicochemical properties and volatile compounds formed during fermentation, which collectively contribute to the overall flavour and sensory perception of coffee (de Oliveira Junqueira et al., 2019; Yusibani et al., 2023).

Physical characteristics of green coffee beans, such as bean colour, water activity, size, and bulk density, influence heat transfer during roasting, thus influencing the development of the Maillard reaction and the formation of complex flavour compounds (Gonzalez-Sanchez et al., 2024; Pereira et al., 2021). In parallel, chemical components, including caffeine, which contributes to bitterness; chlorogenic acid, which influences flavour complexity and potential health benefits; and other phenolic compounds associated with bitterness and astringency, further shape the sensory characteristics of brewed coffee (Mónica Lois et al., 2024; Reza et al., 2023).

The Robusta coffee plays a strategic role in Indonesia, as it is one of the main export priorities for plantation commodities (Syamsuri, 2023). Meanwhile, its flavour characteristics are strongly influenced by diverse local terroirs, yet to date, it remains relatively under-explored scientifically. Variations in climate, soil conditions, and altitude contribute to the complexity and diversity of the sensory characteristics of the Indonesian Robusta (Putri et al., 2019), which holds great potential for developing product quality and differentiation.

Recent advances in postharvest processing, particularly anaerobic fermentation, have opened up new possibilities for enhancing coffee flavour. These techniques can alter key flavour precursors, such as amino acids and sugars, which participate in the Maillard reaction during roasting and play a crucial role in shaping the coffee's final sensory profile (Cao et al., 2023; Leblanc, 2021; Yusibani et al., 2023).

Solid-phase microextraction combined with gas chromatography-mass spectrometry (SPME-GC-MS) provides a solvent-free and efficient approach to profile volatile compounds in roasted coffee, allowing its complex aromas to be captured with minimal sample preparation (Obando & Figueroa, 2024). This technique is suitable for quality assessment and for evaluating how postharvest practices affect aroma development.

In this study, we examined the effect of three postharvest processing methods (wet, semi-wet, and hybrid) on the physicochemical properties and flavour profile of the Robusta coffee. By identifying specific volatile compounds associated with sensory preferences, these findings will provide a scientific basis for optimising postharvest processes, enabling farmers to improve the product consistency and market competitiveness of the Robusta coffee.

MATERIALS AND METHODS

Coffee Postharvest Processes

Ripe red Robusta coffee cherries were collected from smallholder farms in the Samigaluh Subdistrict, Menoreh Hills, Yogyakarta, Indonesia (≈900 m a.s.l.), during the July-September 2023 dry season. The area experiences low rainfall (<50 mm/month), daytime temperatures of 21-30 °C, and is characterised by well-drained volcanic Inceptisol soils. Fermentation treatments were selected to reflect postharvest practices commonly used by local smallholder farmers.

Three postharvest processing methods were applied: wet (removal of skin, pulp, and mucilage followed by 24-hour fermentation and washing), semi-wet (removal of skin, pulp, and mucilage without fermentation), and hybrid (removal of skin, pulp, and mucilage followed by 72-hour anaerobic fermentation in sealed plastic bags). After processing, all beans were sun-dried on raised racks for approximately two weeks. Each treatment was replicated four times, with 5 kg of cherries per replicate. Green beans were evaluated for physical and chemical properties, while roasted beans were analysed for volatile compounds and sensory characteristics.

Physical Characteristics Determination

Green bean defects were classified according to the Indonesian National Standard (SNI 2907:2008). Bean colour (*L*, a*, b**) was measured using a chroma meter (Spectra Magic

NX Pro, Konica Minolta). Bulk density and bean volume were determined following the method described by Widyotomo (Widyotomo et al., 2010). Water activity was measured at 25 °C using an Aqualab 4TE, while pH was determined in a 1:20 water-sample slurry using a calibrated LAQUA twin metre to ensure consistent and reliable measurements across treatments (Emanuel et al., 2025).

Chemical Characteristics Determination

Proximate composition was analysed using standard methods. Moisture, ash, and crude fibre contents were determined gravimetrically; crude protein was measured using the Kjeldahl method; crude fat was determined by Soxhlet extraction with *n*-hexane; and total carbohydrate content was calculated by difference (Thiex, 2009). Hot water extraction was applied as a standardised approach for extracting polar coffee constituents. Green beans (5 g) were extracted in ultrapure water at 90 °C for 1 min following a previously reported protocol (Yulianti et al., 2022) with minor modifications. The extract was immediately cooled in an ice bath and vortex-mixed for 2 min to rapidly quench thermal effects and ensure homogenisation, followed by centrifugation. The supernatant was filtered (0.22 μm) for sugar, caffeine, and chlorogenic acid (CGA). Aliquots of the same filtered supernatant were used as stock solutions for the determination of total flavonoid content (TFC), total phenolic content (TPC), and antioxidant activity determined by IC_{50} of 2,2-Diphenyl-1-Picrylhydrazyl (DPPH) and ABTS radical scavenging assays, following established methods (Priftis et al., 2015; Wołosiak et al., 2022). For the ABTS assay, Trolox was used as a reference antioxidant (TEAC; μmol Trolox equivalents/g sample), and aliquots of the filtered extract were serially diluted (50,000-3,125 ppm) for analysis. Identical extraction conditions were applied across all treatments to enable valid relative comparisons.

Sugars (glucose, fructose, sucrose) were quantified by UHPLC-CAD using an Aminex HPX-87H column with acetonitrile-water (80:20; v/v) as mobile phase. Sugar identification and quantification were based on retention times and external calibration curves over a range of 50-2500 ppm. Limit of detection (LOD) 0.03 ppm for glucose, 0.13 ppm for sucrose, and 0.16 ppm for fructose, respectively, with correlation coefficients (R) = 0.99 for all sugars. To minimise the matrix effects, all samples were analysed under identical conditions within the detector's linear range; therefore, sugar concentrations are interpreted comparatively rather than as absolute values.

Caffeine and CGA were determined by HPLC-UV/Vis using the Zorbax C18 columns. (Yulianti et al., 2022). Caffeine was detected at 254 nm, with concentration determined from a five-point calibration curve (20-100 mg/L) with a LOD of 0.04 ppm and R = 0.99. CGA detection occurred at 320 nm, determining CGA concentration via a five-point calibration curve, with a LOD of 0.01 ppm and R = 0.99. TFC was determined spectrophotometrically at 435 nm using quercetin as the reference standard (Stankovic, 2011), while TPC was

measured at 765 nm with gallic acid as the standard (Wu et al., 2022). Antioxidant activity was evaluated using the DPPH radical scavenging assay, with IC_{50} values calculated from absorbance at 517 nm (Fadilah & Happyana, 2024), alongside the ABTS assay (Thaipong et al., 2006).

Profiling Volatile Compounds via SPME-GCMS

Coffee samples were roasted according to SCA guidelines for the Robusta coffee using a laboratory-scale roaster with a 250 g batch size. The roaster was preheated to 190-200 °C, and all samples were processed using the same heat input profile. Roasting was carried out to a medium-dark level, with final temperatures of approximately 210-220 °C reached within 9-11 minutes (around ±3 minutes after first crack). After roasting, all samples were cooled using the same procedure and subsequently analysed for volatile compounds using SPME-GC-MS (Caporaso et al., 2018). Ground roasted (100 mg in 5 mL vial) was equilibrated for 10 min (40°C), followed by fibre exposure (20 min), and injection (5 min) with a 1 cm 50/30 µm DVB/Carboxen/PDMS fibre. GC analysis was performed using a Zebron ZB-WAX column with helium as the carrier gas at a flow rate of 1 mL/min. The oven temperature was held at 40 °C for 5 minutes, increased to 180 °C at 3 °C/min, and then raised to 250 °C at 10 °C/min with a final hold of 5 minutes. The ion source and interface temperatures were set to 300 °C and 275 °C, respectively. Mass spectra were recorded in electron impact mode (70 eV) over an m/z range of 50-350 with a scan time of 2 seconds (Akiyama et al., 2007; Ribeiro et al., 2018). Volatile compounds were identified using NIST mass spectral library matching, based on the similarity index values, characteristic fragmentation patterns, consistent retention times with known coffee volatiles, and reproducible detection across samples, with relative abundances expressed as peak area percentages.

Sensory Analysis

Sensory evaluation was conducted using the SCA Robusta cupping protocol (SCAA, 2009; UCDA, 2010) by four trained panellists from the Indonesian Coffee and Cocoa Research Institute. Attributes assessed included fragrance, flavour, aftertaste, acidity, sweetness, balance, cleanliness, body, and overall quality. Prior to evaluation, panellists completed a brief calibration session using reference coffees to align sensory descriptors, and all samples were cupped under standardised conditions. The panel size was selected to support descriptive and comparative profiling and an exploratory multivariate framework. To minimise sensory fatigue, sample presentation was randomised, the number of samples per session was limited, and palate cleansing with water was applied between evaluations. Coffee samples receiving a final score of 80 or above were designated as the Fine Robusta.

Statistical Analysis

Data were analysed using one-way ANOVA followed by Duncan's Multiple Range Test (DMRT). Principal Component Analysis (PCA) was used for dimensionality reduction and visualisation of grouping patterns based on standardised green bean chemical variables averaged by treatment and was intended for descriptive rather than inferential interpretation. While Pearson correlation assessed variable relationships. Partial Least Squares Regression (PLS-R) was applied to model the relationship between physicochemical traits and volatile groups, and the influence of volatiles on sensory preferences. It was applied as an exploratory, cross-validated approach with restricted latent components to examine associative covariance among physicochemical traits, volatile groups, and sensory attributes while minimising overfitting. VIP scores were used as relative contribution indicators and not for strict variable selection or inferential conclusions. All analyses were performed using XLSTAT software.

RESULTS AND DISCUSSION

The fermentation method used in this study was selected to reflect prevailing postharvest practices used by smallholder coffee farmers in the Samigaluh (Menoreh Hills) rather than laboratory-optimised conditions. On the Indonesian island of Java, wet fermentation typically lasts 24 hours to help break down the mucilage. Hybrid anaerobic fermentation, on the other hand, typically lasts 72 hours, allowing biochemical changes to occur over a longer period with less oxygen exposure.

Coffee Bean Physical Characterisations

According to SNI 2907:2008, green coffee in the first quality category must have a maximum defect rate of 11%, as defects may lead to bland or bitter flavours. In this study, all postharvest processing methods produced beans within quality I limits, despite the presence of some internal defects (Figure 1b-f).

Agricultural and environmental factors primarily influence coffee's physical characteristics rather than postharvest processing, though they still affect the roasted coffee flavour (Zainuri et al., 2023). Postharvest processings show no significant differences in defects, bulk density, bean volume, water activity, or moisture content (Table 1), which may be attributed to uniformity of raw materials, including origin, variety, and cherry ripeness.

Green beans density classified as low (0.55-0.64), medium (0.65-0.67), or high (0.68-0.70) (Helena Coffee Processing & Export, 2021). In this study, all green beans had a high bulk density of 0.69 to 0.70 g/cm³ (Table 1). High-density beans require more heat and time during roasting, leading to a more complex flavour (Obando & Figueroa, 2024).

Green beans should have 9%-12% moisture content (Indonesian National Standard, 2008), 0.70 maximum water activity (SCA, 2018), which all treatments achieved. The
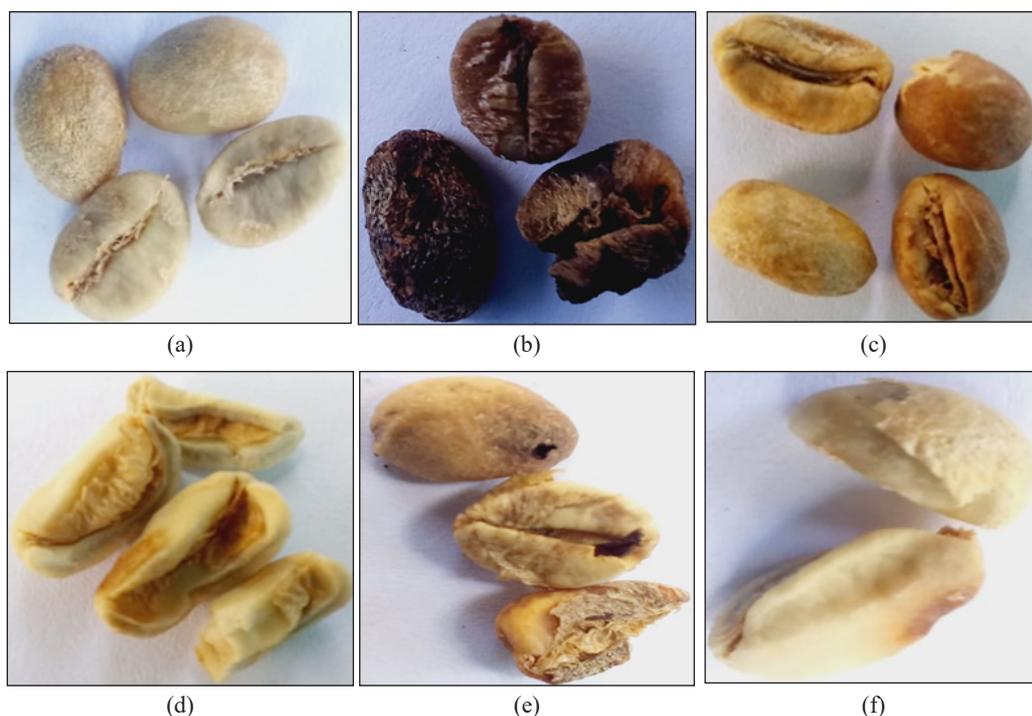
Figure 1. Green coffee beans: (a) Desirable beans vs. internal defects, including (b) Black, (c) Brown, (d) Broken, (e) Hollow, and (f) Shrivelled beans of the Robusta coffee

Table 1

Green bean physical characteristics obtained from three postharvest processes

Physical characteristics	Postharvest processes		
	Wet	Semi-wet	Hybrid
Green bean defect (%)	5.83 ± 1.22[a*]	6.67 ± 1.61[a]	8.33 ± 1.65[a]
Bulk density (g/cm³)	0.70 ± 0.01[a]	0.69 ± 0.02[a]	0.69 ± 0.01[a]
Bean volume (mm³)	425.37 ± 30.48[a]	430.73 ± 37.81[a]	440.70 ± 47.51[a]
Water activity	0.55 ± 0.01[a]	0.58 ± 0.00[b]	0.57 ± 0.00[b]
Moisture (%)	9.20 ± 0.09[a]	9.26 ± 0.08[a]	9.16 ± 0.01[a]
Colour			
L*	42.65 ± 0.06[b*]	43.55 ± 0.01[c]	41.48 ± 0.04[a]
a*	4.97 ± 0.02[b]	4.56 ± 0.02[a]	5.61 ± 0.01[c]
b*	20.53 ± 0.05[a]	21.10 ± 0.08[c]	20.76 ± 0.02[b]

Note. Mean values assigned to the same letter indicate no significant difference at the 5% level based on DMRT (α = 5%)

semi-wet and hybrid processes had higher water activity (0.58% and 0.57%) compared to wet processes (0.55%) due to slower drying with pulp attached (Table 1). Higher water activity reduces air content, enhancing flavour during roasting (Putri et al., 2023)

Postharvest methods influence coffee bean colour and roasting quality (Yulianti et al., 2022), with wet and semi-wet methods producing brighter greens and hybrid methods resulting in darker brown beans (Table 1), indicating longer anaerobic fermentation. Prolonged fermentation increases enzymatic and microbial activity, leading to compound degradation and noticeable changes in bean colour (Obando & Figueroa, 2024).

Coffee Bean Chemical Characteristics

The Robusta coffee beans' chemical characteristics differ greatly depending on the postharvest processing technique used. Key differences were observed in fat, crude fibre, sugar content, caffeine, chlorogenic acid, and antioxidant activity, indicating that processing techniques influence the chemical quality of green beans (Table 2).

Table 2
Green bean chemical characteristics obtained from three postharvest processes

Chemical characteristics	Postharvest processes		
	Wet	Semi-wet	Hybrid
Fat %	$6.46 \pm 0.06^{a*}$	6.79 ± 0.06^{b}	7.76 ± 0.06^{c}
Ash %	4.12 ± 0.02^{a}	4.27 ± 0.22^{a}	4.35 ± 0.04^{a}
Crude fibre %	18.19 ± 0.00^{b}	17.90 ± 0.02^{a}	19.96 ± 0.06^{c}
Protein %	14.32 ± 0.05^{ab}	14.24 ± 0.08^{a}	14.72 ± 0.36^{b}
Carbohydrate %	65.37 ± 0.44^{b}	65.66 ± 0.10^{b}	63.86 ± 0.10^{a}
Glucose %	0.05 ± 0.00^{a}	0.12 ± 0.00^{b}	0.17 ± 0.00^{c}
Fructose %	0.29 ± 0.00^{a}	0.51 ± 0.02^{b}	0.78 ± 0.03^{c}
Sucrose %	5.18 ± 0.55^{b}	4.96 ± 0.26^{a}	5.47 ± 0.64^{c}
pH of green bean	5.93 ± 0.03^{a}	5.90 ± 0.09^{a}	4.75 ± 2.13^{a}
pH roasted bean	5.17 ± 0.03^{b}	5.17 ± 0.03^{b}	5.10 ± 0.04^{a}
Chlorogenic acid (%)	$0.21 \pm 0.00^{a*}$	0.41 ± 0.02^{b}	0.48 ± 0.10^{b}
Caffeine (%)	2.21 ± 0.00^{a}	2.45 ± 0.30^{ab}	2.80 ± 0.30^{b}
Antioxidant activity by IC_{50} value of DPPH (ppm)	7.51 ± 2.53^{a}	12.88 ± 3.07^{b}	11.58 ± 1.21^{ab}
ABTS (%)	88.32 ± 1.40^{a}	85.44 ± 0.54^{b}	84.28 ± 0.47^{c}
TFC (QE mg/g)	139.45 ± 6.08^{b}	96.68 ± 6.05^{a}	109.30 ± 14.80^{a}
TPC (GAE mg/g)	181.22 ± 13.71^{c}	125.37 ± 6.84^{a}	154.84 ± 10.91^{b}

Note. Mean values assigned to the same letter indicate no significant difference at the 5% level based on DMRT. TFC and TPC represent total flavonoid and phenolic contents, respectively

The Robusta green bean fat content has been reported to range from 10% - 16.29% (Speer & Kölling-Speer, 2006; M. Zhu et al., 2021). In this study, lower contents (4.46-7.76%) were observed, which may be attributed to the genetic background, environmental conditions, and cultivation practices specific to the study area (Yani & Novitasari, 2022; Zainuri et al., 2023). The hybrid processes were linked to comparatively higher levels of fat, protein, ash, and sugar among the postharvest treatments (Table 2). The hybrid process produces a higher fat content by retaining mucilage, which promotes lipid synthesis, and involves longer fermentation, which increases microbial activity (Wibowo et al., 2021). Rather than indicating lipid biosynthesis, the higher fat content observed in hybrid-processed beans is discussed in relation to mucilage retention and prolonged fermentation conditions, which may modify the fermentation environment surrounding the bean. As lipid metabolic pathways were not directly assessed, this interpretation is presented as associative rather than as evidence of active lipid synthesis during fermentation (Wang et al., 2025; Zhang et al., 2019). The overall lower fat contents seen in this study compared to widely reported the Robusta reference ranges are probably due to differences in biology and region rather than analytical errors. We used a standard gravimetric Soxhlet extraction method to find the crude fat and reported it as a percentage of the dry weight. This made sure that the analysis was consistent and that the results could be compared between groups.

Ash content in coffee beans affects flavour, condition, and complexity (Janda et al., 2020). The ash content in this study ranged from 4.12% to 4.35%, in accordance with the INS 2907:2008 standard ($\leq$5%). Anaerobic fermentation increases the level of free amino acids by partially breaking down proteins. During roasting, proteins interact with phenolic compounds to create melanoidins, which contribute to the brown colour and aroma of coffee (Pereira et al., 2021).

Fermentation contributes to variations in the sugar composition of coffee beans, including glucose, fructose, and sucrose. Longer anaerobic fermentation breaks down mucilage polysaccharides, affecting the coffee's aroma and flavour (Cruz-O'Byrne et al., 2023), with fructose enhancing fruity flavours, glucose offering neutrality, and sucrose providing balanced sweetness (Li et al., 2023). Accordingly, differences in sugar profiles among treatments are interpreted as relative, process-associated variations rather than absolute concentrations.

Fermentation influences the sugar composition of green bean coffee, particularly glucose, fructose, and sucrose. Extended anaerobic fermentation can promote the breakdown of mucilage polysaccharides, which in turn affects aroma and flavour (Cruz-O'Byrne et al., 2023). Fructose is commonly associated with fruity notes, glucose contributes a more neutral sweetness, and sucrose provides balanced sweetness in the cup (Li et al., 2023). Accordingly, differences in sugar profiles among treatments are interpreted as relative, process-related variations rather than absolute sugar concentrations.

Carbohydrate content was calculated by difference and treated as a derived compositional parameter rather than an independently measured variable. Statistical comparisons were therefore applied to each directly measured proximate component before interpreting carbohydrate values, which were discussed in relation to corresponding changes in other proximate fractions rather than as standalone results. This approach helps reduce the risk of overstating treatment effects associated with carbohydrate calculated by difference (McCleary et al., 2020).

During harvest processing, both green and roasted coffee showed pH variations, especially under prolonged fermentation conditions (Pan et al., 2021). Coffee acidity is influenced by these pH changes, which in turn impact perceptions of bitterness, sourness, and scent expression (Bayle, 2019). Accordingly, pH changes among fermentation methods were interpreted as indirect indicators of fermentation-associated biochemical transformations and microbial involvement, rather than as direct evidence of microbial activity (de Oliveira Junqueira et al., 2019).

Postharvest processes also play a crucial role in shaping the chemical composition of coffee, particularly key bioactive compounds such as caffeine and chlorogenic acid (CGA). As identical hot-water extraction conditions (90 °C, 1 min) were applied across all treatments, differences in phenolic and caffeine contents are interpreted as relative process-associated variations rather than as absolute extraction yields. In this study, the hybrid processes, involving longer anaerobic fermentation, resulted in the highest levels of both caffeine and CGA (Table 2). This aligns with earlier research indicating that anaerobic fermentation is associated with reduced compositional changes in caffeine and CGA. As enzymatic and microbial activities were not directly measured, references to enzymatic and microbial pathways are provided solely as a literature-based context, rather than as mechanistic evidence. Observed changes in sugar profiles, phenolic content, antioxidant activity, and fermentation volatiles - related volatiles are therefore interpreted as indirect outcomes commonly associated with the coffee fermentation process (Barney et al., 2023; Swasti et al., 2024). In the hybrid process, fermentation duration and oxygen availability were not experimentally separated, as this treatment reflects an integrated fermentation practice used by farmers. Consequently, the observed physicochemical, volatile, and sensory differences are interpreted as an effect of the combined fermentation environment, rather than as isolated influences of time or oxygen.

Postharvest processes also affect coffee's antioxidant activity, as reflected by DPPH IC_{50}, ABTS assay result, TPC, and TFC, particularly under water-based processing conditions that may enhance the release of antioxidant compounds (Várady et al., 2022). Although extraction temperature can influence the absolute quantification of TPC and TFC values, identical extraction conditions (90 °C, 1 min) were applied across all treatments. Therefore, temperature-related effects are considered systematic rather than treatment-specific.

Accordingly, differences in TPC and TFC are interpreted as relative variations among postharvest processing methods, consistent with previous reports showing higher TPC and CGA yields under hot-water extraction (±90 °C) compared with lower-temperature conditions (Anh-Dao et al., 2024).

Wet processing exhibits the highest antioxidant activity as indicated by the lowest DPPH IC_{50} value and the highest ABTS assay result, as well as the highest TPC and TFC values (Table 2), due to soaking and washing, which remove inhibitory compounds and enhance β-glucosidase activity (Bressani et al., 2021). This pattern may be related to soaking and washing steps that facilitate the removal of inhibitory compounds and enhance the extractability of phenolic constituents. Similar patterns have been discussed in the literature in relation to enzymatic processes, including β-glucosidase-mediated hydrolysis (Bressani et al., 2021; Várady et al., 2022). However, as enzyme activity was not directly measured in the present study, these references are provided solely as literature-based contextual explanations and not as evidence of increased enzymatic activity under wet processing.

In contrast, hybrid processing, which involves prolonged anaerobic fermentation, may increase microbial enzyme activity, leading to reduced antioxidant potential and increasing IC_{50} values, partly through the hydrolysis of chlorogenic acids into quinic and caffeic acids (Bastian et al., 2021). Consistent with the DPPH IC_{50} results, ABTS radical scavenging activity showed a similar relative pattern across postharvest treatments, supporting a comparative interpretation of antioxidant capacity. Wet processing showed the strongest antioxidant activity, indicated by the lowest DPPH IC_{50} value (7.51 ppm) and the highest ABTS inhibition at 50,000 ppm (88.32%), followed by semi-wet processing (DPPH IC_{50} = 12.88 ppm; ABTS = 85.44%) and hybrid processing (DPPH IC_{50} = 11.58 ppm; ABTS = 82.28%). This trend aligns with the observed patterns in total phenolic and flavonoid contents. The high ABTS inhibition values observed at 50,000 ppm reflect assay saturation at elevated extract concentrations and were therefore interpreted comparatively rather than as indicators of absolute antioxidant capacity.

Pearson correlation analysis result found a strong negative relationship between DPPH IC_{50} value with TFC and TPC, with coefficients of -0.998 and -0.950, respectively. This means higher TFC and TPC levels are linked to stronger antioxidant activity, reflected by lower DPPH IC_{50} values. Additionally, TPC and TFC had a strong positive correlation (0.967), indicating that higher TFC corresponds to higher TPC. A significant relationship ($p < 0.05$) was observed across all correlation analyses.

The PCA biplot (Figure 2) illustrated the differences in the Robusta green coffee beans' chemical characteristics across postharvest processes. The first two principal components (F1 and F2) cumulatively explained 100% of the variation (F1 = 64.46%, F2 = 35.54%), reflecting the use of a selected set of averaged chemical variables for exploratory visualisation rather than inferential statistical analysis. Accordingly, PCA was applied to

illustrate relative separation patterns among processing treatments and not to establish causal relationships.
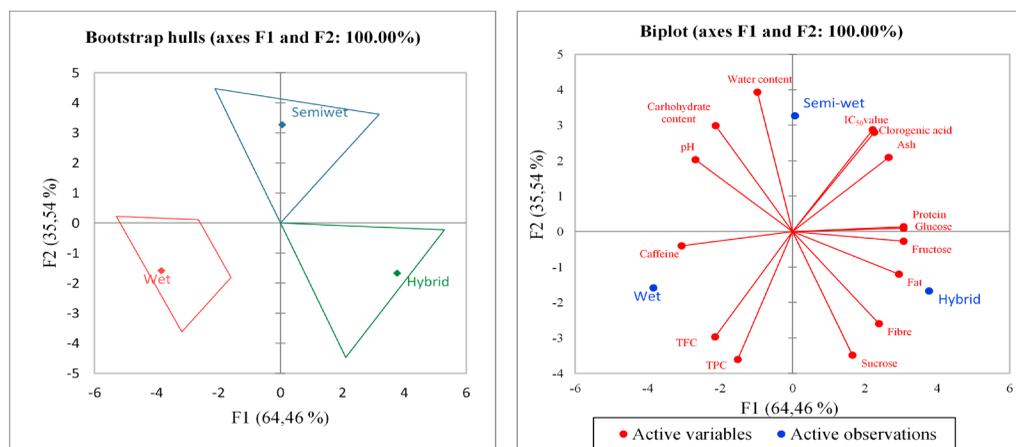

Figure 2. PCA biplot of green bean chemical characteristics across postharvest processing methods.
Note. TFC and TPC represent total flavonoid and phenolic contents, respectively. The first two principal components (F1 and F2) cumulatively explain 100% of the variance and are presented for exploratory visualisation of relative separation among treatments

Based on the squared cosine values of variables and observations, PCA indicated that the hybrid processing method was characterised by elevated levels of glucose, fructose, chlorogenic acid (CGA), fat, ash, fibre, and protein. The wet processing method was associated with the lowest caffeine content and the highest pH value, whereas the semi-wet method showed the highest carbohydrate content.

Roasted Coffee Beans Profiling Compounds by SPME-GCMS

SPME-GCMS analysis identified 36 compounds in roasted coffee from wet, 52 in semi-wet, and 40 in the hybrid method. Among these, only 15 (wet), 21 (semi-wet), and 16 (hybrid) volatile compounds were identified as potential flavour-forming compounds, based on references (Marie et al., 2024; Martinez et al., 2024; Marwani et al., 2024; Obando & Figueroa, 2024). These results reveal variations in flavour potential between postharvest treatments (Table 3).

Consistent dominating compound classes across biological replicates evaluated under similar SPME-GCMS settings supported volatile profile repeatability, with multivariate analysis revealing postharvest processing technique clustering as the primary factor. Because SPME is non-exhaustive and compound-dependent, volatile compounds were classed as flavour-forming or background based on known sensory importance in coffee

Table 3
Compounds, area (%), and retention time (RT) detected in roasted beans from three postharvest methods identified by SPME-GCMS

Compounds	Formula	RT (min)	Postharvest processing (% area)			Odour characteristics
			Wet	Semi-wet	Hybrid	
Keton						
Acetylated hydroxyacetone	$C_5H_8O_3$	5.385	1.63	1.49	1.82	Sweet and frutty Zakariyya et al., 2024
3-Octanone	$C_8H_{16}O$	11.372	nd	0.82	nd	Fruity and floral (Wang et al., 2024)
Pyrazine		6.141				
2.5-dimethyl Pyrazine	$C_6H_8N_2$		1.21	0.78	1.05	Nutty, coffee, spicy, and roasted (Elhalis et al., 2023; Martinez et al., 2022)
Aldehyde						
3-methyl 2-Butenal.	C_5H_8O	6.204	2.36	2.53	nd	Almond, roasted (Liu et al., 2021)
5-methyl 2-Furancarboxaldehyde	$C_6H_6O_2$	6.948	0.88	0.70	0.87	Nutty, caramelly, roasted, and burned (Yuwono et al., 2019)
Hexanal	$C_6H_{12}O$	4.402	nd	7.16	nd	Grassy, green, fatty-green (Caporaso et al., 2018)
E, E-Decadienal	$C_{10}H_{16}O$	12.443	nd	0.65	nd	Fruity (Marie et al., 2024)
E-2-Nonenal	$C_9H_{16}O$	9.091	nd	0.54	nd	Fatty (Poisson & Schieberle, 2008)
Acetaldehyde	CH_3CHO	16.917	nd	0.61	nd	Fruity, pungent, ethereal, fresh (Lester et al., 2021)
Benzaldehyde 2-nitro-diaminomethylidenhydrazone	$C_8H_9N_5O_2$		nd	0.58	nd	almond (Mei et al., 2022),
Hydrocarbon						
1.1-dimethyl Cyclohexane	C_8H_{16}	6.709	1.10	1.22	1.60	Spicy (Albak & Tekin, 2016)
Nonadecane	$C_{19}H_{40}$	18.253; 17.157	0.44	0.67	1.04	-
Hexadecane	$C_{16}H_{34}$	16.01	nd	1.33	4.96	Fresh, green, fatty, aldehydic (Lester et al., 2021)
Heptadecane	$C_{17}H_{36}$	17.157	1.68	nd	nd	Waxy (Zhao et al., 2023)
(3-methyl-2-butenyl) Benzene	$C_{11}H_{14}$	24.756;	0.81	nd	nd	-
Propane	C_3H_8	10.124	nd	0.63	nd	Unpleasant (Nagata, 2003)
Tetradecane	$C_{14}H_{30}$	16.01; 18.853	0.35	nd	0.24	Waxy (de Oliveira Junqueira et al., 2019)

Table 3 (*continued*)

Compounds	Formula	RT (min)	Postharvest processing (% area)			Odour characteristics
			Wet	Semi-wet	Hybrid	
Furan						
2-Furanmethanol	$C_8H_{10}O_3$	5.158	6.94	5.25	6.46	Caramel, bready, coffee, spicy (Wu et al., 2023)
2.3-dihydro-4-methyl Furan	C_5H_8O	2.75	nd	nd	2.75	Caramel, sweet
2-Furanmethanol. acetate	$C_7H_8O_3$	7.414	0.77	1.22	0.83	Frutty, sweet (Afriliana et al., 2018)
Phenol						
2-Methoxy-4-vinylphenol	$C_9H_{10}O_2$	12.342	0.46	nd	nd	Sweet, spicy, cloves, peanut, curry (Wu et al., 2023)(The Metabolomic Innovation Centre, 2024)
Phenol. 4-(2-aminoethyl)	$C_8H_{11}NO$	12.355	nd	0.35	nd	-
Ester						
Hexadecanoic acid. methyl ester	$C_{17}H_{34}O_2$	19.551	0.38	0.64	0.97	Fatty oily, waxy (Rodriguez-Campos et al., 2011; Seninde & Chambers, 2020)
2-Butoxy-1-methyl-2-oxoethyl butanoate	$C_{11}H_{20}O_4$	15.884	nd	nd	0.40	Creamy and buttery (G. Zhu et al., 2015)
Sarcosine. N-isobutyryl-. tetradecyl ester	$C_{11}H_{21}NO_3$	24.353	nd	nd	0.30	-
Alcohol						
(S)-3-Ethyl-4-methylpentanol	$C_8H_{18}O$	9.128	nd	1.15	nd	Fruity and sweet
Flavonoid						
6.4'-Dimethoxy-3-hydroxyflavon	$C_{17}H_{14}O_5$	25.109	12.80	21.77	11.38	-
Amine						
1-Propanamine. N.2-dimethyl-	$C_5H_{13}N$	21.252	nd	nd	0.41	-
Alkaloid						
Caffeine	$C_8H_{10}N_4O_2$	18.820	66.44	48.36	61.30	Rubbery, spicy (Seninde & Chambers, 2020)

Note. nd = not detected

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literature, and identification was considered preliminary; abundances were given as relative peak area percentages.

Potential fibre saturation effects associated with SPME sampling were reduced by using similar extraction settings across all treatments, including fibre type, extraction duration, temperature, and sample mass. As volatile compounds were evaluated based on relative peak area percentages, any saturation-related bias would be systematic rather than treatment-specific. Accordingly, volatile profiles were interpreted in a comparative context to assess process-related flavour potential rather than as absolute quantitative or causal measures.

Although green bean density can influence optimal roasting conditions, a single roasting profile was applied in this study to prioritise comparability among postharvest treatments rather than roast optimisation. Volatile compound profiles in coffee are notably influenced by postharvest processes, affecting both in terms of their occurrence and relative abundance. Wet processes remove mucilage and water, soluble precursor compounds, while semi-wet and hybrid processes retain these substrates through microbial and enzymatic activities, leading to variations in volatile compounds. SPME-GC-MS analysis shows that the hybrid method closely resembles the wet process (Figure 3a), with the green colour indicating a positive association between postharvest treatments and specific volatile compounds such as hydrocarbons, furans, and esters. Caffeine is not a major volatile in coffee, but it can be detected in SPME-GC-MS analysis due to its semi-volatile nature and heat stability (Marwani et al., 2024).

Although caffeine was detected through SPME-GC-MS in all processing methods, it is not deemed aroma-active due to low volatility and limited odour contribution. Its detection in headspace GC-MS is linked to its semi-volatile nature and thermal stability. Caffeine is reported within the volatile profile for completeness and comparison, but is not considered a contributor to coffee aroma or sensory attributes (Dong et al., 2019).

The wet, semi-wet, and hybrid methods yielded various compound groups (Figure 3b). Variations in these groups are due to postharvest processes (Batali et al., 2022). Flavonoid compounds were found in all methods, with the highest in the semi-wet (Table 3). Flavonoids provide various health benefits (Saud & Salamatullah, 2021) but are odourless (Lin et al., 2022). The high abundance of flavonoid-related compounds observed in SPME-GC-MS analyses is likely due to analytical and matrix-related factors rather than the intrinsic volatility of intact flavonoids. During headspace GC-MS, flavonoids can undergo thermal fragmentation or be detected as semi-volatile derivatives adsorbed by the SPME fibre. Consequently, the representation of relative peak areas may enhance specific compound classes while diminishing others, leading to the interpretation of flavonoid signals as indicative of compositional trends rather than direct evidence of volatile flavonoids (Zhou et al., 2021).
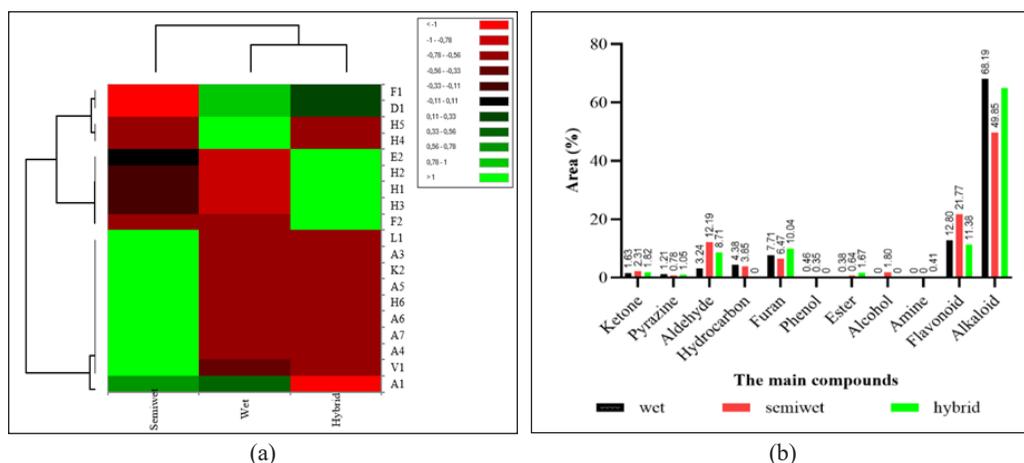
(a)	(b)

Figure 3. (a) The heatmap and (b) Volatile compounds identified by SPME-GCMS from different postharvest processes

Note. K1= Acetylated hydroxyacetone; K2 = 3-Octanone; PP1 = 2.5-dimethyl Pyrazine; A1 = 3-methyl 2-Butenal; A2 = 5-methyl 2-Furancarboxaldehyde; A3 = Hexanal, A4 = E-2-Nonenal; A5 = E,E-Decadienal; A6 = Acetaldehyde; A7 = Benzaldehyde 2-nitro- Diaminomethylidenhydrazone; H1 = 1.1-dimethyl Cyclohexane; H2 = Nonadecane; H3 = Hexadecane; H4 = Heptadecane; H5 = (3-methyl-2-butenyl) Benzene; H6 = Propane; H7 = Tetradecane; F1 = 2-Furanmethanol; F2 = 2.3-dihydro-4-methyl Furan; F3 = 2-Furanmethanol acetate; P1 = 2-Methoxy-4-vinylphenol; P2 = Phenol 4-(2-aminoethyl); E1 = Hexadecanoic acid; E2 = 2-Butoxy-1-methyl-2-oxoethyl butanoate; E3 = Sarcosine. N-isobutyryl-. tetradecyl ester; L1 = (S)-3-Ethyl-4-methylpentanol; V1 = 6.4'-Dimethoxy-3-hydroxyflavon; D1 = Caffeine

Furans contribute to coffee's sweetness and aroma through sugar and amino acid interactions. Wet-processed coffee has reduced furans because mucilage is removed, reducing sugar availability (Zakidou et al., 2021). Because coffee chromatogrammes have a lot of complicated areas with lots of furan and aldehyde, co-elution cannot be ruled out completely. To do this, compound identification in these areas was limited to mass spectral deconvolution and repeatable retention behaviour, and conclusions were limited to comparing trends rather than giving exact numbers. In all of these steps, eight volatile compounds are used.

Hydrocarbons detected in the volatile profile are not considered direct contributors to coffee aroma because of their low odour activity and high perception thresholds. Instead, they are better interpreted as process-related markers, reflecting factors such as thermal exposure and lipid degradation during processing. Although they help differentiate samples in sensory models, their contribution to sensory perception is viewed as associative rather than causative.

The absence of certain Maillard-derived sulfur compounds typically found in roasted coffee is probably due to the limitations of the analysis, not because they were completely missing from the study samples. A lot of sulfur-containing aroma compounds are very volatile, reactive, and found in very low amounts, which regular SPME-GC-MS might not

be able to find. In addition, competitive adsorption on the SPME fibre by more abundant compounds and the use of a standardised roasting profile may further limit their detection. Accordingly, volatile profiling in this study emphasises comparative trends among postharvest processing methods, supported by reproducible compositional patterns across biological replicates and multivariate analysis showing that variability among processing methods exceeded intra-method variability.

Odour thresholds and odour activity values were not incorporated in this study, as absolute concentrations of individual volatile compounds were not determined, and odour thresholds are highly compound- and matrix-specific. Given the complexity of the coffee matrix and the interactive effects among volatile compounds, sensory interpretation based solely on odour thresholds may not adequately reflect perceived aroma (Chen et al., 2025).

Sensory Quality

Coffee sensory quality is strongly influenced by postharvest processing (Wibowo et al., 2021). Accordingly, sensory interpretations in this study reflect process-driven descriptive profiles evaluated by trained Indonesian cuppers under standardised protocols rather than culturally generalised consumer preferences. Consumer preference testing was beyond the scope of this study and is identified as a relevant direction for future research linking sensory profiles with market acceptance. All processes achieved cupping scores above 80, classifying them as the Fine Robusta coffee with sensory profiles shown in Figure 4a.
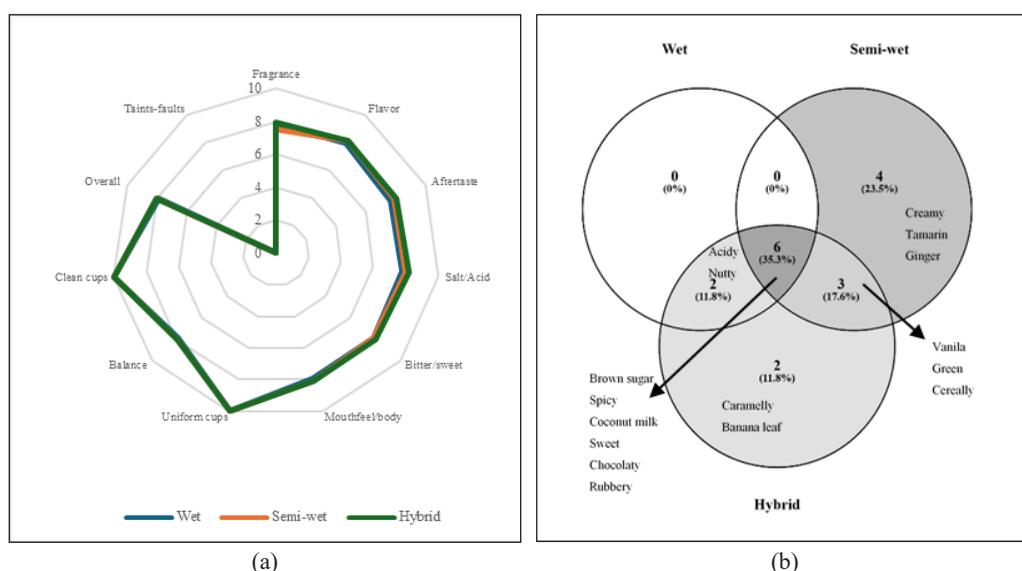

(a) (b)

Figure 4. (a) Cupping test results and (b) Flavour in a Venn diagramme from postharvest processes

The hybrid postharvest coffee exhibited the highest sensory score (Figure 4a), characterised by a sweet, clean aftertaste with notes of brown sugar, spice, buttery coconut milk, chocolate, rubber, caramel, and banana leaf. Across postharvest methods, a 35.29% overlap in sensory attributes, including brown sugar, spice, coconut milk, sweet, chocolate, and rubbery notes, which indicates partial sensory similarity rather than a definitive process-driven identity of the Robusta coffee (Figure 4b). Accordingly, sensory differentiation among processes is supported by converging evidence from multivariate separation patterns, statistically significant differences in sensory attributes, and corresponding variations in volatile compound abundances, rather than by the overlap metric alone (Table 3).

Relating Physicochemical Attributes, Volatile Compounds, and Sensory Preferences by PLS-R

Partial Least Squares - Regression (PLS-R) analysis revealed a clear associative relationship between the physicochemical characteristics of green beans and the volatile compounds formed after roasting. Although the explained variance of the volatile predictor block was relatively limited, the PLS-R model explained 62.6% of the variation in the physicochemical properties of green beans (X) and 50.8% of the variation of volatile compounds in roasted beans (Y), highlighting the relevance of precursor-volatile linkages rather than model predictability (Figure 5a).

Green beans from the semi-wet process were associated with ketones, alcohols, and flavonoids, which are commonly linked to fruity and floral flavours, sensory attributes, and are consistent with shorter fermentation and partial sugar degradation (Table 2). These volatile compound groups showed strong associations with moisture content, CGA, and sucrose (VIP > 1) (Figure 5b), while TPC and TFC acted as important precursors to volatile phenolics.

Hydrocarbons, phenols, pyrazines, and alkaloids, which correlate to nutty, spicy, earthy, and roasted notes, were linked to the wet process, according to PLS-R analysis. These groups of compounds exhibited strong correlations with bulk density (VIP > 1), TPC, and TFC. During fermentation, the hybrid process produces furans, amines, and esters that give off caramel, creamy, and sweet scents. These changes are probably caused by the breakdown of amino acids and microbial activity. Despite having a VIP score below 1, protein content might have an indirect impact through roasting-related non-enzymatic reactions.

In general, PLS-R was used as an exploratory tool to look at how physicochemical characteristics, groups of volatile compounds, and sensory attributes are related to each other, not to make predictive models. The results are analysed in an exploratory context because the volatile predictor block has a low explained variance, and the variable-to-observation ratio is low. Variables exhibiting elevated VIP values are analysed as relative contributors to observed covariance patterns rather than as conclusive determinants of

sensory quality. Consequently, correlations between the physicochemical characteristics of green beans and roasted volatile compounds are regarded as process-driven associations rather than indications of direct causation.
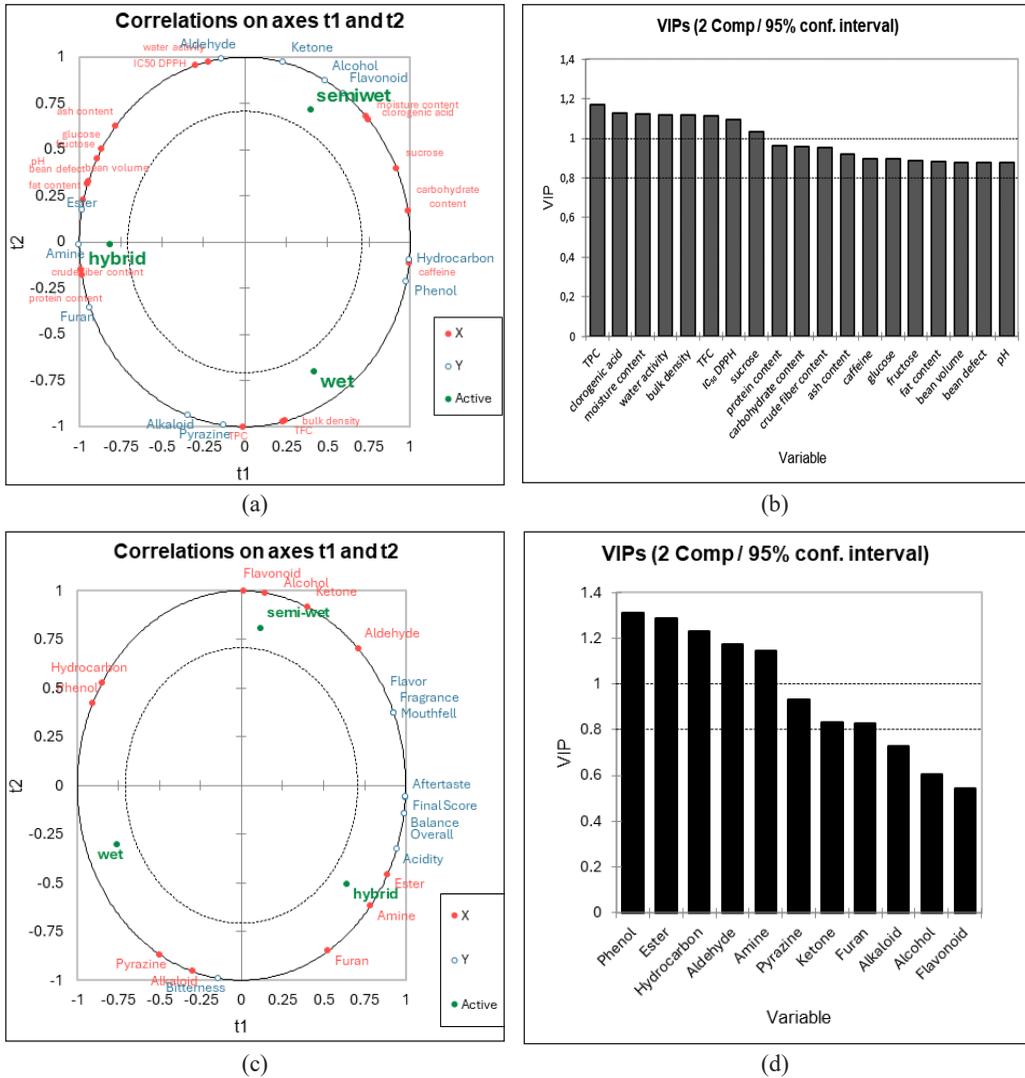

(a)

(b)

(c)

(d)

Figure 5. PLS-R biplot correlation and variable importance analysis: (a) Relationship between green bean physicochemical characteristics (X) and volatile compounds of roasted bean (Y), (b) Relationship between volatile compounds (X) and sensory preferences of roasted bean (Y), (c) VIP score of green bean key physicochemical characteristics, and (d) VIP score of roasted bean main compounds contributing to sensory differentiation

The analysis was further extended to examine the relationship between volatile functional groups (X) and sensory preferences (Y) across the three processing methods. In

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this model, the PLS-R model explained a high proportion of variance in sensory responses (R^2Y = 82.8%), while the explained variance of volatile predictors remained lower (R^2X = 38.7%) (Fig. 5c). This is acceptable in complex chemical matrices, where volatile data often contain redundant signals and high noise (Genisheva et al., 2018). As shown in Fig. 5d, esters, aldehydes, and amines (VIP > 1) contributed positively to sensory quality, particularly in hybrid processing. In contrast, phenols and hydrocarbons (VIP > 1) were associated with negative attributes like bitterness, which may reduce consumer acceptance (Genisheva et al., 2018).

The findings suggest that the relationships observed between postharvest processing, physicochemical properties, volatile formation, and sensory expression are relevant to the Robusta coffee, although their expression may vary across regions due to differences in climate and local processing practices. Rather than presenting definitive quantitative benchmarks, the results provide practical insight into how processing choices can be used to steer coffee quality. These outcomes are inherently context-specific and should therefore be interpreted in relation to local environmental conditions and on-farm process management.

Several limitations impact the findings, including the absence of direct measurements of microbial and enzymatic activities, relying instead on literature-based interpretations. Although roasting was standardised by maintaining identical temperature targets and timelines, no instrumental verification was conducted for roast degree, leaving some variability unaccounted for. Furthermore, volatile-sensory relationships were inferred from statistical data rather than validated through aroma experiments. As a result, the differences in volatile profiles are interpreted as primarily due to postharvest processing, with these constraints noted to support flavour potential comparisons, rather than definitive causal conclusions.

CONCLUSION

Postharvest processing was found to influence the physicochemical, volatile compounds, and sensory preferences of the Robusta coffee. The hybrid processing produces a more balanced profile, characterised by relatively higher glucose, fructose, caffeine, and fibre content, while the wet processing is more closely associated with higher antioxidant-related attributes. Semi-wet processing contributed to greater perceived sweetness and body. Sensory evaluation showed a 35.29% overlap in flavour profiles similarity across methods, including brown sugar, spicy, coconut milk, sweet, chocolate, and rubber notes, with all samples classified as the Fine Robusta Coffee. Furthermore, PLS-R analysis indicated that process-related differences in green bean characteristics were associated with the formation of aroma-active volatile compounds and subsequent sensory expression. Together, these results support the use of a process-comparative, decision-oriented approach to guide the Robusta coffee quality development, rather than the selection of a single optimal postharvest processing.

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AI DISCLOSURE STATEMENT

The authors confirm that this manuscript is based on original research data, analysis, and interpretation, and that no generative artificial intelligence tools were used to produce its scientific content.

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