







Mycotoxins, antioxidant capacity, physicochemical and sensory quality of specialty coffees from Cajamarca, Peru

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ABSTRACT

Coffee is a globally important crop with significant economic and social relevance, particularly in the Cajamarca region of Peru, which is recognized for the production of high-quality beans. This study aimed to evaluate the occurrence of mycotoxins in three specialty coffee varieties while simultaneously assessing their physical, sensory, and compositional characteristics. A total of 36 parchment coffee samples were randomly collected from two storage facilities located in the provinces of Jaén and San Ignacio. The results revealed the exclusive presence of aflatoxin G₂, with concentrations varying between storage conditions. The Catimor variety exhibited the highest antioxidant activity and total polyphenol content; however, it showed lower physical yield and reduced sensory scores. In contrast, the Bourbon variety displayed a more balanced profile between bean composition and cup quality, producing a beverage with superior physical and sensory attributes and enriched with bioactive compounds associated with potential health benefits. These findings highlight the relevance of varietal selection, post-harvest management, and storage conditions for maintaining coffee quality. Nevertheless, the detection of aflatoxin G₂ indicates persistent food safety concerns, emphasizing the need for stricter monitoring and control measures during harvesting, drying, storage, and handling to mitigate potential health risks.

1. Introduction

Coffee is one of the most widely consumed beverages worldwide and is recognized for its health-promoting properties, stimulant effects, and sensory attributes, particularly aroma and flavor (Kodape & Kodape, 2024). It constitutes a fundamental economic pillar for >70 producing countries, including Peru (Qin et al., 2024). In 2024, Peruvian coffee exports reached USD 1108,804 and, by August of the same year, totaled USD 746,178 (Ministerio de Desarrollo Agrario y Riego [MIDAGRI], 2025). Coffee cultivation in Peru extends across 16 of the country's 24 departments, with Cajamarca being the second most important

producing region, contributing 20.48 % of national production. Within this region, the provinces of Jaén and San Ignacio constitute the main production hubs, supplying both domestic consumption and international markets. These areas have consolidated their position as centers of high-quality coffee production, consistently achieving prominent rankings in national specialty coffee competitions in recent years.

Coffee is classified as specialty when it achieves a score higher than 80 points in sensory evaluations, according to the Specialty Coffee Association of America (SCAA) (Oliva-Cruz et al., 2024). This market segment has experienced significant consolidation, driven by increasingly demanding consumers and the adoption of innovative processing

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methods aimed at maximizing quality and enhancing distinctive sensory attributes (Costa et al., 2025; Kodape & Kodape, 2024). Consequently, specialty coffees have positioned themselves as differentiated, high value-added products, consistently exhibiting growth rates that surpass those of conventional coffee. Factors such as environmental conditions, good agricultural practices, and postharvest management influence the physicochemical and sensory quality of coffee beans (Aung Moon et al., 2025a; Oliva-Cruz et al., 2024). These beans contain bioactive compounds in their composition, such as caffeine, chlorogenic acids, minerals, and vitamins, which contribute not only to their sensory attributes aroma, acidity, and body but also to their nutritional and functional value (Todhanakasem et al., 2025). Moreover, several studies have demonstrated that variety is a determining factor in the physical and sensory quality of coffee (Oliva-Cruz et al., 2024).

Nevertheless, despite the beneficial compounds present in coffee beans, there is growing consumer concern regarding the presence of contaminants that may affect product safety. In this context, the international coffee market is subject to strict food safety regulatory frameworks that establish quality and safety standards, as well as maximum permissible limits for contaminants such as mycotoxins, pesticide residues, and heavy metals (Adi et al., 2025). These regulations, defined by international authorities such as the European Union, the Codex Alimentarius, and the FDA, aim to protect consumer health and ensure the competitiveness of coffee in international markets (Mancusi et al., 2025).

In this context, monitoring contaminants such as mycotoxins is critically important, as coffee beans are susceptible to colonization by fungal communities, particularly filamentous fungi belonging to the genera *Aspergillus* and *Penicillium* (Wang et al., 2025). These species thrive under conditions of high humidity and temperature during storage, and their development may vary depending on the bean variety, its chemical composition, and postharvest management practices (Qin et al., 2024). Such fungi promote the production of mycotoxins, including aflatoxins and ochratoxins, compounds known for their hepatotoxic, nephrotoxic, immunotoxic, and potentially carcinogenic effects, thereby representing a significant risk to consumer health (Yazdanfar et al., 2022). In addition, they compromise the sensory quality of the beverage by generating off-flavors and undesirable aromas that reduce consumer acceptability and the commercial value of the product (Wang et al., 2025).

Despite the growing interest in specialty coffees, most studies have focused on analyzing individual aspects of coffee quality, such as sensory attributes, chemical composition, or the presence of contaminants such as mycotoxins. However, few studies have comprehensively evaluated the relationship among mycotoxin occurrence, antioxidant capacity, physicochemical properties, and sensory quality in specialty coffee varieties. This approach is particularly relevant in producing regions such as Cajamarca, Peru, where specialty coffee production holds significant economic importance but may also be affected by environmental conditions and postharvest practices that influence both product quality and safety.

In this context, the present study aimed to comprehensively evaluate the physicochemical and sensory quality, phenolic compound content, antioxidant capacity, and occurrence of mycotoxins in three varieties of parchment coffee obtained from two storage facilities located in the provinces of Jaén and San Ignacio (Cajamarca, Peru). In addition, the potential relationships among these variables were examined to provide an integrated understanding of the factors governing the quality and safety of specialty coffee under commercial storage conditions. It was hypothesized that the sensory quality of coffee is significantly influenced by varietal characteristics and storage conditions, and that the observed differences are associated with variations in phenolic compound content, antioxidant capacity, and mycotoxin contamination levels.

2. Materials and methods

2.1. Sample collection

A total of 36 composite samples of parchment coffee were collected from two storage facilities located in the provinces of Jaén and San Ignacio (Cajamarca, Peru). Sampling was conducted in accordance with the Peruvian Technical Standard NTP-ISO 4072:2016, which specifies the random extraction of coffee beans using a sampling probe inserted into randomly selected bags.

For each extraction, between 24 and 36 g of parchment coffee were obtained until approximately 1 kg of sample was completed per variety (Bourbon, Catimor, and Marsellesa), with five replicates per storage facility. During sample collection, environmental parameters associated with each bag were recorded, specifically temperature (°C) and relative humidity (RH, %), using a digital thermohygrometer (model TH0510) equipped with an external sensor.

2.2. Physical and sensory analysis

2.2.1. Physical quality

To assess the physical quality of the coffee beans, the following parameters were determined: bean moisture content (H), bulk density (D), defective beans (DS), husk content (C), secondary beans (S), and physical yield (RT). For this analysis, 400 g of each sample were used after hulling, and the measurements were performed using standardized instruments, analytical procedures, and corresponding calculation equations.

Bean moisture content was determined using a Gehaka Moisture G610i moisture meter. Bulk density was measured using a 1 L graduated cylinder, which was filled with parchment coffee up to the reference mark and subsequently weighed (ρ). The results were calculated according to Eqs. (1) and (2) (Yusibani et al., 2023).

The proportions of defective beans, husk content, secondary beans, and physical yield were determined by hulling 100 g of parchment coffee per sample. The hulled beans were classified using metal sieves No. 20, 18, 16, and 14, arranged in descending order. Each fraction was separated, weighed, and analyzed, and the corresponding percentages were calculated according to Eqs. (3)-(6) (Gebreselassie et al., 2024).

$$m = \rho \text{ total} - \rho \text{ container} \quad (1)$$

Donde m es la masa neta del café pergamino y ρ es el peso en gramos.

$$\rho = \frac{m}{V} \quad (2)$$

Donde ρ corresponde a la densidad expresada en g/L, m es la masa del café pergamino en gramos y V representa el volumen del recipiente utilizado.

$$\text{Discarded grains (\%)} = \frac{\text{Discarded g}}{100 \text{ g}} \times 100 \quad (3)$$

$$\text{Peel (\%)} = \frac{\text{Peel g}}{100 \text{ g}} \times 100 \quad (4)$$

$$\text{Second - grade grains (\%)} = \frac{\text{Second g}}{100 \text{ g}} \times 100 \quad (5)$$

$$\text{Physical grain yield (\%)} = \frac{\text{Yield g}}{100 \text{ g}} \times 100 \quad (6)$$

2.2.2. Sensory quality

Sensory evaluation of the coffee samples was conducted following the cupping protocol established by the Specialty Coffee Association of America (SCAA) (Oliva-Cruz et al., 2024). The procedure began with cleaning the samples to remove residual husk fragments and fibers. From each sample, 120 g of parchment coffee were collected and hulled

prior to analysis. The beans were then roasted to a medium level (48–63 Agron) using a Giesen roaster and ground with an EK43 grinder to ensure a uniform particle size.

For the cupping session, five cups were prepared per sample, each containing 8.25 g of roasted coffee. Hot water at 92–94 °C was poured over the ground coffee and allowed to steep for four minutes prior to breaking the crust. The beverage was subsequently evaluated by a panel of certified Q-graders, who applied the sensory attributes and scoring scales established in the SCAA methodology (Fig. S1).

2.3. Analysis of polyphenols and antioxidant capacity

2.3.1. Sample preparation for polyphenol profile, total polyphenols, and antioxidant capacity

To evaluate the polyphenol profile, total polyphenol content, and antioxidant capacity, a conventional extraction was first performed following the methodology described by Vilcanqui et al. (2021). Briefly, 5 g of ground dry coffee were mixed with 100 mL of 60 % methanol and subjected to magnetic stirring with heating for 60 min at 30 °C and 550 rpm. The resulting solution was then centrifuged at 4000 rpm for 10 min, and the supernatant was filtered through Whatman No. 42 filter paper to remove solid impurities. Each analytical sample consisted of a composite mixture of the replicates for each variety under each storage condition, resulting in a total of six samples.

2.3.2. Polyphenols profile

For the identification and quantification of the polyphenol profile, the extracts were processed using a solid-phase extraction (SPE) procedure. Briefly, the samples were loaded onto C18 cartridges (500 mg, 3 mL, 60 Å), previously conditioned with 10 mL of methanol (99.7 % purity) followed by 10 mL of ultrapure water. The eluate was then filtered through a 0.22 µm syringe filter and analyzed using an ultra-high-performance liquid chromatography system coupled with a diode array detector (UHPLC-DAD). Chromatographic separation was performed using a Poroshell EC-C18 column (2.1 × 150 mm, 2.7 µm), maintained at 30 °C, with a flow rate of 0.3 mL min⁻¹ and an injection volume of 2 µL. The mobile phase consisted of two solvents: (A) ultrapure water acidified with 0.1 % formic acid and (B) acetonitrile containing 0.1 % formic acid. Compound separation was achieved using a 25 min gradient elution program under the conditions described in Table S1.

The identification of phenolic compounds was performed by comparing retention times and UV–Vis spectra obtained with the diode array detector (200–400 nm) with those of authentic reference standards whenever available. For compounds lacking commercial standards, identification was tentatively assigned based on the comparison of chromatographic behavior and spectral characteristics with data reported in the literature for coffee and related plant matrices. Quantification was carried out using external calibration curves constructed with representative phenolic standards (Esquivel et al., 2020; Kuppusamy et al., 2018).

2.3.3. Total polyphenols

Total polyphenol content was determined using the Folin-Ciocalteu colorimetric method, following the procedure described by Huamán-Castilla et al. (2024). The assay consisted of mixing 150 µL of distilled water and 20 µL of the previously diluted extract (1:10) with 10 µL of Folin-Ciocalteu reagent (1 N). The mixture was vortexed for 3 min, followed by the addition of 20 µL of a 10 % sodium carbonate solution. The samples were then incubated in the dark for 60 min at room temperature prior to analysis. Absorbance was measured using a Synergy™ HTX multimode microplate reader. The results were quantified against a gallic acid standard calibration curve (0.02–0.08 mg mL⁻¹) to determine the total phenolic compound concentration in each sample.

2.3.4. Antioxidants

Antioxidant capacity was assessed using two complementary assays. The first method was based on the inhibition of the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical, following the procedure described by Huamán-Castilla et al. (2024). Briefly, 10 µL of the prepared extract were mixed with 290 µL of a DPPH solution and incubated for 30 min in the dark at room temperature. Absorbance was measured using a Synergy™ HTX multimode microplate reader. Methanol was used as the positive control, while pure methanol (without extract).

The antioxidant activity was expressed as IC₅₀ (mg mL⁻¹), defined as the extract concentration required to inhibit 50 % of the initial DPPH radical activity. Therefore, lower IC₅₀ values indicate higher radical-scavenging capacity and, consequently, greater antioxidant potential of the sample.

In addition, the oxygen radical absorbance capacity (ORAC) assay was performed using the same instrument to provide a complementary measure of antioxidant performance. Prior to analysis, the extracts were diluted in 75 mM phosphate-buffered saline (PBS), prepared with Type I water and adjusted to pH 7.4. The PBS buffer was used to prepare a reaction mixture containing fluorescein (55 nM) and 2,2'-azobis(2-amidinopropane) dihydrochloride (AAPH, 153 mM). Trolox was used as the reference standard at concentrations of 8, 16, 24, 32, and 40 µM for the different extract dilutions.

The reaction mixtures were transferred to a black 96-well microplate, and 25 µL of Trolox or PBS buffer were added to each well. The plate was incubated at 37 °C for 10 min, after which the instrument automatically injected 25 µL of AAPH into each well. Fluorescence readings were recorded at 1 min intervals for 50 min. Final ORAC values were calculated from the area under the fluorescence decay curve (AUC) and expressed as µmol Trolox equivalents per gram of dry sample (µmol TE g⁻¹ dw). Higher ORAC values indicate a greater capacity to neutralize peroxy radicals and, therefore, stronger overall antioxidant activity.

2.4. Mycotoxin analysis

For the analysis and quantification of aflatoxins (B₁, B₂, G₁, and G₂) and ochratoxin A, high-performance liquid chromatography (HPLC) was performed using a Shimadzu system equipped with a degasser (DGU-20A5R), autosampler (SIL-30AC), quaternary pump (LC-30AD), column oven (CTO-20AC), fluorescence detector (RF-20AXs), and system controller (SBM-20A). Chromatographic separation was achieved using a reverse-phase C18 column (250 mm × 4.6 mm i.d., 5 µm particle size; Restek). In addition, sample extraction and purification were carried out using an ultrasonic bath (Wisd Laboratory Instruments) and immunoaffinity columns specific for ochratoxin A (NEOCOLUMN).

For the quantification of aflatoxins B₁, B₂, G₁, and G₂, each sample consisted of 25 g of parchment coffee. The samples were homogenized at high speed with 5 g of sodium chloride (NaCl) and 100 mL of a solution containing 80 % methanol and 20 % distilled water for 1 min. The resulting mixture was filtered through folded filter paper, and 10 mL of the filtrate were collected in a 50 mL graduated cylinder. The volume was then adjusted to 50 mL with distilled water, followed by a second filtration through glass fiber filter paper. This procedure was carried out according to the method described by Franco et al. (2014).

For the determination of ochratoxin A, 20 g of the previously ground sample were weighed into a centrifuge tube and mixed with 30 mL of hydrochloric acid (HCl, 2 mol L⁻¹), 50 mL of magnesium chloride (MgCl₂, 0.4 mol L⁻¹), and 100 mL of toluene. The mixtures were mechanically shaken for 60 min, after which 50 mL of the upper organic phase were recovered and purified using a silica solid-phase extraction (SPE) column previously conditioned. The column was sequentially washed with n-hexane (2 × 10 mL), acetone:toluene (5:95, v/v) (2 × 10 mL), and toluene (5 mL), and all washing fractions were discarded. Subsequently, the extract was divided into two 15 mL fractions, diluted with a toluene:acetic acid mixture (90:10, v/v), and evaporated to dryness at 40 °C. The resulting residue was reconstituted in 1 mL of the

mobile phase (acetonitrile:water:acetic acid, 99:99:2, v/v/v), filtered through a 0.45 μm polytetrafluoroethylene (PTFE) membrane, and analyzed by HPLC according to the procedure described by Milla Flores et al. (2020).

2.5. Statistical analysis

Physical quality variables were evaluated using the nonparametric Kruskal-Wallis test, following verification of the assumptions of normality, linearity, homoscedasticity, and independence under a bifactorial model (varieties \times storage facilities). Physical quality was visualized using boxplots, whereas sensory attributes were compared among varieties using radar charts. To explore differentiation among varieties based on selected physical and sensory variables, partial least squares discriminant analysis (PLS-DA) was applied, and model performance was evaluated using R^2 and Q^2 with five-fold cross-validation. The most influential variables were identified through variable importance in projection (VIP) values. Chemical variables were analyzed using heatmaps and stacked bar charts, and their relationships with physical and sensory variables were also assessed. Finally, for aflatoxin G2, stacked charts and boxplots were used, and its correlations with environmental storage variables (temperature and humidity of the jute sack) and with the other study variables were analyzed. All statistical analyses were performed in RStudio (v4.3.3) and Google Colab.

3. Results

3.1. Determination of physical and sensory quality of coffee

The results of the Kruskal-Wallis test revealed significant differences ($p < 0.05$) among the evaluated coffee varieties and storage facilities,

with the exception of bean moisture content, husk percentage, and defective beans (Table S2). Among the varieties, Marsellesa exhibited the highest bean moisture content compared with Catimor and Bourbon (Fig. 1a). This variety also demonstrated superior performance in terms of bulk density and a lower proportion of discarded beans (Figs. 1b and c). In contrast, Bourbon showed a significantly higher husk percentage than Catimor and Marsellesa (Fig. 1d). Furthermore, Catimor recorded the highest proportion of secondary-grade beans (Fig. 1e), whereas Bourbon achieved the greatest physical yield of coffee beans (Fig. 1f).

The sensory analysis revealed that Warehouse No. 1 exhibited lower cup quality scores compared to Warehouse No. 2. In Warehouse No. 1, the Bourbon variety achieved the highest cup score (84.05 points), distinguished by its balance, body, acidity, and flavor, as well as its fragrance/aroma and aftertaste, relative to the other varieties (Fig. 2a). In contrast, in Warehouse No. 2, Bourbon obtained a higher average score (85.76 points), surpassing Catimor (85.08 points) and Marsellesa (82.46 points) (Fig. 2b). Furthermore, the score differences between Catimor and Marsellesa were 2.62 and - 0.15 points, respectively, reinforcing the consistent superiority of the Bourbon variety under both storage conditions.

Multivariate analysis using partial least squares discriminant analysis (PLS-DA) explored the differences among the evaluated coffee varieties based on physical and sensory variables. The model explained 36 % of the total variability of the analyzed variables and exhibited limited predictive capacity according to cross-validation. The results indicated a differentiation between the Bourbon and Catimor varieties, whereas Marsellesa showed considerable overlap with the other varieties. Furthermore, cup score (pt) showed strong associations with flavor (S), fragrance/aroma (FA), and acidity (AC). In contrast, the physical bean yield (RF) showed a considerable association only with bean moisture (H). On the other hand, negative associations were observed between H

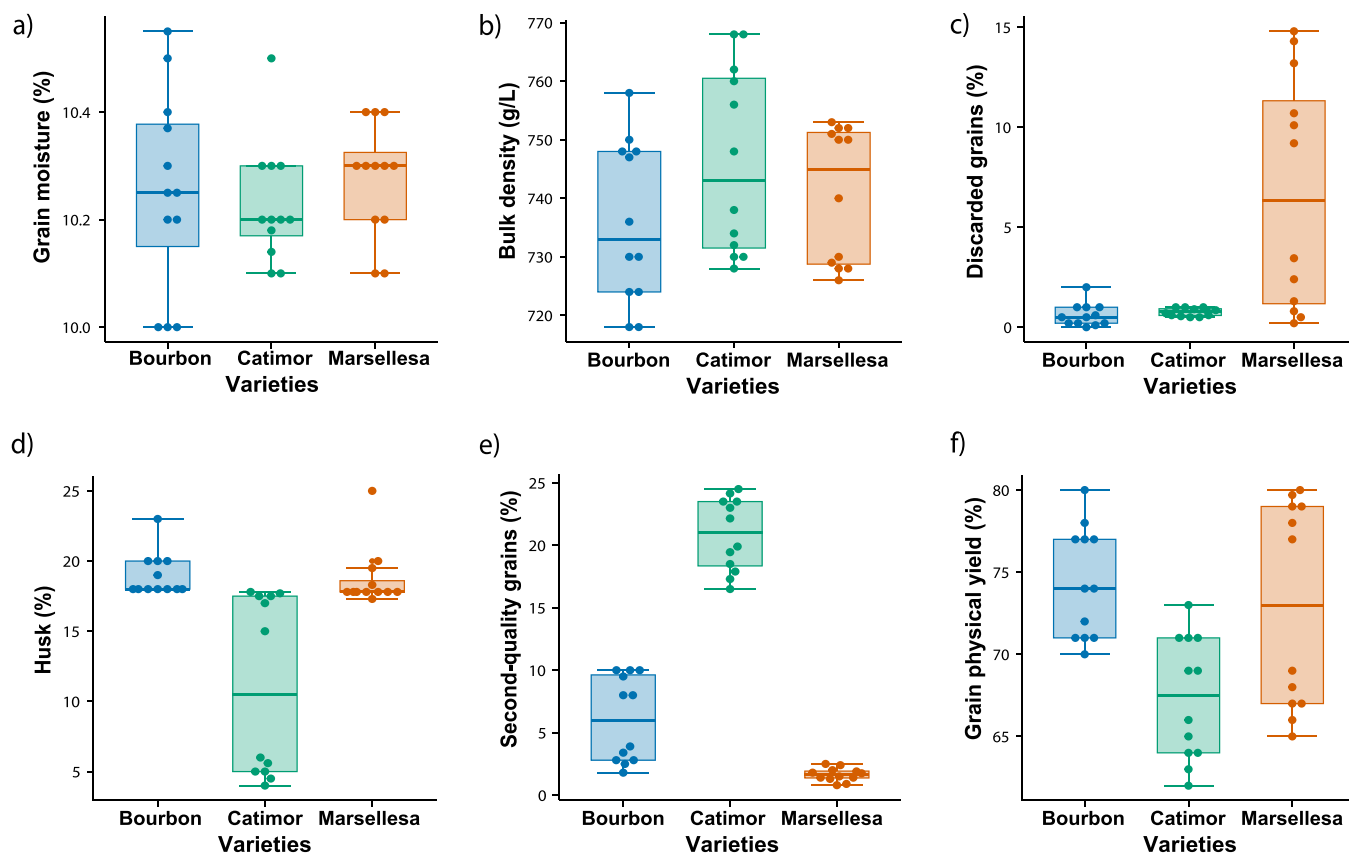
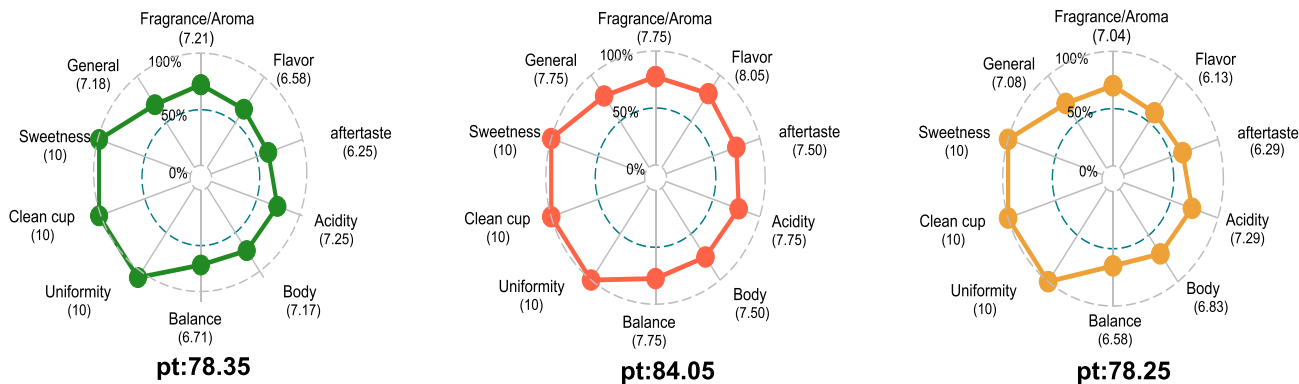
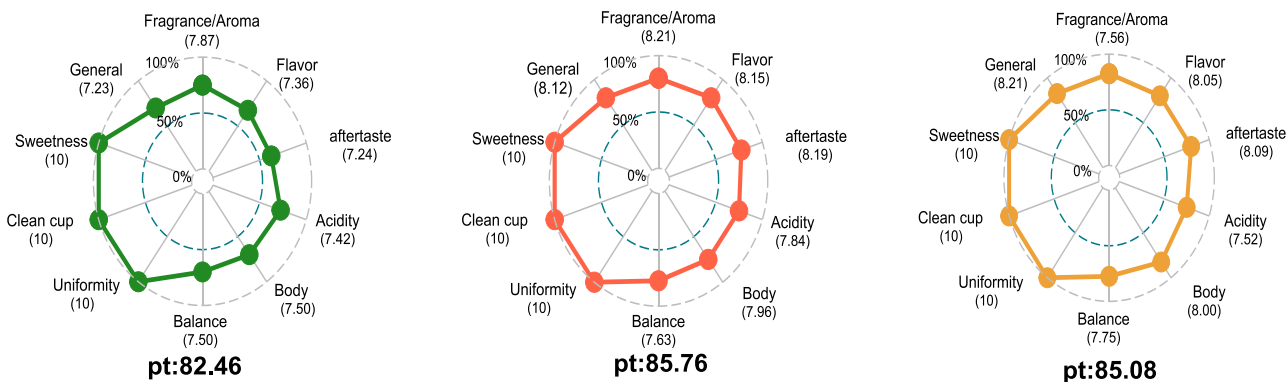


Fig. 1. Evaluation of the physical quality of coffee from three varieties (Bourbon, Catimor, and Marsellesa) analyzed in two storage facilities. (a) Grain moisture content (%), (b) bulk density (g L^{-1}), (c) proportion of rejected beans (%), (d) husk content (%), (e) proportion of second-grade beans (%), and (f) physical yield of the beans (%).

a) Storage Facility N°1



b) Storage Facility N°2



● Marsellese ● Bourbon ● Catimor pt: Cupping score

Fig. 2. Comparison of the sensory profile of coffee from three varieties (Bourbon, Catimor, and Marsellese) evaluated in two warehouses. (a) Sensory profile of samples from Warehouse No. 1, showing average values obtained from the SCAA analysis. (b) Sensory profile of samples from Warehouse No. 2, showing average values obtained from the SCAA analysis.

and D, in contrast to the relationship between pt and D (Fig. 3). Finally,

the variable importance in projection (VIP) analysis revealed that RF, pt, and S were the parameters that contributed most to varietal discrimination (Fig. S2).

3.2. Polifenoles y antioxidantes

The results of the polyphenol profile analysis showed that the Bourbon variety exhibited the highest concentrations of gallic acid, epicatechin, procyanidin A2, and kaempferol in both storage facilities (No. 1 and No. 2). In addition, Bourbon consistently presented a higher concentration of caffeic acid compared with the Catimor and Marsellese varieties under both storage conditions. It is noteworthy that certain polyphenols, including procyanidin B2, quercetin, and kaempferol, were not detected in some samples (Fig. 4).

In contrast, the Marsellese variety exhibited the highest concentrations of catechin, vanillin, and rutin among the varieties evaluated in Warehouse No. 1 (Fig. 4a). However, in Warehouse No. 2, the highest concentrations were observed for procyanidin B2 and quercetin. However, the Catimor variety in Warehouse No. 2 exhibited the highest concentrations of catechin, vanillin, and rutin (Fig. 4b), whereas in Warehouse No. 1, only procyanidin B2 was detected for this same variety.

Fig. 5 presents three graphs (a, b, and c) comparing the oxygen radical absorbance capacity (ORAC), radical-scavenging capacity (DPPH), and total polyphenol content (TPC) among three coffee varieties evaluated in two warehouses. The results showed that ORAC concentrations were consistently higher in Warehouse No. 2 for all

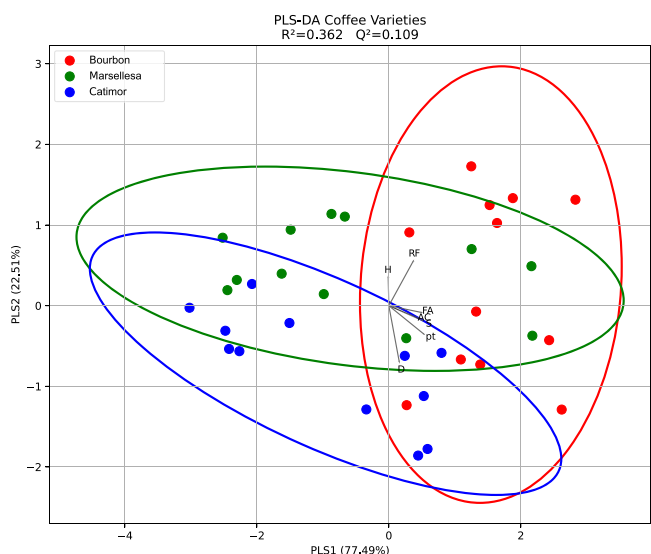


Fig. 3. Principal component analysis (PCA) of the physical and sensory quality of three coffee varieties (Bourbon, Catimor, and Marsellese) evaluated in two warehouses. The figure includes variable projection vectors and ellipses representing 95 % confidence intervals, grouped by variety.

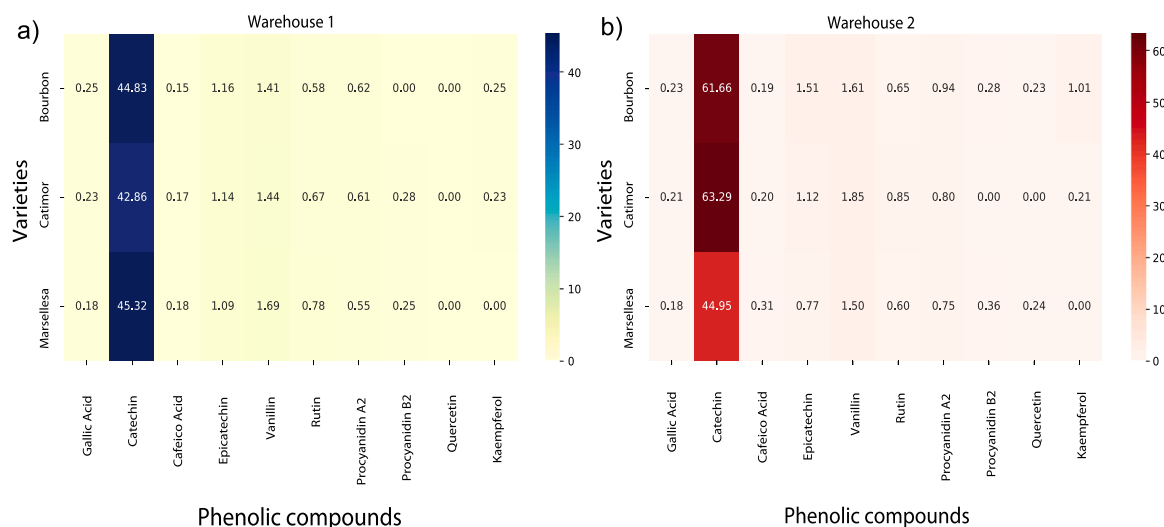


Fig. 4. Heat maps of the polyphenol profile of three coffee varieties (Bourbon, Catimor, and Marsellesa) evaluated in two warehouses (a, b), expressed in parts per million (ppm) and averaged for each bioactive compound.

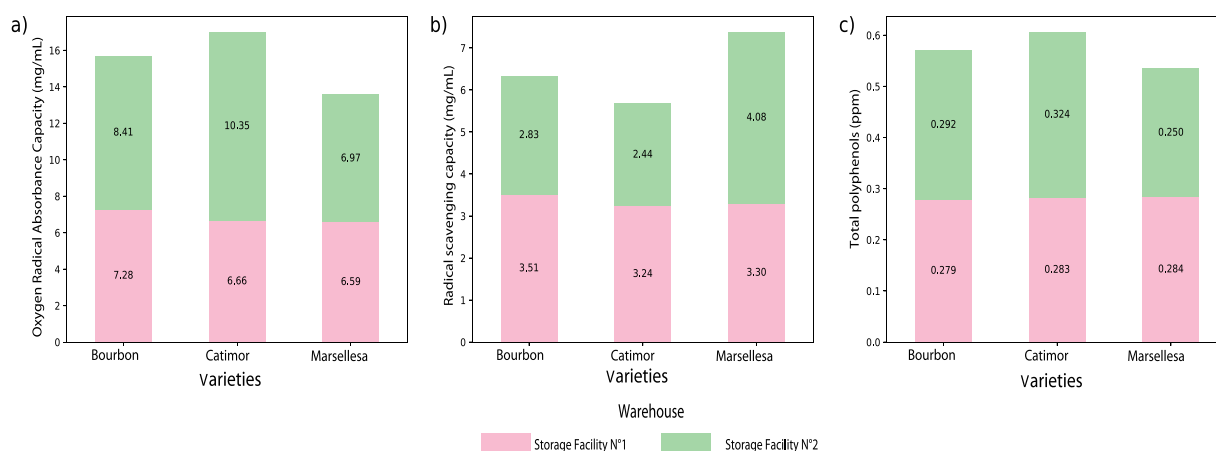


Fig. 5. Stacked graphs of antioxidant activity and total polyphenol content. (a) Average values of Oxygen Radical Absorbance Capacity (ORAC). (b) Average values of DPPH radical scavenging capacity. (c) Average values of Total Polyphenol Content (TPC).

varieties. Notably, the Catimor variety exhibited the highest average ORAC value in this warehouse (10.35 mg mL^{-1}), surpassing Bourbon and Marsellesa (Fig. 5a). In contrast, DPPH concentrations were higher in the Bourbon and Catimor varieties stored in Warehouse No. 1. For the Marsellesa variety, the average DPPH value reached 4.08 mg mL^{-1} in Warehouse No. 2, showing a difference of 0.78 mg mL^{-1} compared to Warehouse No. 1 (Fig. 5b). Finally, the highest TPC concentration was observed in the Catimor variety, with an average value of 0.324 ppm in Warehouse No. 2, followed by Bourbon (0.292 ppm). In contrast, Marsellesa exhibited higher TPC values in Warehouse No. 1 (Fig. 5c).

Table S3 summarizes the simple linear regression analyses performed between ORAC, DPPH, TPC, the average percentages of cup quality, and the physical bean yield. The results showed that ORAC exhibited strong and statistically significant positive correlations with both TPC ($r = 0.81$; $R^2 = 0.66$) and cup quality score ($r = 0.72$; $R^2 = 0.52$). In contrast, DPPH showed a negative and highly significant correlation with TPC ($r = -0.97$; $R^2 = 0.94$), as well as a negative but non-significant correlation with cup quality score ($r = -0.32$; $R^2 = 0.11$). Unlike ORAC, DPPH showed a significant positive correlation with physical bean yield ($r = 0.52$; $R^2 = 0.27$). In turn, total polyphenol content (TPC) showed a positive but non-significant correlation with cup quality score ($r = 0.31$; $R^2 = 0.10$) and a significant negative correlation with physical bean yield ($r = -0.46$; $R^2 = 0.21$). Finally, cup

quality score showed a positive and statistically significant correlation with physical bean yield ($r = 0.62$; $R^2 = 0.39$; $p < 0.01$).

3.3. Mycotoxin analysis

In the identification and quantification of the 36 parchment coffee samples analyzed (Fig. 6), it was determined that 55 % of the samples contained exclusively aflatoxin G₂, with no other types of mycotoxins detected. In Warehouse No. 1, only 13.8 % of the samples showed the presence and concentration of aflatoxin G₂ among the coffee varieties analyzed (Fig. 6a). In Warehouse No. 2, the Catimor variety exhibited the highest concentrations of aflatoxin G₂, representing 41 % of the samples. Additionally, temperature differences were observed for the Catimor variety between the two warehouses, whereas no significant variations were detected for the other varieties (Fig. 6b). Finally, the Marsellesa variety showed the greatest variation in relative humidity depending on storage conditions (Fig. 6c).

Fig S3 summarizes the relationships between aflatoxin G₂ concentration and the environmental variables measured inside the jute sacks, as well as their associations with sensory scores and bean physical yield. Aflatoxin G₂ was detected at temperatures ranging from 32 to $38 \text{ }^\circ\text{C}$ and, to a lesser extent, at lower temperatures between 24 and $28 \text{ }^\circ\text{C}$. Correlation analysis revealed a weak negative relationship between

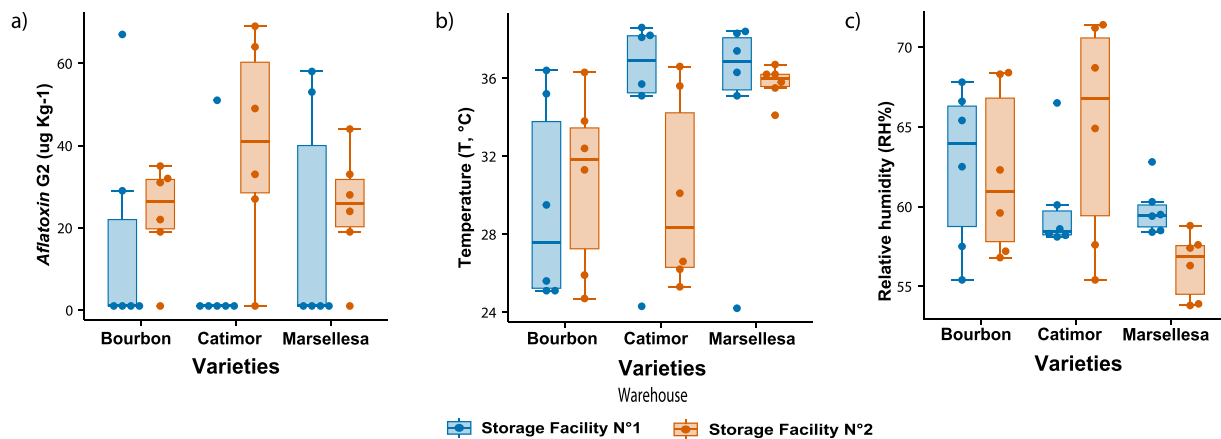


Fig. 6. Evaluation of aflatoxin G₂, temperature, and relative humidity in sampling bags of three coffee varieties (Bourbon, Catimor, and Marsellesa), regardless of storage location. (a) Concentration of aflatoxin G₂ (µg/kg) in the three coffee varieties. (b) Mean temperature values recorded in the coffee varieties. (c) Mean relative humidity values of the air across the three coffee varieties.

temperature and aflatoxin G₂ concentration ($r = -0.19$; $R^2 = 0.04$) (Fig. S3a). In contrast, air relative humidity showed a weak to moderate positive correlation with aflatoxin G₂ concentration ($r = 0.34$; $R^2 = 0.12$). Notably, the occurrence of aflatoxin was observed primarily within relative humidity ranges of 50 - 60 % and 65 - 75 % (Fig. S3b).

Sensory scores showed a weak positive association with aflatoxin G₂ concentration ($r = 0.29$; $R^2 = 0.09$), with higher aflatoxin levels detected in sensory scores ranging from 82.5 to 90 points (Fig. S3c). Bean physical yield did not exhibit a significant relationship with aflatoxin G₂ concentration ($r = 0.09$; $R^2 = 0.01$); however, the highest occurrence of aflatoxin was observed at physical yield values between 65 % and 75 % (Fig. S3d). Finally, a strong negative correlation was observed between temperature and relative humidity ($r = -0.88$; $R^2 = 0.78$), indicating that increases in temperature were associated with decreases in relative humidity both within the storage facilities and inside the sacks used for coffee storage (Fig. S3e).

4. Discusión

The analysis of the physical quality of parchment coffee revealed significant differences among the evaluated varieties (Bourbon, Catimor, and Marsellesa), but not between the two storage facilities (1 and 2), with the exception of bean moisture, husk, and defective beans (Table S1). Coffee quality is influenced by both environmental and genetic factors, which affect the synthesis and accumulation of carbohydrates, proteins, oils, caffeine, and chlorogenic acids (Aung Moon et al., 2025b; Oliva-Cruz et al., 2024). Moisture content is a key parameter, generally maintained between 10 % and 12 %, a range considered optimal for the commercialization of this product (Anokye-Bempah et al., 2023). Likewise, the apparent density of the bean allows differentiation of endosperm composition among varieties (Balcázar-Zumaeta et al., 2025). These differences in physical quality may be influenced by the environmental conditions of the production areas, management practices, agronomic techniques, plantation age, and inadequate calibration of depulping equipment (Worku et al., 2022). Overall, the results reflect the combined influence of the intrinsic characteristics of the varieties and management practices on the physical attributes of coffee beans.

Regarding the physical quality, the Bourbon variety exhibited the highest percentage compared with Catimor and Marsellesa, which is associated with a lower proportion of second-quality and defective beans (Fig. 1). However, this variety has high nutrient requirements and is susceptible to coffee leaf rust, which may lead to a reduction in bean production if it is not properly managed or fertilized (Julca-Otiniano et al., 2023). This varietal behavior may be attributed to edaphoclimatic

factors that limit the plant's ability to express its genetic potential and consequently affect its physiological and productive performance. These processes are also influenced by deficiencies in agronomic management (Balcázar-Zumaeta et al., 2025). Therefore, the high physical quality observed may be associated with well-managed coffee plantations established under favorable edaphoclimatic conditions. In this context, the interaction between varietal genetics and environmental conditions appears to play a predominant role in determining the physical quality of coffee beans, rather than controlled storage conditions, highlighting the need for differentiated management programs according to each coffee variety.

In the sensory evaluation of coffee, Warehouse No. 2 showed higher cup scores compared with Warehouse No. 1, with the Bourbon variety standing out by reaching average scores of 84.05 and 85.76 out of 100 points. Similarly, comparable results were observed for sweetness, as well as differences in aroma and flavor among the three varieties and the two warehouses (Fig. 2). Our results are consistent with those reported by Oliva-Cruz et al. (2024), where the Catimor variety exhibited the lowest cup score compared with other varieties. Likewise, these cup quality scores fall within the specialty coffee range. These results may be attributed to the influence of the physical performance of the beans, particularly their density and moisture content, which are closely associated with genetic expression and varietal adaptation (Collazos-Escobar et al., 2025).

Multivariate analysis using PLS-DA indicated that the physical and sensory variables considered only partially explain the differentiation among the evaluated varieties. Additionally, a negative correlation was observed between bean moisture and density, whereas density showed a positive correlation with both physical yield and cup score (Fig. 3). Likewise, the variable importance in projection (VIP) analysis identified bean physical quality (RF), cup score (pt), and flavor (S) as the parameters with the greatest contribution to discrimination among varieties (Fig. S1), suggesting that factors such as environmental conditions, agronomic management, and postharvest processing also influence this differentiation (Aung Moon et al., 2025). These findings are consistent with previous reports by Martínez et al. (2024), who indicate that maintaining optimal moisture levels, adequate density, and high physical performance is essential to achieve excellent cup quality. However, some parameters evaluated to determine cup quality may also be influenced by other stages of postharvest processing (Costa et al., 2025). Overall, the sensory quality of coffee is not determined solely by postharvest management but also depends on the interaction between the physical performance of the bean, moisture content, and apparent density.

The polyphenol profile and antioxidant capacity of the three coffee

varieties showed clear intervarietal differences influenced by both edaphoclimatic conditions and storage management. The Catimor variety stood out in Warehouse No. 2, presenting high concentrations of catechin and vanillin, as well as higher levels of DPPH and total polyphenols (TPC). In contrast, Marsellesa exhibited greater diversity and richness of phenolic compounds in Warehouse No. 1 and reached the highest oxygen radical absorbance capacity (ORAC). Meanwhile, the Bourbon variety maintained a stable and balanced phenolic profile in both warehouses, reflecting its consistency in physical and chemical quality. These results indicate that the synthesis of bioactive compounds is strongly influenced by varietal genetics, environmental conditions, and agronomic management practices (Aung Moon et al., 2025b).

The relationship between the chemical, physical, and sensory properties of coffee beans has demonstrated that physical quality is closely linked to chemical composition. In this context, this interaction is associated with oxidative processes occurring during postharvest, which contribute to the stabilization of chemical compounds. As a result, these processes influence sensory perception, promoting the development of an appealing, attractive profile with a subtle touch of acidity (Dulsat-Serra et al., 2016). In this context, the ORAC method showed significant positive correlations with both total polyphenol content (TPC) ($r = 0.81, p < 0.001$) and cup quality score ($r = 0.72, p < 0.001$), indicating its greater capacity to reflect the overall antioxidant fraction, including not only phenolic compounds but also other components associated with sensory expression. This behavior is consistent with its methodological basis on hydrogen atom transfer (HAT), in contrast to other antioxidant assays whose results depend on the predominant reaction mechanism (Munteanu & Apetrei, 2021). In contrast, the DPPH assay showed a very high negative correlation with TPC ($r = -0.97, p < 0.001$) and absence of a significant association with cup quality, suggesting that its analytical response is limited to the reactivity of a specific subset of compounds under particular assay conditions, without adequately representing the integral antioxidant capacity of coffee. This limitation is explained by the use of a stable synthetic radical in the DPPH method, whereas the antioxidant activity of coffee depends on the synergistic interaction of multiple compounds, not restricted solely to phenolics (Liang & Kitts, 2014).

Moreover, although TPC was closely associated with antioxidant capacity, it did not show a significant correlation with cup quality, indicating that a higher total concentration of phenolic compounds does not necessarily translate into improved sensory performance. This result is consistent with previous evidence indicating that coffee sensory quality arises from the complex interaction between volatile and non-volatile compounds, and that chlorogenic acids contribute to attributes such as bitterness, astringency, mouthcoating sensation, pigmentation, and aroma-related characteristics, rather than uniformly enhancing cup quality (Linne et al., 2023; Sunarharum et al., 2014). Overall, these findings suggest that the ORAC method exhibits greater sensitivity than DPPH in reflecting antioxidant components closely linked to sensory quality in specialty coffees, whereas TPC more accurately describes overall antioxidant potential, but not sensory excellence.

In the mycotoxin analysis, only aflatoxin G₂ was detected Warehouse No. 1 showed the lowest incidence of this contaminant, whereas Warehouse No. 2 exhibited a higher proportion of affected samples, mainly corresponding to the Catimor variety. This result may be attributed to inadequate cherry selection resulting from improper agricultural practices, together with the influence of microclimatic conditions and storage duration (Conrad & De Rosa, 2025). Such environmental conditions favor the proliferation of filamentous fungi, particularly *Aspergillus parasiticus*, the main producer of aflatoxin G₂ (das Neves et al., 2021; Qin et al., 2024).

The physical and sensory quality parameters showed weak associations with the concentration of aflatoxin G₂, suggesting that the occurrence of mycotoxins is determined by other factors acting throughout the production chain. Moreover, it has been demonstrated that coffee

beverage preparation reduces aflatoxin levels and hinders their sensory detection (Al-Ghouthi et al., 2022), indicating that the presence and concentration of aflatoxins are more closely related to environmental conditions and storage practices than to intrinsic quality attributes.

The concentration in each sample exceeded the limit established by the European Union of 10 µg·kg⁻¹ for green coffee (Díaz Rodríguez et al., 2018). Although these mycotoxins have been associated with hepatotoxic, immunosuppressive, and carcinogenic effects, the magnitude of the risk depends on the level of exposure as well as on storage conditions and processing practices (Espinosa-Plascencia & Bermúdez-Almada, 2023). In particular, aflatoxin G₂ has been classified as a probable carcinogen according to reports from the International Agency for Research on Cancer (Ostry et al., 2016), highlighting the need to maintain effective monitoring and control systems. Nevertheless, several emerging technologies, including nanomaterial-based approaches, innovative physical processes, and advanced biological strategies, have shown considerable potential for the degradation of these mycotoxins (Kodape & Kodape, 2024). Collectively, these findings reinforce the importance of strengthening control and management strategies throughout the coffee production chain. At the same time, emerging technologies represent a promising alternative to improve product safety without compromising its quality.

5. Conclusions

This study demonstrated that the Bourbon variety achieved the highest overall performance in terms of physical quality, sensory attributes, and functional composition, confirming its suitability for the production of premium specialty coffee. Its elevated concentrations of gallic acid, epicatechin, procyanidin A2, and kaempferol further support its potential as a valuable source of health-related bioactive compounds. Marsellesa exhibited intermediate performance, characterized by acceptable bean quality and competitive sensory scores, whereas Catimor showed lower physical quality and comparatively reduced sensory performance. These findings emphasize the significant effect of genotype on key quality traits in coffee. The detection of aflatoxin G₂ highlights the relevance of strict postharvest management, particularly during drying and storage, to preserve product safety and commercial value. Overall, the results identify Bourbon as the most promising genotype among those evaluated and provide a scientific basis for breeding programs aimed at integrating productivity, superior cup quality, and functional properties to meet the demands of high-value specialty coffee markets.

Ethical statement

The sensory analysis study was conducted in Peru without formal review by an ethics committee, in accordance with local regulations. All participants were volunteers, provided written informed consent, could withdraw at any time without penalty, and data confidentiality was ensured. The tests were performed following a standardized protocol from the Specialty Coffee Association (SCA) for the sensory evaluation of specialty coffee, adhering to international ethical principles as well as institutional, national, and international guidelines for responsible research. The authors confirm that the study complies with the ethical standards of Food Chemistry Advances and relevant regulations.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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Data availability

Data will be made available on request.

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