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Effect of Cultivation Region on the Physicochemical and Quality Characteristics of Arabica Coffee (Red Bourbon Variety) from Bean to Brew †

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Abstract

Caffeine is one of the most well-known biologically active compounds in coffee beans, and its content largely determines the taste and stimulating properties of the drink. However, the amount of caffeine in beans can vary significantly depending on growing conditions, even within the same coffee variety. The growing global demand for coffee and the current market dynamics emphasize the necessity to investigate how the origin of coffee beans influences beverage quality. Arabica beans, particularly the Red Bourbon variety, are known to exhibit variations in chemical composition, sensory characteristics, and technological behavior depending on their cultivation environment. The study aimed to evaluate the physicochemical and sensory properties of Arabica Red Bourbon beans sourced from distinct geographic regions, considering factors such as altitude and local environmental conditions. The sensory characteristics of the resulting beverages were evaluated using the capping method, and water activity, density, moisture content, color, pH, extractivity and caffeine content were determined. Roasted bean color ranged from 61.4 to 62.5, while ground coffee color was 72.5–75.4. Moisture content was highest in Col and R (3.4%) and lowest in Con (3.1%). The greatest moisture loss during roasting occurred in S and R (13.4%). Water activity decreased from 0.50–0.56 in green beans to 0.18–0.30 post-roasting. Extraction yield ranged from 20.03 to 21.21%, and total dissolved solids (TDS) varied at 1.23–1.30%. The least acidic sample was S (pH 5.04). Colombian beans contained unusually high caffeine. The conducted research confirmed that the geographical origin of Arabica Red Bourbon beans significantly impacts their physicochemical and sensory attributes. Variations in moisture, acidity, and caffeine content were observed among the samples, despite a consistent roasting profile.

Keywords: Arabica coffee; caffeine; geographic regions; water activity

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1. Introduction

The overall chemical profile of coffee beans, including caffeine and other key compounds, can vary within the same variety as a function of terroir, which integrates environmental, climatic, and soil-related conditions [1–3]. Terroir encompasses factors such as soil and mineral composition, temperature, humidity, altitude and solar radiation intensity.

The altitude at which Arabica beans are grown significantly modulates their chemical composition, affecting the accumulation of key metabolites such as carbohydrates, proteins, lipids and caffeine. The soil nutrient profile, including the nitrogen, potassium, magnesium, and phosphorus content, may exert a notable influence on the physiological development of the coffee cherry and the subsequent chemical composition of the beans. Nitrogen, in particular, is a key element in the synthesis of alkaloids, which include caffeine. Poor or degraded soils can reduce the overall caffeine content, while balanced mineral nutrition promotes its accumulation [4,5]. The temperature regime determines the growth rate of coffee berries. At moderate temperatures (18–22 °C for *Coffea arabica*), the ripening process is slower, which contributes to a more complex chemical profile of the beans. An increase in altitude (e.g., 1400 m compared to 1200 m for Enrekang beans) leads to an increase in carbohydrate (up to 24.03%) and lipid (up to 10.73%) content, which is explained by slower fruit ripening at low temperatures and more intense photosynthesis [6]. High humidity combined with warm temperatures activates the biosynthesis of alkaloids, but excessive humidity can cause physiological stress in plants [7]. As altitude increases, the average daily temperature decreases and the ripening period of the berries lengthens, leading to changes in the ratio of caffeine, chlorogenic acids and sugars. Previous studies indicate that the effect of altitude on caffeine accumulation and chemical composition of coffee beans is not uniform and cannot be interpreted as a single-directional relationship [8]. Some authors report that coffee cultivated at higher altitudes tends to exhibit lower or moderate caffeine content while developing a more complex aromatic profile [9]. In contrast, other studies demonstrate that under certain environmental conditions, increasing altitude may be associated with higher protein and caffeine contents, which contribute to aroma development and bitterness through Maillard reactions during roasting [10–13]. These discrepancies highlight the difficulty of directly comparing samples from different growing regions, as altitude interacts with temperature regime, soil composition, and overall climatic conditions, which collectively exert a more complex influence on coffee bean chemistry than altitude alone. Consequently, despite the potentially richer chemical composition observed at higher elevations, superior sensory quality (cup score) is often reported at medium altitudes (around 1200 m), a phenomenon frequently attributed to optimal soil fertility and balanced growing conditions rather than elevation itself [14,15]. The level of insolation directly affects the photosynthetic activity of the plant. Shade-grown coffee promotes slower caffeine accumulation and the formation of a more balanced chemical composition. Excessive insolation can stimulate increased caffeine synthesis as a protective response of the plant to stress [16].

The terroir of the studied regions represents a diverse environmental matrix. Rwanda (Nyaruguru) is characterized by acidic volcanic soils and a temperate tropical climate with average temperatures of 18–20 °C [17]. South Kivu (Congo) features nutrient-rich volcanic soils in the Lake Kivu basin, combined with high humidity and relatively stable solar radiation. Huila (Colombia) is distinguished by nitrogen-rich volcanic ash soils and pronounced diurnal temperature variations [18], whereas Santa Ana (El Salvador) is characterized by well-drained loamy volcanic soils and clearly defined wet and dry seasons that regulate fruit development and ripening dynamics [19]. Such contrasts in edaphic and climatic conditions may influence nutrient uptake, bean maturation, and the formation of chemical precursors that subsequently determine roasting behavior and beverage characteristics. However, despite extensive discussion of terroir effects in the literature, comparative studies evaluating green bean properties, post-roast parameters, and brewed extract characteristics under standardized technological conditions remain limited. Therefore, the aim of this study was to assess how terroir-related factors affect the physicochemical, structural, and sensory properties of Red Bourbon coffee from selected regions when roasted according to an identical profile, thereby isolating the effect of raw material origin from technological variability. In this context, the study sought to determine whether regional differences are reflected in green bean composition, whether these differences persist after roasting, and to what extent they influence the properties of the brewed beverage under controlled extraction conditions (Figure 1).

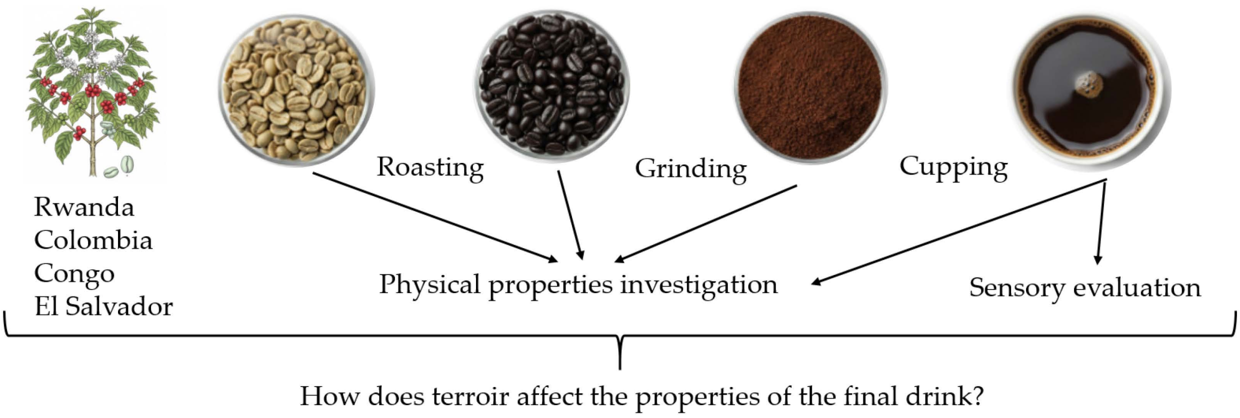

Figure 1. Experimental workflow and research concept for assessing terroir-driven variations in coffee quality.

2. Materials and Methods

2.1. Materials

This study investigated four distinct samples of *Coffea arabica* L. (variety *Red Bourbon* for African origins and unspecified varieties for Latin American samples). The samples were identified and characterized as follows: Sample R (11-23-10, Rwanda), sourced from the Southern Province, Nyaruguru District (2°31′ S, 29°35′ E) and processed at the Fugi washing station, was harvested in 2023 (March–June) at an altitude of 1750 m a.s.l.; Sample Con (11-23-07, Congo), sourced from the South Kivu Province (2°03′ S, 28°53′ E) and processed at the Nyamasasa washing station, was harvested in 2023 (March–June) at an altitude of 1800 m a.s.l.; Sample Col (07-23-32, Colombia), sourced from the Huila region, San Agustin municipality (1°53′ N, 76°16′ W) and produced at the La Aldea farm, was harvested in 2023 (May–August) at an altitude of 1850 m a.s.l.; and Sample S (03-24-44, El Salvador), sourced from the Apaneca-Ilamatepec region, Santa Ana municipality (13°51′ N, 89°47′ W) and produced at the La Esperanza farm, was harvested during the 2023–2024 season (December–March) at an altitude of 1500 m a.s.l.

2.2. Sample Preparation

Green beans washed according to the requirements of the Specialty Coffee Association (SCA) [20] were visually assessed for defects, after which green coffee beans were roasted in a Kaffelogic Nano 7 electric roaster using a standardized temperature-time profile [21]. Coffee beans were roasted according to a controlled profile. At the initial stage, the beans were heated until the first crack occurred, which was recorded at a temperature of 207.5–208 °C 6 min and 15 s after the start of the process. After the first crack, the bean development stage was implemented, which accounted for 18% of the total roasting profile and lasted 1 min 22 s, during which the temperature increased by 9 °C. When the final temperature of 215 °C was reached and the total roasting time was 7 min 37 s, the process was stopped. Upon reaching the final roasting endpoint, the cooling process was automatically initiated within the roast chamber (in situ). The samples were cooled using forced ambient air convection provided by the roaster's high-airflow fan system.

2.3. Methods

The color of the roasted beans was determined using a Lighttells CM-100 Plus Roast Analyzer infrared coffee roasting analyzer. Total dissolved solids (TDS) and extraction yield (EXT) were measured using a DiFluid R2 Extract device. Before conducting analytical studies, each coffee sample was ground in a Mahlkönig Omnia coffee grinder with a set distance between the burrs of 450 μm. The water activity in the powder was determined using an electronic water activity meter 'LabMasteraw neo' by Novasina AG (Lachen, Switzerland) at a temperature of 20 °C. An EM 120-HR moisture analyser was used to determine moisture content.

HPLC caffeine content determination was performed on BDS-hypersil-C18 150 × 2 mm column from Keystone Scientific. 25 mkl of coffee extracts were injected and the flow rate was 1 mL/min. Caffeine peak was identified by the retention time with UV-vis LCD 2563 detector at 254 nm. A 1:1 mixture of water and acetonitrile was used as the mobile phase and for the preparation of caffeine reference solutions. Calibration data were fit by the linear trend $y = 0.0053x + 0.0951$ ($R^2 = 0.9857$), from which surface area corresponding to the 1 mkg/mL was recalculated per portion.

Sensory analysis was performed by a panel of 4 coffee professionals, led and calibrated by a certified Q Grader, strictly following the SCA cupping protocol [22]. Each sample was evaluated for ten attributes (Fragrance/Aroma, Flavor, Aftertaste, Acidity, Body, Balance, Clean Cup, Uniformity, Sweetness, and Overall) on a scale from 6 to 10 points. The total score was calculated as the sum of these individual attribute scores. For organoleptic evaluation (cupping method [23]), the mass of ground coffee was standardized to 12 g, which was weighed in special tasting cups. Extraction was carried out by pouring 200 mL of hot distilled water at a temperature of 95 °C over the samples, followed by intensive stirring with a stream of water. At the fourth minute of extraction, the crust was broken, after which the drink was considered ready for organoleptic evaluation.

3. Results and Discussions

3.1. Physico-Chemical Properties of Coffee

3.1.1. Green Beans Characteristics

The characteristics of Red Bourbon green coffee are the starting point for understanding the potential for flavor development during roasting. The physical and chemical properties of raw beans, such as moisture content, water activity (aw) and bulk density, are critical indicators of product quality and stability (Table 1).

Table 1. Physical Characteristics of Green Coffee Beans.

Sample Name	Code (Alpha-Numeric)	Altitude, m.a.s.l.	Moisture Content, %	Bulk Density (ρ_{avg}), g/L	Water Activity (aw)
Colombia	Col (07-23-32)	1850	4.9 ± 0.1	729.5 ± 0.9	0.5898 ± 0.0005
Congo	Con (11-23-07)	1800	4.6 ± 0.3	715.7 ± 1.1	0.5163 ± 0.0003
Rwanda	R (11-23-10)	1500	4.8 ± 0.2	732.5 ± 1.4	0.5611 ± 0.0005
El Salvador	S (03-24-44)	1500	3.7 ± 0.2	719.80 ± 0.7	0.5666 ± 0.0009

Analysis of the physicochemical indicators of the green coffee samples indicates their high quality and compliance with specialty coffee standards. The differences in moisture content among the samples Col, Con and R are not statistically significant and fall within the experimental error. The obtained moisture values of 3.7–4.9% are slightly lower than the generally accepted commercial standards [24], but water activity at the level of 0.51–0.59 ensures the stability of the beans during storage and prevents microbiological spoilage [25]. The table shows that altitude is not a determining factor of terroir, i.e., the same absolute altitude in different regions does not mean the same growing conditions. In terms of the combination of temperature conditions, humidity and solar radiation intensity, an altitude of 1500 m above sea level in Rwanda corresponds to a higher altitude in terms of slowing down grain metabolism. The slower the ripening, the higher the structural density of the endosperm. This explains the high bulk density of the samples, especially in lots from Rwanda (732.48 g/L) and Colombia (729.54 g/L) [26].

3.1.2. Roasted Beans Characteristics

During roasting, coffee beans typically lose 12 to 20% of their weight. For light roasting, this loss is approximately 12–14%, for medium—15–17%, and for dark roasting—18–20% or even more in the case of deep roasting [27] volatile compounds, and the thermal decomposition of organic substances. Green coffee contains approximately 10–12% moisture, which evaporates almost completely during the heat treatment process. In addition, gases are released from the beans, including carbon dioxide, organic acids and aromatic substances [28]. The weight loss for all samples remained consistent between 9.3% and 13.4%, which is typical for a medium specialty roast profile (Table 2).

Table 2. Post-roast physical parameters and colorimetric analysis of the investigated coffee lots. Values are expressed as mean ± analytical uncertainty based on technical replicates.

Sample Name	Weight Loss (%)	Moisture Content (%)	Moisture Loss (%)	Bulk Density (ρ_{avg}), g/L	Water Activity (aw)	Color (L*)
Rwanda	13.4 ± 0.1	1.1 ± 0.2	3,7 ± 0.2	402.8 ± 0.8	0.2846 ± 0.0002	60.9 ± 1.1
Colombia	12.9 ± 0.2	0.9 ± 0.3	4,0 ± 0.1	394.3 ± 1.1	0.2736 ± 0.0005	62.1 ± 1.0
Congo	9.3 ± 0.1	0.9 ± 0.1	3,7 ± 0.3	417.2 ± 0.9	0.2872 ± 0.0003	61.4 ± 0.9
El Salvador	13.4 ± 0.1	0.8 ± 0.2	2,9 ± 0.1	356.7 ± 1.4	0.2513 ± 0.0003	61.5 ± 1.0

L* represents the lightness coordinate in the CIE L*a*b color space (ranging from 0 for black to 100 for white).

Coffee grown in high-altitude terroirs, particularly samples from Congo (1800 m above sea level; 9.3% weight loss) and Colombia (1850 m above sea level; 12.9%), shows a reduced tendency to lose both weight and moisture during roasting. This indicates higher thermal stability and better structural integrity of the endosperm, which probably results in slower degassing and dehydration processes compared to beans from lower altitudes. The lowest residual moisture content was recorded for beans from El Salvador, which at the same time are characterized by the lowest bulk density (356.7 g/L), the highest total weight loss (13.4%) and the lowest moisture loss (2.9%), which suggests that a portion of its weight loss came from the organic matter breakdown rather than just water evaporation. Post-roast water activity (aw) for all samples was recorded between 0.2513 and 0.2872. These values sit within the optimal range for roasted coffee stability, preventing microbial spoilage while minimizing the rate of non-enzymatic browning and lipid oxidation [20].

In general, the physical characteristics of the samples after roasting (Table 2) show a sufficient level of interregional differentiation. The greatest variability was observed in the mass loss indicator, which emphasizes the specific response of the grain structure of each terroir to the process of thermal destruction. At the same time, the color parameters (L*) of all roasted coffee samples were very similar, indicating a comparable degree of roasting across all lots. This allows the influence of roast degree on subsequent physicochemical and analytical results to be reasonably excluded.

3.1.3. Physicochemical Analysis of the Coffee Brew

The extraction dynamics of the roasted Red Bourbon samples were evaluated through Total Dissolved Solids (TDS), pH levels, and Extraction Yield (EXT) (Table 3).

Despite the lower initial moisture content of the green beans, all samples demonstrated efficient solubility, with the Rwanda lot reaching the highest extraction yield of 20.03%. This indicates an optimal balance between structure and availability of soluble compounds. The

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pH values across all samples ranged from 4.86 to 5.04, which is consistent with the optimal acidity development for medium-roasted specialty Arabica. It is generally accepted that pH, extractivity, and TDS values are significantly influenced by a combination of natural growing conditions [29]. Beans from high-altitude regions tend to have higher acidity due to slower ripening, which promotes the accumulation of organic acids. However, analysis of the physicochemical parameters of extracts (TDS, Brix, pH and extractivity) indicates that any origin-related effects, if present, were smaller than the analytical variability of the applied methods.

Table 3. Physicochemical properties and extraction parameters of Arabica coffee samples from different geographical origins. Values are expressed as mean ± analytical uncertainty based on technical replicates.

Sample Name	Ground Color (L*)	Extraction Yield (EXT, %)	TDS (%)	pH	Brix (%)	Caffeine Content (mg/200 g)
Rwanda	74.6 ± 1.1	20.03 ± 0.03	1.26 ± 0.02	4.86 ± 0.05	1.51 ± 0.02	317.2 ± 15.1
Colombia	74.1 ± 0.9	19.55 ± 0.02	1.23 ± 0.03	4.92 ± 0.05	1.49 ± 0.02	496.3 ± 21.0
Congo	74.1 ± 1.2	19.30 ± 0.03	1.25 ± 0.03	5.04 ± 0.05	1.51 ± 0.03	388.6 ± 12.3
El Salvador	76.1 ± 1.1	19.47 ± 0.04	1.23 ± 0.03	4.93 ± 0.05	1.49 ± 0.01	397.3 ± 18.2

L* represents the lightness coordinate in the CIE L*a*b color space (ranging from 0 for black to 100 for white).

The generally accepted hypothesis is that Arabica grown at high altitudes tends to have a slightly lower caffeine content than Arabica grown at lower altitudes [4,13,15]. This is because the climate at high altitudes is usually cooler, ripening is slower, and, most importantly, there are fewer pests and diseases [30,31]. Our research shows that altitude alone cannot be the sole or most important factor determining caffeine content. Instead, specific genetic variants or unique local environmental stressors likely play a decisive role in shaping this indicator (Table 3). The high caffeine content in the Colombian sample (496.3 mg/200 g) can be further attributed to the specific microclimate of the region, characterized by high humidity and elevated average daily temperatures. While altitude typically leads to lower caffeine levels due to cooler conditions, the presence of heat and moisture acts as a significant environmental stressor. Under these conditions, the coffee tree upregulates the synthesis of caffeine as a chemical defense mechanism against increased biotic pressures, such as fungal pathogens and pests, which thrive in humid environments [32]. This suggests that in Colombian terroir, climatic stressors override the traditional altitudinal cooling effect, leading to an accelerated accumulation of alkaloids.

3.1.4. Organoleptic Analysis and Clean Cup Assessment

Sensory evaluation of samples was conducted to determine the influence of terroir on the organoleptic characteristics of the beverage, assuming identical roasting degrees and extraction parameters. The comprehensive analysis included a descriptive profile and a scoring assessment based on key quality attributes (Figure 2, Table 4). The results reveal a dichotomy between the chemical composition of the extracts and their organoleptic characteristics. Despite the statistical homogeneity of the basic physicochemical parameters (TDS, Brix, pH), which indicates the identity of the quantitative yield of soluble compounds, the sensory identification of samples retains a clear territorial link. The terroirs of Central America are traditionally determined by experts through the concept of a 'clean cup', characterized by high sensory purity and balance. At the same time, samples of African origin (Rwanda, Congo) are distinguished by authentic fruit profiles with high acidity intensity. The complexity of these profiles is often accompanied by lower organoleptic stability compared to Latin American samples, due to the specifics of regional fermentation methods and microbiological background [33].

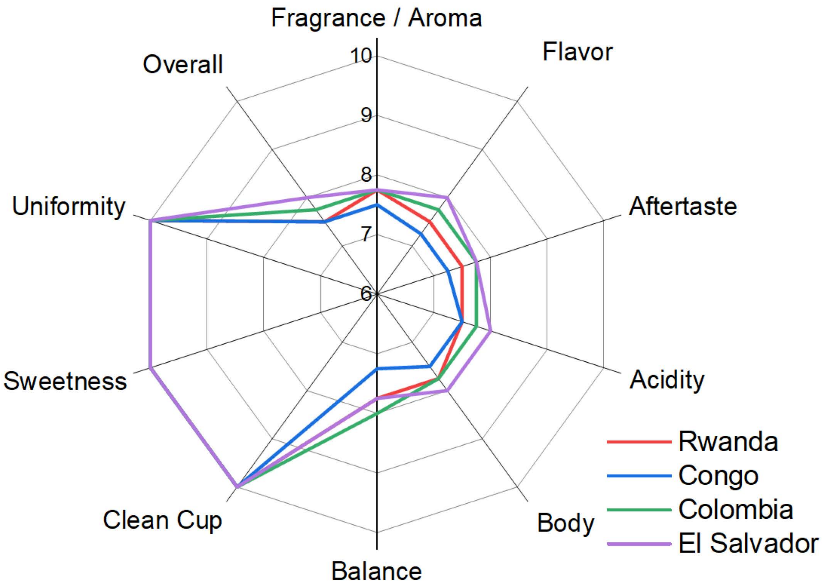

Figure 2. Sensory profile of coffee samples from different origins.

Table 4. Sensory Descriptors and Regional Profiles of Coffee Samples.

	Rwanda	Congo	Colombia	El Salvador
Flavor and Aroma	Citrus, caramel, vanilla, chocolate, nuts, and floral notes	Distinct red berries and fig	Bright fruits and pronounced sweetness	Dark grapes, pomegranate, and whiskey (complex profile)
Acidity	Moderate, fruity acidity	Moderate and well-balanced	Harmonious, "sparkling" acidity	Medium, winey acidity
Body and Aftertaste	Gentle creamy body; clean finish	Rich body; dominant fruity notes	Medium-bodied; clean, long-lasting aftertaste	Dense creamy body; deep aftertaste
Balance and Overall	High equilibrium across all descriptors	Clearly defined, stable profile	High sweetness with balanced bitterness	Highly complex

The highest overall scores were given to samples from El Salvador (85.25) and Colombia (84.50), which correlates with their high ratings for 'Balance' and 'Overall'. Samples from Rwanda and Congo showed stable results (83.25 and 81.75, respectively), but had specific body characteristics ('creamy' vs. 'rich dominant body'). As can be seen from the radar chart (Figure 2), the 'Uniformity', 'Clean Cup' and 'Sweetness' indicators are almost identical for all locations. This confirms that unified technological processing allows for stable quality of the basic attributes of the beverage while preserving unique regional nuances of taste and aroma.

4. Conclusions

The physical characteristics of the roasted coffee beans demonstrated clear interregional differentiation. Differences in weight loss during roasting and residual moisture content indicate variability in bean structure, density, and internal morphology, which are plausibly associated with terroir-related factors such as cultivation altitude, climatic conditions, and soil composition. At the same time, the colorimetric parameters remained highly consistent across all samples, confirming the reproducibility of the roasting protocol and excluding variations in roast degree as a confounding factor in the observed structural differences.

In contrast, the physicochemical parameters of the prepared coffee extracts (TDS, Brix, pH, and extraction yield) remained within a narrow range across all origins. Under unified brewing conditions, these indicators showed a high degree of consistency, suggesting that standardized thermal processing and extraction largely mitigate differences in general soluble solids and primary chemical characteristics of the beverage. Despite the physicochemical similarity of the extracts, the samples exhibited a distinct descriptive individuality. The Central and South American profiles were characterized by descriptors such as 'bright fruits' and 'sparkling acidity' (Colombia), as well as 'dark grapes' and 'winey acidity' (El Salvador), which align with the concept of high sensory purity. The African samples demonstrated complex profiles with accents on 'citrus' and 'floral notes' (Rwanda), and 'red berries' and 'fig' (Congo).

Caffeine content represented the most dynamic chemical parameter among the analyzed constituents. Its concentration ranged from 317.2 mg/200 g (Rwanda, 1500 m a.s.l.) to 496.3 mg/200 g (Colombia, 1850 m a.s.l.), indicating substantial variability between samples. Unlike general extractive parameters, caffeine appears to retain sensitivity to environmental and physiological growing conditions despite identical roasting and extraction regimes. It is possible that high humidity and average daily temperatures are decisive factors that can invert the typical altitudinal trend of caffeine reduction. In the case of the Colombian terroir, these climatic factors stimulated a defensive physiological response, resulting in the highest observed caffeine concentration (496.3 mg/200 g) among the studied regions.

Future research should focus on expanding the sample set to include multiple replicates from each geographical zone, ideally collected over different harvest years. Such a longitudinal approach would allow for a more reliable statistical analysis and help distinguish permanent terroir effects from seasonal variations. Expanding the geographical scope while maintaining identical processing protocols will remain a priority for further validating the 'soil-to-cup' impact model.

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