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Efectos de la altitud y de los métodos de beneficio sobre la calidad organoléptica del café robusta

Effects of Altitude and Processing Methods on the Organoleptic Quality of Robusta Coffee

Doctorando

Sofía Del Rocío Velásquez Cedeño

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TITULO: *EFECTOS DE LA ALTITUD Y DE LOS MÉTODOS DE BENEFICIO SOBRE LA CALIDAD ORGANOLÉPTICA DEL CAFÉ ROBUSTA*

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DOCTORANDA/O

Sofía del Rocío Velásquez Cedeño

TÍTULO DE LA TESIS:

EFECTOS DE LA ALTITUD Y DE LOS MÉTODOS DE BENEFICIO SOBRE LA CALIDAD ORGANOLÉPTICA DEL CAFÉ ROBUSTA

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La tesis doctoral presentada por Sofía del Rocío Velásquez Cedeño bajo nuestra supervisión.
Consideramos que la doctoranda ha cumplido correctamente las etapas implícitas en el desarrollo de la tesis doctoral, lo que ha permitido su correcta formación como investigadora Durante el desarrollo de la tesis doctoral, la doctoranda ha desarrollado las destrezas propias del proceso de investigación (planteamiento y contraste de hipótesis, búsqueda bibliográfica, análisis estadístico, redacción de artículos…) y ha sabido sobrepasar las dificultades inherentes al iniciarse en la investigación. Creemos que la doctoranda tiene la formación necesaria para continuar trabajando en la misma línea de investigación, y desarrollar su carrera investigadora. El documento final de su tesis doctoral cumple con los requisitos establecidos en la normativa actual para poder finalizar su tesis doctoral. Concretamente, la tesis incluye tres capítulos, cada uno de los cuales está publicado en revistas incluidas en el Journal Citation Report (JCR), en los que la doctoranda figura como primera autora. Dos de los trabajos han sido publicados en revistas del tercer cuartil (Q3) y uno en una revista situada en el segundo cuartil (Q2).
Además, consideramos que el documento está redactado correctamente, siendo su contenido consecuencia del trabajo realizado por la doctoranda bajo la coordinación de los directores, siendo información inédita no publicada en otras partes.

Por todo lo expuesto anteriormente, consideramos que la tesis cumple con todos los requisitos para ser defendida.

Por todo ello, se autoriza la presentación de la tesis doctoral.

Córdoba, a 18 de diciembre de 2023

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Contenido

Resumen

Teniendo en cuenta la importancia del perfil aromático y el sabor único del café Arábica, la mayor parte de la literatura se centra en esta especie debido a su alta participación en el mercado; sin embargo, hoy en día, el café Robusta se destaca por su creciente valor industrial y resistencia a la sequía. El presente trabajo enfatiza la importancia del café como producto agrícola, y por tanto se presenta una evaluación de la influencia de factores pre y poscosecha en la calidad organoléptica de la taza de café. Para esto, en el primer capítulo se presenta una revisión bibliográfica que abarca información relevante a los factores de pre y poscosecha que influyen en el procesamiento y calidad de las dos especies más importantes de café: *Coffea arabica* y *Coffea canephora*. En el segundo capítulo, se exponen los resultados de una evaluación de la calidad organoléptica de tazas de café C. canephora de los grupos congolensis y conilon, granos que fueron cultivados a diferentes altitudes de Ecuador y sometidos a diferentes métodos poscosecha. El tercer capítulo trata sobre la influencia de diferentes métodos de procesamiento poscosecha en la calidad física y sensorial (notas de degustación) de los granos de café Robusta congolensis y conilon.

Palabras clave: análisis sensorial, *Coffea canephora,* altitud, post-cosecha

Abstract

Taking into account the importance of the aromatic profile and unique flavor of Arabica coffee, most of the literature focuses on this species due to its high market share; however, today, Robusta coffee stands out for its increasing industrial value and drought resistance. The present work emphasizes the importance of coffee as an agricultural product, and therefore an evaluation of the influence of pre- and post-harvest factors on the organoleptic quality of the cup of coffee is presented. For this, the first chapter presents a bibliographic review that covers information relevant to the pre- and post-harvest factors that influence the processing and quality of the two most important coffee species: *Coffea arabica* and *Coffea canephora*. In the second chapter, the results of an evaluation of the organoleptic quality of cups of *C. canephora* coffee from the congolensis and conilon groups are presented, beans that were grown at different altitudes in Ecuador and subjected to different post-harvest methods. The third chapter deals with the influence of different post-harvest processing methods on the physical and sensory quality (tasting notes) of Robusta congolensis and conilon coffee beans.

Keywords: sensory analysis, *Coffea canephora*, altitude

Introducción

La producción mundial de café al año 2020 fue de 169,34 millones de sacos. Del café Arábica se ha logrado producir hasta 101,9 millones de sacos de y 73,5 millones de sacos de Robusta, lo que representa un 64 y 36 % de importancia comercial respectivamente (ICO, 2021). El café Arábica es mundialmente famoso por su aroma y acidez; en tanto, Robusta tiene mayor cuerpo, pero menor aroma (Campuzano-Duque, Herrera, Ged, y Blair, 2021). Robusta se distingue por su excelente valor industrial, resistencia a la sequía y tolerancia al calor (Bunn et al, 2015; Byrareddy et al 2021; Kath et al, 2021). Arábica tiende a tener una producción menor durante uno o dos años después de alcanzar su pico de producción (Bosselmann et al, 2009; Ahmed et al., 2021; Kittichotsatsawat, Jangkrajarng, y Tippayawong, 2021). El cultivo de arábica enfrenta problemas de ataques de plagas, cambio climático y enfermedades; por lo tanto, la calidad del sabor de la taza de café se ve fuertemente afectada (Leroy et al., 2006; Prawitasari, 2020). Según proyecciones, las áreas de cultivo de Arábica serían 300 metros más bajas para el año 2050 debido a estos problemas climáticos y afectaciones de los cultivos por agentes patógenos (Chemura, Mudereri, Yalew, y Gornott, 2021; Läderach et al., 2017). Esto representa un potencial problema para los países en donde se cultiva el café Arábica. En cambio, el café Robusta se destaca por su alto valor industrial y resistencia a la sequía; es así que, se utiliza como materia prima en la industria solubilizada y como componente en la formulación de mezclas junto con el café Arábica (Pereira et al., 2019).

El altiplano de los continentes y el bosque tropical que va desde 600-2200 metros sobre el nivel del mar con regiones de altitud media como las Américas y las islas del Caribe, son los hábitats naturales de Arábica, mientras que las regiones de tierras bajas a altitudes medias (menos de 900 metros de altitud) son los de Robusta (Tolessa et al, 2017). La altitud influye positivamente en las características fisicoquímicas y por lo tanto en la calidad organoléptica del café, pero se publica sobre las características del café Robusta (Worku et al, 2018). Por ejemplo, no existe en Ecuador trabajos científicos que comprueben cómo la relación entre la altitud y los métodos de post-cosecha afectan las propiedades organolépticas del café Robusta.

Los granos de café se someten a un procedimiento post-cosecha o también conocido como procedimiento *beneficio* para transformarlos en un estado más estable, transportable y tostable, con un nivel de humedad de entre 10 y 12 por ciento para evitar fermentaciones no deseadas (Rodriguez et al, 2020). Esta post-cosecha influye directamente en la calidad organoléptica de la taza de café. Y consiste en retirar las capas de piel, mucílago y pergamino que están firmemente unidas a los granos del café. Estos métodos de post-cosecha también se conocen con el nombre de beneficio; así pues, existen los beneficios por vía húmeda, beneficio húmedo enzimático, beneficio semihúmedo y beneficio por vía seca (Bastian et al., 2021).

El café de especialidad se define como un café, de origen geográfico conocido, que tiene un valor superior al café de grado comercial debido a su alta calidad en taza y atributos sensoriales. Por tanto, una tendencia futura para los pequeños productores sería la comercialización de cafés especiales. Países como Ecuador, Colombia, Guatemala, entre otros han optado por diferenciar su oferta con la intención de incrementar la calidad, y consecuentemente mejorar la demanda. Un desafío por delante es que los países productores de cafés especiales también se conviertan en consumidores. Además, se promueven varios usos a los subproductos del café aplicando un enfoque de economía circular con el uso de la biomasa residual generada y mejorando la economía de los productores, que muchas veces se basa únicamente en la venta de granos de café.

Ante lo expuesto, el presente trabajo plantea como hipótesis que la altitud y los métodos post-cosecha de beneficio por vía húmeda, húmedo enzimático, semihúmedo y por vía seca, tienen un efecto significativo sobre la calidad física del grano y organoléptica de la bebida de café Robusta.

Objetivo general

Valorar la calidad organoléptica del café Robusta de los grupos genéticos Robusta (Congolensis) y Conilón procedentes de diferentes altitudes y preparados mediante distintos métodos post-cosecha de beneficio.

Objetivos específicos

- Establecer la relación entre la calidad organoléptica y los métodos post-cosecha de beneficio del café Robusta de los grupos Robusta (Congolensis) y Conilón.
- Determinar la calidad física del grano de café así como su calidad organoléptica de bebida en función de la altitud de las zonas de cultivo.

El presente trabajo resume en cada capítulo un artículo científico publicado en revistas JCR:

Capítulo 1:

Velásquez, S., Banchón, C. *Influence of pre-and post-harvest factors on the organoleptic and physicochemical quality of coffee: a short review*. Journal of Food Science and Technology (2022). https://doi.org/10.1007/s13197-022-05569-z

Capítulo 2:

Velázquez, S.; Banchón, C.; Chilán, W.; Guerrero-Casado, J. *Effect of three post-harvest methods at different altitudes on the organoleptic quality of robusta coffee.* Beverages (2022) https://doi.org/10.3390/beverages8040083

Capítulo 3:

Velásquez, S., Banchón, C.; Farfán, D.; Guerrero-Casado, J. Postharvest Effects on the Physical Quality and Sensory Characteristics of Coffea canephora. Acta Scientiarum Polonorum Technologia Alimentaria (2023). http://dx.doi.org/10.17306/J.AFS.2023.1181

Capítulo 1

Influencia de los factores pre- y post-cosecha en la calidad organoléptica y fisicoquímica del café

Resumen

La calidad del café se ve afectada por un 40% de manejo antes de la cosecha, 40% después de la cosecha y un 20% de exportación. Además, los riesgos futuros para la industria del café están relacionados con el cambio climático y el aumento de patógenos. Teniendo en cuenta la importancia del perfil de aroma y sabor único del café Arábica, la mayoría de la literatura se centra en esta variedad debido a la alta participación de mercado; sin embargo, hoy en día, el café Robusta se destaca por su creciente valor industrial y resistencia a la sequía. En la presente revisión bibliográfica, se enfatizan ambas especies, destacando los aspectos sensoriales de posibles nuevos productos mezclados con una mayor proporción de Robusta dadas las tendencias del mercado de bebidas amargas. En el presente trabajo, una búsqueda sistemática de literatura revisada por pares evalúa cómo la calidad de la taza de café y las características fisicoquímicas de Robusta y Arábica están influenciadas por factores ambientales, agronómicos y de procesamiento adicionales.

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REVIEW ARTICLE

Influence of pre-and post-harvest factors on the organoleptic and physicochemical quality of coffee: a short review

Sofía Velásquez[1,2] · Carlos Banchón[1]

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Abstract The coffee quality is affected by 40% pre-harvest, 40% post-harvest, and 20% export handling. Besides, future risks for the coffee industry are related with climate change and increased pathogens. Considering the importance of the aroma profile and unique flavor of Arabica coffee, most literature focuses on this variety because of the high market share; however, nowadays, Robusta coffee stands out for its increasing industrial value and resistance to drought. In this review, both species are emphasized, highlighting sensory aspects of possible new products mixed with a higher proportion of Robusta given market trends for bitter beverages. In the present work, a systematic search of peer-reviewed literature evaluates how the coffee cup quality and physicochemical characteristics of Robusta and Arabica are influenced by environmental, agronomic, and further processing factors.

Keywords *Coffea arabica* · *Coffea canephora* · Organoleptic quality · Coffee

Abbreviations
CGA Chlorogenic acid
CLR Coffee leaf rust
CBB Coffee berry borer

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Introduction

The world coffee production up to 2020 was 10.2 million tones with 5.7 million tons of *Coffea arabica* and 4.3 million tons of *C. canephora* (ICO 2021). Globally, only two species of the genus Coffea are of economic importance: *Coffea arabica* (Arabica coffee) and *Coffea canephora* (Robusta coffee or Conilon), representing 66 and 34% of commercial importance respectively (Salcedo-Sarmiento et al. 2021). However, coffee-producing countries are under great pressure due to rising input costs, market instability, lack of incentives to improve quality, increased pathogen resistance, and climate change; these factors cause deterioration of physical and organoleptic quality attributes of the coffee (Hameed et al. 2018; Kittichotsatsawat et al. 2021). Besides, the coffee harvest is getting more difficult to implement than other products due to the height and architecture of the plant, the uneven maturity of the beans, and their moisture content (Louzada & Rizzo 2021). The increase in Arabica production is achieved through intensification, which implies more beans per unit area, and this requires improvements to cultivation systems and expansion of planting areas. Unfortunately, Arabica coffee tends to decrease yield for one or two years after the peak in production (biennial bearings). As a sustainable solution for the food sector, nowadays it is a common industrial practice to blend Arabica and Robusta coffees (Mulindwa et al. 2021). Robusta coffee stands out for its high industrial value and resistance to drought. Thus, Robusta is used as a raw material in the solubilized industry to be blended with Arabica coffee (Pereira et al. 2019). In this sense, special attention should be paid to the organoleptic quality and physicochemical characteristics of both Robusta and Arabica.

Arabica, which generally grows at higher altitudes, is a weak-bodied, acidic, and aromatic coffee because its caffeine and CGA content is low; while Robusta grows in a lower-altitude with sensory characteristics like full-body, bitterness, less aroma, and less acid (Schwan and Fleet 2014). Besides, the quality of coffee beverages is related with the cherry maturity, which depends on pre-harvest factors like genetic strain, geographical location, altitude, latitude, land slope, coffee variety, soil, fertilization, rainfall, irrigation, shade, and frost (Seninde and Chambers 2020). The ripe coffee cherries contain suitable chemical compositions that are responsible for the flavor properties. Consequently, the selection of the appropriate cherry maturity affects flavor, which is a combination of taste, aroma, texture, and mouthfeel (Bastian et al. 2021). Coffee's flavor is determined by its volatile and non-volatile content. Alkaloids (caffeine and trigonelline), CGA, carboxylic acids, carbohydrates, lipids, proteins, melanoidins, and minerals are non-volatiles responsible for the basic taste sensations of sourness, bitterness, and astringency (Yeretzian et al. 2002). These compounds are affected in all stages of coffee processing, and therefore there is an impact on the physicochemical and sensory characteristics of the final product. On average, coffee quality is affected by 40% pre-harvest, 40% post-harvest, and 20% export handling due to spoilage and quality loss (Ferreira et al. 2016; Kumar and Kalita 2017).

In the present work, a systematic search of peer-reviewed literature was performed to evaluate how the sensory and physicochemical properties of coffee are influenced by environmental, agronomic practices, and further processing factors. The papers were selected through the ISI Web of Science, and Scopus from 2000 to 2021. Two information criteria were used. Criterion 1: A search of articles about pre-harvest factors as an influence on coffee quality. Pre-harvest data were compared with Cupping Protocol criteria, in which beverage is standardized according to fragrance/aroma, flavor, aftertaste, salt/acid aspect ratio, bitter/sweet aspect ratio, mouthfeel, balance, uniform cup, clean cup, and overall attributes. Criterion 2: Post-harvest methods influencing the organoleptic quality of coffee.

Influence of pre-harvest factors

Green Arabica coffee beans are up to 50–60% carbohydrates (9% sucrose), 15–20% lipids, 10–15% proteins, 3–5% minerals, 3–7% CGAs, 1.5% caffeine and 1% trigonelline (Folmer 2017). Robusta coffee has a similar composition but with more caffeine and CGAs, and less sucrose, trigonelline and lipids. In coffee beans, galactomannans and arabinogalactans constitute the cell wall structure, and they influence the organoleptic properties, mainly due to the structural modifications they undergo during the roasting process (Li et al. 2021). These polysaccharides react with other coffee components at high temperatures to form brown compounds known as melanoidins, which contribute to the color, texture, and flavor of roasted coffees. CGAs are polyphenols strongly related with the astringent, sweet, and sour tastes of coffee. The total content of CGA in green beans varies depending on the coffee variety, degree of maturation, climate, geographic location, and nutrient state of soil (Munyendo et al. 2021). In the following sections, a review of factors that influence the flavor of a cup of coffee is presented.

Altitude

The high plateau of continents and tropical forest going from 600 to 2200 m above sea level with mid-altitude regions like the Americas and Caribbean islands, are the natural habitats of Arabica, while lowland to mid-altitude regions (less than 900 m in altitude) are the harbors of Robusta (Tolessa et al. 2017). Arabica is regarded as high mountain coffee. Altitude positively influences the physicochemical characteristics and therefore organoleptic quality of coffee, but little is known about metabolism modifications that lead to this feature (Worku et al. 2018). Some studies report that shade and warm climate also have a positive effect on coffee cup quality at lower elevations (Bosselmann et al. 2009; Tolessa et al. 2017).

At higher altitudes due to the slower maturation rate, the leaves and fruits of the coffee tree accumulate more concentrations of photoassimilates (sucrose, polyols, and amino acids), which are related with good aroma. At high altitudes, the most representative flavor attributes are caramel, brown sugar, fruity, almond, apricot, intensely sweet, coconut bullet, and fruity (Pereira et al. 2021); meanwhile, Robusta grown at the altitude of 300 m produces coffee with inferior scores and unpleasant attributes like woody and herbal flavors. At high altitudes, there is a higher precipitation index, compared to lower altitudes, and for each 100 m increment in altitude, there is a temperature decrease around 1 °C; this is beneficial for a more uniform coffee ripening process. Above 1200 m coffee fruit ripening takes place through extended periods on a proper kinetics of ethylene biosynthesis, compared to altitudes below 1000 m (Santos et al. 2018). A slower ripening process allows more effects on greater production of phenolic compounds and more intense flavored beans than those grown in lower areas, or under full sunlight (Avelino et al. 2007; Joët et al. 2010).

Altitude and shade certainly impact the biochemical composition of coffee beans depending on site or growing conditions. Some studies reported a positive effect of higher altitudes on Arabica´s flavor related with the content of trigonelline, chlorogenic acids, fat, sucrose, and caffeine, although there is no effect related to shade or post-harvest (Avelino et al. 2007; Veeraiyan and Giridhar 2013). Figure 1 presents a sensory evaluation of 11 Arabica coffee genotypes from Brazil, which were harvested at different altitudes:

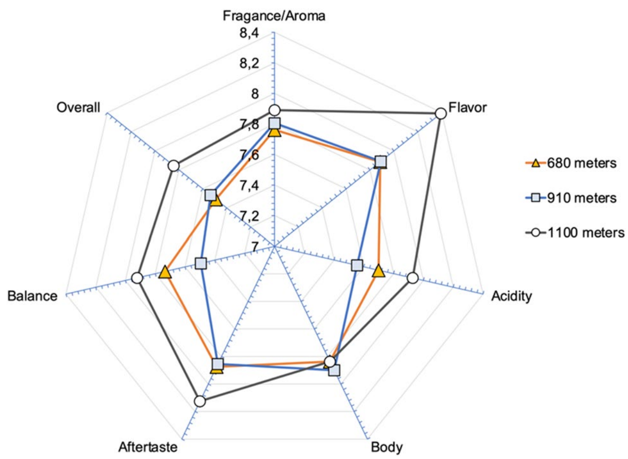

Fig. 1 Sensory analysis of Arabica coffee harvested at different altitudes from Brazil. Adapted from Barbosa et al. 2020

680, 910, and 1100 m, respectively. Fragance/aroma, acidity, body, flavor, clean cup, sweetness, uniformity, aftertaste, balance, and overall score attributes were in the range of 6–10 points (Barbosa et al. 2020). In total, those evaluations with more than 80 points were considered as specialty coffees Grade 1. As a result, altitude was the main factor that influenced the coffee sensory quality.

Table 1 presents the effects of increased altitude on chemical composition, taste, and cup quality. At higher altitudes (from 1200 to 2200 m), sucrose is the most abundant simple carbohydrate in Arabica. Sucrose acts as an aroma precursor to the formation of furans, aldehydes, and carboxylic acids, which contribute to caramel aftertaste (Pinheiro et al. 2019). Also, at higher altitudes, CGA concentration decreases from 3.20 to 2.17% with an increase in altitude from 1200 to 1960 m (Worku et al. 2018; Gebrekidan et al. 2019; Girma et al. 2020; Zakidou et al. 2021). As altitude increases, caffeine and CGA content in Arabica tend to

Table 1 Effects of increased altitude on chemical composition of sucrose, chlorogenic acid, caffeine and trigonelline

Altitude range (meters)	Variety	Weather conditions	Compounds	Percent % (w/w)	Effects on the taste	Effects on the cup quality	References
1200–1800	Arabica	12–27 °C, Rf = 1737 mm, Southwestern Ethiopia	Sucrose	3.20–5.00	With increasing altitude, more acidity, caramel aftertaste, sweet and smoother taste	Grade 2	Worku (2018)
1200–1960		19–25 °C, Rf = 1880–2018 mm, Southwestern Ethiopia	Chlorogenic acid	3.20–2.17		Grade 2	Girma (2020)
1200–1800		12–27 °C, Rf = 1737 mm, Southwestern Ethiopia	Caffeine	1.42–1.30		Grade 1	Worku (2018)
1500–2200		19–25 °C, Rf = 1880–2018 mm, Southwestern Ethiopia	Trigonelline	1.40–0.80		Grade 1	Gebrekidan (2019)
700–1300	Robusta	26–32 °C, Rf = 254 mm, South Sumatra	Sucrose	2.91–2.88	With increasing altitude, more bitterness, astringency, strength, and body	Grade 2	Marsilani (2020)
720–1344		24.5–30 °C, Rf = 1123 mm, Espírito Santo, Brazil	Chlorogenic acid	7.72–9.08		Grade 2	Pinheiro (2019)
700–1300		26–32 °C, Rf = 254 mm, South Sumatra	Caffeine	1.62–1.76		Grade 3	Marsilani (2020)
914–1127		22–34 °C, Rf = 3456 mm, Karnataka, India	Trigonelline	0.70–0.92		Grade 3	Veeraiyan (2013)

Rf = Mean annual rainfall; Grade 1 ≥ 85, Grade 2 = 75–84, Grade 3 = 63–74, Grade 4 = 47–62, and Grade 5 = 31–46 points decrease astringency, strength, body, and bitterness; therefore, the brewed coffee increases its sweetness, smoother taste, and cup quality. Although any Arabica cultivar has the potential to produce high-quality coffees, different flavors are found in different environments (Figueiredo et al. 2018).

According to Table 1, at high altitude levels between 700 and 1300 m, the sucrose concentrations range from 2.91 to 2.88%. The composition of caffeine and CGA in Robusta increases. Caffeine from 1.62 to 1.76% and CGA from 7.72—9.08% compositions were found. Thus, bitterness in Robusta tend to increase at high altitude levels (Marsilani et al. 2020). According most references, the higher the altitude, the higher the sensory quality of coffee (Avelino et al. 2007; Silveira et al. 2016; Tolessa et al. 2017; Worku et al. 2018). Although bitter is the second basic taste that consumers expect in specialty coffee, Arabica has a lower bitterness compared to Robusta (Bressani et al. 2021a, b). In this sense, new markets for bitterer products need to be explore.

Pathogens

The cultivation of Robusta coffee started after the damage to Arabica coffee caused by the leaf rust disease in Southern Asia, in the late nineteenth century (Schwan & Fleet 2014). Coffee Leaf Rust (CLR) is caused by the fungus *Hemileia vastatrix* (Hv), and it is a devastating disease leading to defoliation of up to 50% and yield losses up to 50%, specifically in *C. arabica* instead of Robusta (Salcedo-Sarmiento et al. 2021; Documet et al. 2022). Hv contributes to degradation of sugars in beans, which affects cup quality into a woody, grassy, and earthy taste (Table 2). Currently, 45 pathogenic races of Hv have been characterized by the type of virulence factor, as more intense fungal epidemics from 2008 to 2013 were observed in Mexico, Colombia, Ecuador, Peru, and Caribbean countries (McCook 2006). Hv fungus develops when the temperature is between 21 and 25 °C and high humidity promotes the spores transmission through raindrops (Talhinhas et al. 2017; Toniutti et al. 2017). Therefore, rust development is affected by temperatures below 15 °C hampering spore germination.

Pathogens have a direct impact on the coffee production, as well as the cup quality. For example, fungi like *Colletotrichum kahawae* invades the berry during the green stage producing dark brown spots that end up covering the cherry and affecting bean development (Gichimu et al. 2014). Therefore, this kind of fungi changes the chemical composition of beans (endosperms), as it promotes a reduction of taste, aroma, and acidity (Folmer 2017). The degradation of sugars at the endosperm leads to a lower quality coffee with harsh and woody cup characteristics. In some cases, fungi like *Mycena citricolor* can cause undesirable fermentations to increase astringency and sourness. In general, the presence of damaged berries affects the sensory quality of coffee samples.

One of the leading pests worldwide is *Hypothenemus hampei* (Ferrari) (CBB), which has invaded almost every coffee-producing country (Johnson et al. 2020). Mostly, Arabica cultivation faces problems due to the attack by pests and diseases, and consequently the coffee cup taste quality is strongly affected. On the other hand, Robusta have a more effective defense mechanism of the plant against pathogens compared with Arabica because of having more caffeine and chlorogenic acids (Durand et al. 2009). Besides, cultivation under shade and adequate nitrogen fertilization contributes to control the spread of pathogens, as well as the use of biopesticides based on *B. thuringiensis*, *B. subtilis*, and *P. putida* (Salcedo-Sarmiento et al. 2021). Plant resistance to pests is genetically controlled; however, the environment and cultural practices affect the plant tolerance or resistance to pathogens.

In Fig. 2, evidence of three Robusta coffee pathogens was collected from Ecuadorian crops in the coastal region under 600 m of altitude. According to references, shaded crops are prone to American leaf spot disease (*Mycena citricolor*); the coffee green scale insect *Coccus viridis* is related with dry seasons; and the fungal plant pathogen *Mycosphaerella coffeicola* is related with full-sun crops (Iverson et al. 2021).

Table 2 Effects of pathogens on chemical composition, taste, and cup quality

Major pathogens	Variety	Geographical location	Changes of major compounds	Effects on taste	Effects on the cup quality	References
Hemileia vastatrix	Arabica	800–1000 m, San Martin, Peru	Degradation of sugars	Woody, grassy, earthy taste	Grade 5	Documet et al. (2022)
Colletotrichum kahawae		1524 m, Kisii, Kenya	High concentration of phenolics	Loss of aroma and acidity, off-flavors	Grade 5	Gichimu et al. (2014)
Hypothenemus hampei	Robusta	Almost worldwide	High concentration of phenolics	Bitter taste, astringency, off-flavors	Grade 5	Johnson et al. (2020)

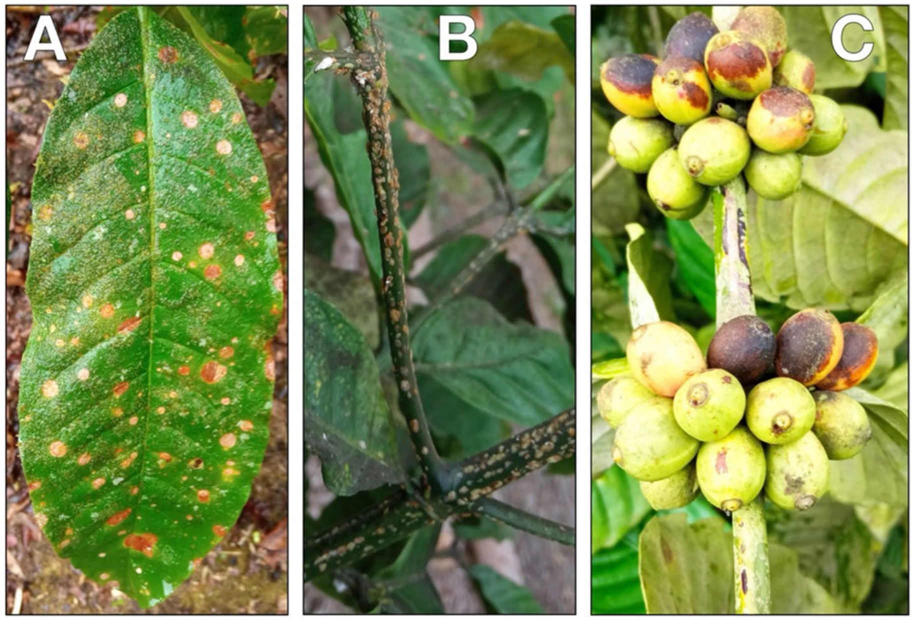

Fig. 2 Robusta coffee plant pathogens from Ecuadorian crops: **A** Leaf spots produced by *Mycena citricolor*; **B** the coffee green scale *Coccus viridis*; **C** fungal plant pathogen *Mycosphaerella coffeicola*

Climate change

The main concerns due to climate change are the alteration of biodiversity and wildlife distribution, which translates into the reduction of available spaces for agriculture, and therefore a production crisis that impacts severely the smallholders (Rojas-Múnera et al. 2021). With climate change, the coffee farmers' behavior is to shift their cultivation to other areas and it will cause deforestation, land degradation, drought, and flood, destroy of germplasm, and water bodies deterioration (Hameed et al. 2018). Coffee producers like in Central America are increasingly experiencing climate conditions outside optimal ranges, including heat waves and droughts that are expected to impact coffee production and its geographic range (Ahmed et al. 2021). It has been estimated that areas to grow Arabica will be affected by 300 m up the altitudinal gradient until 2050 (Chemura et al. 2021; Läderach et al. 2017). Therefore, farmers may have to abandon coffee plantations at lower elevations. Being Arabica coffee is a highly sensitive plant to temperature, thus Robusta coffee would gain bigger market participation.

To respond to heat stress, plants employ adaptation mechanisms by biochemical changes related with the decrease of hemicellulose and pectin in cell wall (Li et al. 2021). Therefore, a decrease of suitability to produce coffee beans with high flavor is highly influenced by the environmental conditions where the coffee is grown (Läderach et al. 2017; Chemura et al. 2021). Considering the current scenario of global warming, the heat-resistant nature of Robusta is of relevance. The impacts of climate change on coffee production have gained recent interests, but the effects on sensorial analysis are not yet fully researched.

Soil properties and agrochemicals

The acidity of coffee brews is recognized as an important attribute of cup quality, and it is correlated with coffee grown at very high altitudes and rich mineral soil. Coffee from Central America and East Africa tends to be more acidic because coffee plants are grown on rich volcanic soils (Barbosa et al. 2020). Volcanic soils are known as Andisols and are composed of up to 25% of dark organic matter; approximately 50% of Andisols occur in the tropics (Gamonal et al. 2017). Andisols contain allophane and imogolite, both being aluminum silicate clays; ferrihydrite and more aluminum/iron organic matter complexes (Delmelle et al. 2015). Volcanic Andisols are common in Chile, Peru, Ecuador, Colombia, Central America, the United States, Japan, the Philippines, Indonesia, Papa New Guinea, New Zealand, and the Southwest Pacific.

The application of nitrogen fertilizers to the soil affects coffee quality, compared to unfertilized fields, because an excess of nitrogen increases caffeine content and thus resulting in a more bitter taste (Bosselmann et al. 2009; di Donfrancesco et al. 2019). In contrast, an excess of phosphorus, calcium, potassium, and magnesium does not affect caffeine and chlorogenic acid content, but a deficiency in magnesium, and excess of calcium and potassium produce a more bitter taste (Louzada and Rizzo 2021). Soil pH and organic matter content decrease with continuous cropping and have a significant negative effect on the bacterial and fungal community compositions.

As previously reported, an increase in macronutrient content of soils is associated with an increase in sensory attributes. Excessive Ca, Mg and K produce a bitter tasting coffee,

Table 3 Soil requirements and weather conditions to produce good quality coffee

Variety	pH	K:Ca:Mg	Organic matter	Nitrogen	Phosphorus	References
Robusta	5.5–6.5	1:12:3	> 2%	0.10%	> 5 mg/ 100 g soil	Folmer (2017)
Arabica	5.5–6.5	1:6:2	> 4%	0.28%	> 25 mg/ 100 g soil	

due to an increase in lipids, citric acid and CGAs (Morales-Ramos et al. 2020). Generally, the total content of CGA in beans varies depending on the coffee variety, degree of maturation, climate, geographic location, and nutrient state of soil (Munyendo et al. 2021). Besides, the higher the concentration of available phosphorous in relation to organic matter or total nitrogen, the better the organoleptic quality of coffee.

Robusta requires a yearly rainfall range of 2200 mm to 3000 mm at an ambient temperature of 15–24 °C, meanwhile Arabica a range of 1200–2200 mm over 22 °C. Both species can tolerate low temperatures, but not frost (Ahmed et al. 2021). Table 3 presents soil characteristics for good coffee quality.

Influence of post-harvest treatment

A coffee cherry is made up of several layers which include skin, mucilage, and parchment. After the cherries are picked, they require post-harvest treatment which involves removing these layers which are firmly attached to the beans. This can be done in different ways, and each process can impart a different cup profile on the coffee. When mature, the coffee fruits present lower concentrations of phenolic compounds, which implies a reduction of astringency. Coffee cherries show a higher content of volatile compounds (aldehydes, ketones, and higher alcohols) in comparison to immature fruits (Yeretzian et al. 2002). Coffee harvesting should be initiated when the plant reaches a homogeneous stage of maturation with a minimum prevalence of immature fruits. The choice of harvesting method will interfere directly in the quality of the fruit used for further steps of processing. Handpicking allows the selection of coffee cherries in their ideal stage of maturation; however, this method is expensive and laborious. After harvesting, coffee processing should begin quickly to prevent fruit spoilage by unfavorable fermentation (de Melo Pereira et al. 2019) (Table 4).

Coffee processing

After harvesting, coffee beans have a post-harvest process for a more stable, transportable, and roastable form, with a moisture content between 10–12% to avoid unwanted fermentations (Rodriguez et al. 2020). Green coffee seeds are managed by one of three methods known as dry, wet, and semi-dry processing (Table 4). All methods aim to remove the fruit flesh of the cherries.

In the dry method, the whole cherry (bean, mucilage, and pulp) is dried under the sun or in a mechanical dryer, followed by the mechanical removal of the dried outer parts. The deterioration caused by fungus and bacteria is stopped by this drying process (Duarte et al. 2010). Natural drying involves drying the whole grain under the sun, with manual or mechanical removal of unwanted outer layers (Joët et al. 2010). Thus, a sweet and complex body and sensory attributes are offered. During natural drying, fermentation occurs in the pulp and mucilage of the grain using pectinolytic microorganisms to produce alcohols, organic acids, and other metabolites. The inoculation of yeasts, separately or together in the fermentation process, impacts the quality of low-altitude coffees with the highest sensory scores (Bressani et al. 2021a, b). However, sun drying is a long process with a high labor cost and requires a large surface area for drying; despite this, 95% of Arabica coffee from Brazil, Ethiopia, Haiti, Indonesia, Paraguay, India, and Ecuador are dried under the sun to obtain a uniform quality and avoid raw green coffee beans (Kulapichitr et al. 2019). The flavor of coffee could be affected if insufficient or excessive drying is applied because coffee beans are hygroscopic. Green coffee beans are characterized by an unpleasant taste, because more than 1000 volatile compounds are generally detected during thermal processes, but only about 200 compounds are found in green beans. During the drying process in static dryers, column dryers, round dryers, or forced air dryers, hydrolysis of proteins takes place to produce a wide variety of free amino acids. Coffee temperatures during drying should not exceed 40 °C for parchment and 45 °C for cherries; in this sense, temperature, air flow, relative humidity and pressure should be controlled, to avoid excessive drying due to water evaporation outside the bean. So far, scarce information is available about specific volatile compounds through the drying process, because most studies have focused on the major chemical compounds like sugars and proteins (Li et al. 2021).

In the wet method, a substantial amount of water (40 L/Kg) is used to remove the pulp and mucilage from ripe coffee cherries. This is carried out by chemical products or by fermentation with starter cultures like *S. cerevisiae* (Martins et al. 2020; Seninde & Chambers 2020). At the end of the fermentation, the seeds are washed and dried. The longer the soaking period in the wet method the more changes in the chemical composition (Duarte et al. 2010). During the soaking, trigonelline, glucose and fructose contents are lowered due to microbial metabolism (Schwan et al. 2012). The anoxic conditions of wet processing promote alcoholic or lactic fermentation of sugars. In this wet method, the depulped cherries

Table 4 Processing methods and their mechanisms, expected changes, and final cup quality

Processing method	Mechanisms	Expected changes	Effect on the cup quality	References
Natural drying	Slow drying at 40–45 °C of fruits from all maturation stages	Polysaccharides (pectin) from pulp and mucilage are degraded	Sweet and complex body and sensory attributes	Sunarharum et al. (2014)
	Water evaporation	Production of alcohols, organic acids, aldehyde, and lipid esters	Less aroma and more acid	
	Fermentation by pectinolytic microorganisms	Production of free amino acids	More consistency (hard body)	
	Hydrolysis of proteins	Reduction of fungi and bacteria populations		
Wet	High amount of water for mucilage removal in mature fruits	Pectinolytic activity	Aromatic level with fine acidity and little astringency	Seninde et al. (2020)
	Fermentation	Decrease of reducing sugars (fructose, mannose, and glucose) during fermentation	High quality coffee: less consistency (body), higher acidity; vanilla, and floral aroma	
	Sugar metabolism	Production of free amino acids		Schwan & Fleet (2014)
	Starter cultures: *Pichia fermentans, Leuconostoc mesenteroides, Lactobacillus plantarum*			
Semi-dry	Slow drying at 40–45 °C	Low levels of fructose, glucose, arabinose, and galactose	Intermediate body	Duarte et al. (2010)
	High amount of water consumption	Pectinolytic activity	High quality coffee: high acidity; honey-like aroma	Bastian et al. (2021)
	Starter culture: *S. cerevisiae*		Furans provide herbal or fruity notes	
			Starter cultures produces caramel flavors	

have shown high microbial counts like lactic acid bacteria, acetic acid bacteria, enterobacteria, and yeast (Zhang et al. 2019). Nevertheless, wet-processed coffee beans have a better aroma and a higher consumer acceptance than dry-processed ones, because the high volatiles concentration, less body and more pleasant aroma (Sunarharum et al. 2014; Gumecindo-Alejo et al. 2021). In contrast, beans processed without fermentation are less rich in volatiles and even exhibit unpleasant sulfurous aromas and acidic profile (Schwan & Fleet 2014). On the other hand, under- or over-fermentation could lead to the growth of spoilage bacteria and fungi, which would produce butyric and propionic acids (onion taste) (Bastian et al. 2021).

In the semi-dry or pulped natural method, the system aims to separate immature cherries from mature ones when nonselective harvesting is used (Schwan & Fleet 2014). This method is also called honey process, because the mucilage is dried along with the coffee beans and produces a honey-like or sugar-like aroma after the drying process (Bastian et al. 2021). Being a combination of dry and wet processing, it requires more processing time and water consumption. The cherries are pulped, and the seeds dried while surrounded by the mucilage, without the fermentation step for mucilage removal (Kipkorir et al. 2015). In Colombia, Central America, Hawaii, the wet method is used to remove the exocarp and mesocarp from coffees. Regarding top quality coffees, the semi-dry method promotes a major enhancement in consistency (body), felt on the palate, acidity, and more caramel-fruity or herbal flavor (Ferreira et al. 2021). CGA is found in lower concentrations in the semi-dry method than in the dry process, while sucrose content is higher in the semi-dry process than in either the dry or wet processes; therefore, pulped natural coffees are strongly appreciated in blends for *espresso* (Bastian et al. 2021). According to literature, caffeine and sucrose are not affected in any post-harvest process.

Roasting

Roasting is the process where dried-coffee beans are subjected to temperatures between 200 and 240 °C for different times depending on the desired characteristics of the coffee cup (Pittia et al. 2001). As relevant loss of water take place, the green beans are converted into a brittle form; besides, several biochemical reactions occur such as those of Maillard and Strecker, to produce more than 1000 types of aromatic compounds (Cordoba et al. 2020; Perrone et al. 2012). A wide variety of volatile compounds are present in roasted coffee beans, such as alcohols, aldehydes, amines, carboxylic acids, dicarbonyls, enoles, esters, furans, furanones, hydrocarbons, imidazoles, indoles, ketones, lactones, oxazoles, phenols, pyrazines, pyridines, pyrroles, quinoxalines, sulfur compounds, terpenes, and thiazoles (Schenker et al. 2002; Hu et al. 2020). These compounds can undergo dramatic changes depending on the thermal profile applied during the roasting process. Thus, roasting is considered the most important step in determining the characteristic flavor and color of the coffee bean. Table 5 presents different roasting conditions, which have a major impact on the physical and chemical properties of roasted coffee beans.

After roasting, the grinding of roasted beans allows to balance the humidity and increases the surface area of the roasted beans for the respective extraction. After roasting, 20–40% of cell wall storage polysaccharides are degraded, but there is no significant loss in terms of caffeine (Campos et al. 2022). Trigonelline changes into N-methylpyridinium and nicotinic acid as its major products, which make them a useful index of the degree of roasting (Li et al. 2021). After the roasting process, microbial-derived metabolites can diffuse into the beans and overcome the thermal process. Among these metabolites, flavor-active esters show great potential to influence the quality of the final coffee beverage. Once green beans are roasted, intricate physical and chemical changes like caramelization occur because a combination of hundreds of biochemical components by the Maillard and Strecker reaction (Hu et al. 2020). The Maillard reaction is an amino-catalyzed sugar degradation leading to aroma, taste, and color. During the initial stages of roasting, acetic acid and formic acid strongly contribute to pungent aroma. The bitterness and astringency flavors are formed with the degradation of chlorogenic acids because of the increase of quinic acid concentration (Sunarharum et al. 2014; Gao et al. 2021). While caffeine is not significatively affected by roasting, CGA and trigonelline undergo a drastic degradation (Moon et al. 2009; Schwan & Fleet 2014). This leads to the hydrolysis products such as quinic acid, ferulic acid, which further degrades forming important phenolic odorants

Table 5 Effects of roasting conditions on reactions, chemical compounds, and taste

Roasting conditions	Reactions	Chemical compounds	Taste	References
Cinnamon: Light roast level with hot air at 190 °C	Maillard and Strecker reactions	Near 30% CGA reduction	Sweet, cocoa, and nutty aromas	Bastian et al. (2021)
	Degradation of amino acids, trigonelline, quinic acid, pigments, and lipids	Degradation of sugars, amines	Light brown color	Seninde et al. (2020)
	Degradation of CGA to produce furanones, lactones and phenols	Production of melanoidins	Prominent acidic	Hu et al. (2020)
	Pyrolysis of amino acids and trigonelline		Peanut like roast	
			Light body	
Full city, Vienna roast: Medium dark brown with hot air roasting at 220–230 °C		Decrease of total phenolic content (TPC)	Bittersweet	Bastian et al. (2021)
		Near 50% CGA reduction	Caramel, floral, and herbal aromas	Sunarharum et al., (2014)
			Less acidity	
			Medium body	
French, Italian roast: Dark brown with hot air roasting at 240–245 °C		Increasing number of volatiles	Shiny black	Schenker et al. (2002)
		Furan and caramel flavors	Roasted flavor	Moon et al. (2009)
		Great loss of TPC	Burnt, bitter, and acrid tones	Bastian et al. (2021)
		Unwanted off-flavors compounds	No acidity	
		Near 90% CGA reduction	Not very sweet, dark chocolate	

such as guaiacol and 4-vinylguaiacol (Heo et al. 2020). Furthermore, trigonelline and certain proteins along with sugars that are present in green beans are broken down into volatile compounds such as pyridines, pyrroles, and pyrazines (Bastian et al. 2021).

Melanoidins are the end products of the Maillard reaction, and they impart the characteristic brown color to coffee beans and may have a retention capacity of the flavor compounds (Perrone et al. 2012). Caffeine is approx. responsible for 30% of the bitter taste, while trigonelline contributes to the formation of desirable and undesirable aroma compounds during roasting (Gao et al. 2021). In the Maillard reaction, asparagine and glucose-fructose may conduce to undesirable components like acrylamides and furan. As part of the Maillard reaction network, the Strecker degradation contributes to the coffee aroma spectrum with volatile aldehydes having malty, potato, sulphury, and honey-like notes.

Influence of coffee beverage preparation

The main parameter to assess the quality of a cup of coffee remains the sensory experience. However, the strength or soluble concentration (total solids in relation to the cup volume) of a coffee brew is a first indicator of the efficacy of extraction (Folmer 2017). The contact of water with roasted coffee solids is the main step for producing a coffee beverage. This process is called solid–liquid extraction, and has a significant impact on the different chemical compounds present in the roasted coffee, and hence, most taste and aroma depend on the brewing methods, which are specific to the geographic, cultural, and social environment (Cordoba et al. 2020). The many chemical species found in roasted coffee exhibit different extraction rates. Therefore, an under- or overextraction of such chemicals could occur if water temperature, contact time or coarse grind are not standardized to produce a good quality cup. Thus, brewing should be adjusted according to personal taste, in agreement with the nature of the beans used.

When we taste coffee, olfaction is the first stage of tasting, because smell is perceived faster than taste. We determine coffee smell as the volatile chemicals come from the brew stimulating the nerves of the nasal cavity. The sensory characteristics of a balanced cup of coffee is linked to its composition in caffeine, trigonelline, CGAs, and volatile compounds like terpenoids (Saloko et al. 2019). High-quality coffee is often defined by a "balanced" cup that is characterized by specific levels of acidity, flavor, aftertaste, and body attributes (Folmer 2017). Arabica coffee tends to be more acidic than Robusta, but this acidity decreases with roasting (Table 6). Perceived acidity is one major driver of consumer preference and represents one of the main categories that the industry uses to score coffee quality. Acids in coffee are divided into organic acids and chlorogenic acids. For instance, citric, malic, and quinic acids the most important characteristic of green coffee beans. In the roasting process, there is an increase in acidity because formic, acetic, glycolic, and lactic acids are formed at this stage. Sucrose is the main precursor to the formation of these acids (Sunarharum et al. 2014). The difference in sucrose concentration will affect the final amounts of acid formation. Thus, to improve the final sensory profile of the coffee cup, the understanding of how to increase acidity in each type of organic or chlorogenic acids is prominent.

The polysaccharides like arabinogalactans, mannans, and cellulose contribute to aroma because they retain volatile compounds, and promotes the increase in viscosity, while the carbohydrate sucrose contributes to the perceived sweetness (di Donfrancesco et al. 2019; Kulapichitr et al. 2019). The texture of the brewed coffee is related to the lipid content, and it also retains volatile compounds because oil particles migrate to the bean surface during roasting. Arabica beans are considered superior in taste, although they have almost 1% less caffeine than Robusta. Arabica has approx. 3% more sucrose than Robusta. Thus, the taste of Arabica

Table 6 Non-volatile compounds of coffee beans, and roasted coffees

Group	Compound	Variety content	Roasted coffee	Aroma descriptor	Reference
Alkaloids	Caffeine	Robusta: 2.2–2.7%	Dark roast: 2.23%	Strength, body, bitterness	Saloko et al. (2019)
		Arabica: 1.2–1.5%	Water soluble: 1.2%		
	Trigonelline	Robusta: 0.75–0.87%	Medium roasted: 0.4%	Bitterness	Bastian et al. (2021)
		Arabica: 1.05–1.53%	Medium roasted: 0.8%		
Phenols	CGA	Robusta: 7.0–10.0%	–	Bitter taste, astringency	Schenker et al. (2002)
		Arabica: 5.5–8.0%	Medium roasted: 3.8%		
Lipids	Triglycerides	Robusta: 8.6–8.9%	Espresso: 2093 mg/L	Stale flavor	Schenker et al. (2002)
		Arabica: 12.4–14.1%	Espresso: 1957 mg/L		
Carbohydrates	Sucrose	Robusta: 3.0–7.0%	–	Caramel aftertaste	Marsilani (2020)
		Arabica: 6.0–9.0%	Medium roasted: 0.2%		

coffee is smoother, sweeter, with flavor notes of chocolate and sugar. Robusta has a stronger, harsher, and bitter taste, with grainy overtones; at low concentrations, chlorogenic acids are responsible for an important part of this flavor profile (Barbosa et al. 2019; Wulandari et al. 2021). Robusta contains almost 2% more chlorogenic acids than Arabica and this higher concentration compromises cup quality. To remove "musty" and "earthy" aromas and to improve the quality of Robusta, steaming is used to create a specific acidic taste and flavor unique for Arabica. Although the information presented herein was compiled from a vast body of research, there is still a lack of knowledge on the chemical profiles of coffee quality which will connect the understanding of the cup score and flavor chemistry.

Future trends

Specialty coffee can be defined as a coffee, of known geographical origin, that has a higher value than commercial grade coffee due to its cup high quality, and the attributes it possesses. Therefore, one future trend for small producers would be the marketing of specialty coffee. Countries such as Ecuador, Colombia, Guatemala, among others have chosen to differentiate their offer with the intention of increasing demand and obtaining better prices. Consumers are guided by products from which they can know their origin and have fair trade. One challenge ahead is for specialty coffee producing countries to also become consumers. Moreover, several uses can be given to coffee by-products by applying a circular economy approach with the use of the residual biomass generated and improving the economy of producers, which is often based solely on the sale of coffee beans.

A coffee business is successful when the consumer desires are fully satisfied. In this sense, the modulation of coffee aroma and taste by roasting is a challenge for future trends. To this end, a deep understanding on the roasting process is required. Besides, ensuring food safety in the era of the Coronavirus (COVID-19) pandemic crisis is highly relevant in terms of human health (Galanakis 2020).

Conclusion

As noted in the present work, Arabica coffee planted at more than 1000 m above sea level has aromatic characteristics, low bitterness, good acidity, and body; while Robusta coffee planted at less than 900 m above sea level has high bitterness, herbaceous taste, low aromatic value, and astringency. Moreover, the coffee cup quality is influenced by pre-harvest factors like the species, cultivars, cultural practices, fertilization, pruning, temperature, and altitude. Furthermore, the climate change scenario of heatwaves and droughts directly affects Arabica coffee production due to its higher sensitivity to climate changes. On the contrary, Robusta coffee would gain more market participation. As post-harvest is critical for the final quality of coffee, any novel change would impact sensory characteristics. In this sense, the coffee industry should provide more products in terms of bitterness or other sensory profiles because the perception of a bitter taste plays a key role in consumer preference. Therefore, understanding the impact of processing parameters on the coffee chemistry will bring new scenarios to the market.

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Code availability Not applicable.

Declarations

Conflict of interest The authors declare no conflict of interest.

Informed consent Informed consent was obtained from all subjects involved in the study.

Ethics approval Ethical approval for this study was obtained from Escuela Superior Politécnica Agropecuaria de Manabí, ESPAM-MFL, Calceta, Ecuador on November 2021.

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Capítulo 2

Efecto de tres métodos post-cosecha a diferentes altitudes sobre la calidad organoléptica del café robusta

Resumen

El café Robusta se distingue por su creciente valor industrial y su resistencia a la sequía. La altitud y los métodos de poscosecha influyen en la calidad de la taza de café; sin embargo, se conoce información modesta sobre Robusta. El objetivo de este estudio fue determinar la relación entre cuatro diferentes altitudes y procesos de poscosecha (seco, miel y húmedo) con la mejora de la calidad organoléptica de la bebida de café robusta congolensis y conilon. Para el procesamiento en seco, congo-lensis y conilon mostraron las puntuaciones más bajas en términos de fragancia/aroma, sabor, regusto, sal-ácido, agridulce y cuerpo. Por encima de los 625 metros, los cafés de proceso seco, honey y húmedo aumentaron puntajes en sus atributos sensoriales, pero no hubo diferencia a altitudes tan altas al comparar muestras poscosecha. Las muestras de café procesado en seco obtuvieron puntajes totales de más de 80 puntos en altitudes elevadas. Conilon fue percibido con los mejores atributos sensoriales a gran altura utilizando el procesamiento de miel. En general, las muestras congolensis y conilon procesadas en húmedo tenían un perfil más sabroso que las procesadas en seco.

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Article

Effect of Three Post-Harvest Methods at Different Altitudes on the Organoleptic Quality of *C. canephora* Coffee

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Abstract: *C. canephora* (syn. *C. robusta*) is distinctive due to its rising industrial value and pathogen resistance. Both altitude and post-harvest methods influence coffee cup quality; however, modest information is known about this coffee species. Therefore, the aim of this study was to determine the relationship between four different altitudes and post-harvest processes (dry, honey, and wet) to the improvement of the organoleptic quality of the *C. canephora* congolensis and conilon drink. For dry processing, congolensis and conilon showed the lowest scores in terms of fragrance/aroma, flavour, aftertaste, salt–acid, bitter–sweet, and body. Above 625 m, coffees from dry, honey, and wet processes increased scores in their sensory attributes, but there was no difference at such high altitudes when comparing post-harvest samples. Dry-processed coffee samples had total scores over 80 points at high altitudes. Conilon was perceived to have the best sensory attributes at high altitudes using honey processing. In general, the wet-processed congolensis and conilon samples had a tastier profile than dry-processed ones.

Keywords: specialty coffee; congolensis; conilon; sensory analysis; flavour

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1. Introduction

World coffee production up to 2020 totalled 169.34 million bags, with 101.9 million bags of *C. arabica* and 73.5 million bags of *C. canephora* (syn. *C. robusta*)—which represent 64% and 36% of commercial importance, respectively [1]. *C. arabica* is world-famous for its aroma and acidity; meanwhile, *C. canephora* has a greater body but a lower aroma [2]. This coffee species is distinguished by its excellent industrial value, drought resilience, and heat tolerance [3–5]; in comparison, *C. arabica* tends to have a lower output for one or two years after reaching its peak production [6–8]. According to projections, *C. arabica* growing areas will be 300 m lower by 2050 [9,10]. Due to climate change, coffee producers are moving their operations to other regions, which will result in the deforestation of new areas [11,12]. Moreover, the production of profitable arabica is being threatened by the fungus *Hemileia vastatrix* (Hv)—known as coffee leaf rust (CLR)—everywhere in the world [13–15]. Previously unfavourable places are now suited for many diseases due to global warming [13,16]. Under these circumstances, blending *C. arabica* and *C. canephora* coffees is a popular industrial technique as a sustainable option for the food industry [17,18].

The quality of the coffee is affected by pre-harvest, post-harvest, and export handling in the proportions of 40%, 40%, and 20%, respectively [19]. Free amino acids, reducing sugars, and phenolic compounds in green coffee beans are engaged in the Maillard reaction, which is responsible for the aroma and flavour [20]; these compounds vary significantly depending on the post-harvest processing method [21,22]. Green coffee seeds are handled using one of three techniques known as dry, wet, or honey (semi-dry) processing after the fruits have been harvested [23–25]. The cherry fruit flesh is intended to be removed using one of these processes. In the dry process, the entire cherry (bean, mucilage, and pulp) is dried in the sun or using a mechanical dryer before the dried exterior pieces are mechanically removed [5]. The dry process produces a so-called "natural coffee" with a full-bodied, fruity, cherry-like flavour [19]. The dry process is the simplest method for growing green coffee beans, but it is difficult to obtain coffee of a good quality [26]. Nonetheless, coffee beverages prepared from beans harvested by the wet process are characterized by their robust aroma and pleasant acidity [27]. Honey processing is less sensitive in terms of fermentation than dry processing, in addition to reducing the levels of flavour and acidity that are present in the coffee [28]. In addition, there is a small amount of mucilage in the honey process, which presents as a sticky sugar-rich mucilage on the coffee beans [29].

The term pre-harvest specifies the sensory properties of the coffee based on the crop's location, height, latitude, land slope, coffee variety, soil, fertilizer, rainfall, irrigation, shadow, frost, climate change, and exposure to pathogens [11,30,31]. Particularly, altitude positively influences the physicochemical properties and consequently the organoleptic quality of coffee, although little is understood about the metabolic changes that lead to this trait [32]. At higher altitudes above 1200 m, sucrose is the most abundant carbohydrate, and it acts as an aroma precursor to the formation of furans, aldehydes, and carboxylic acids which contribute to a caramel aftertaste [33]. However, when cultivated under an altitude of 300 m, *C. canephora* provides coffee with lower ratings and undesirable qualities such as woody and herbal flavours [34]. Coffee beans undergo a post-harvest procedure to transform them into a more stable, transportable, and roastable state, with a moisture level of between 10% and 12% to prevent unintended fermentation [35]. This post-harvest entails removing skin, mucilage, and parchment layers that are firmly connected to the coffee beans. There are three ways to handle green coffee cherries: dry, wet, and semi-dry processing [26].

The hypothesis presented as the study's premise is that altitude and post-harvest processes influence coffee cup quality. Therefore, the aim of this study was to determine the relationship between four different altitudes and three post-harvest methods to the improvement of the organoleptic quality of the *C. canephora* drink. For each coffee variety, the evaluation was performed independently, since the two varieties are not found at the same altitudes.

2. Materials and Methods

2.1. Sampling

The fruits of *C. canephora* congolensis and conilon variants were gathered from 17 Ecuadorian plantations located at various altitudes (Table 1, Figure 1). Twenty plants were randomly chosen from each plantation at each altitude, and at least 5000 g of fresh fruit was harvested. Within twenty-four hours, the samples were placed in sterile plastic bags for additional post-harvest treatment.

2.2. Post-Harvest Treatment

Each farm featured its own processing units, whose altitudes and temperatures are listed in Table 1. Three different post-harvest treatments were applied: dry, wet, and honey [36–41]. In the dry method, the entire crop of mature cherries was sun-dried for 12 days, until the requisite 10% water content was reached [42]. The cherries were exposed uniformly to the sun's rays and constantly scraped to prevent fermentation. The unwanted outer layers were removed manually. There was no yeast inoculation conducted. At the conclusion of the process, the outer layer of the cherries had turned dark brown and brittle. After drying, cherries were milled to remove the fruit and the parchment encasing the seed. Manual sorting was carried out in order to exclude overripe or fermenting beans.

In the wet process, the pulp and mucilage from ripe coffee cherries were removed using a significant amount of water (30 L/Kg) for 24 h. Proteolytic enzymes (Granozyme, Ecuador) were used to break down mucilage for 2 days. The remaining mucilage was washed off. The parchment coffee was cleaned and dried under the sun [19].

Table 1. Features of the 17 sampling coffee farms.

Farm	Province	Coordinates	Altitude, m.a.m.s.l.	Precipitation [a], mm	Temperature [b], °C	Variety
F1	Santa Elena	2°13′36″ S 80°51′30″ W	12	487	26 °C	Congolensis
F2	Santa Elena	2°13′36″ S 80°51′30″ W	12	487	26 °C	Congolensis
F3	Santa Elena	2°13′36″ S 80°51′30″ W	12	487	26 °C	Conilon
F4	Guayas	2°12′00″ S 79°58′00″ W	40	4283	31 °C	Congolensis
F5	Guayas	2°12′00″ S 79°58′00″ W	40	4283	31 °C	Conilon
F6	Los Rios	1°46′00″ S 79°27′00″ W	80	6182	27 °C	Congolensis
F7	Los Rios	1°46′00″ S 79°27′00″ W	80	6182	27 °C	Congolensis
F8	Los Rios	1°46′00″ S 79°27′00″ W	80	6182	27 °C	Congolensis
F9	Santo Domingo	0°15′15″ S 79°10′19″ W	625	4000	23 °C	Conilon
F10	Santo Domingo	0°15′15″ S 79°10′19″ W	625	4000	23 °C	Congolensis
F11	Santo Domingo	0°15′15″ S 79°10′19″ W	625	4000	23 °C	Congolensis
F12	Santo Domingo	0°15′15″ S 79°10′19″ W	625	4000	23 °C	Conilon
F13	Santo Domingo	0°15′15″ S 79°10′19″ W	625	4000	23 °C	Conilon
F14	Santo Domingo	0°15′15″ S 79°10′19″ W	625	4000	23 °C	Congolensis
F15	Bolivar	1°36′ S 79°00′ W	1700	4355	23 °C	Conilon
F16	Bolivar	1°36′ S 79°00′ W	1700	4355	23 °C	Conilon
F17	Bolivar	1°36′ S 79°00′ W	1700	4355	23 °C	Conilon

[a,b] Precipitation and temperature refer to annual mean values.

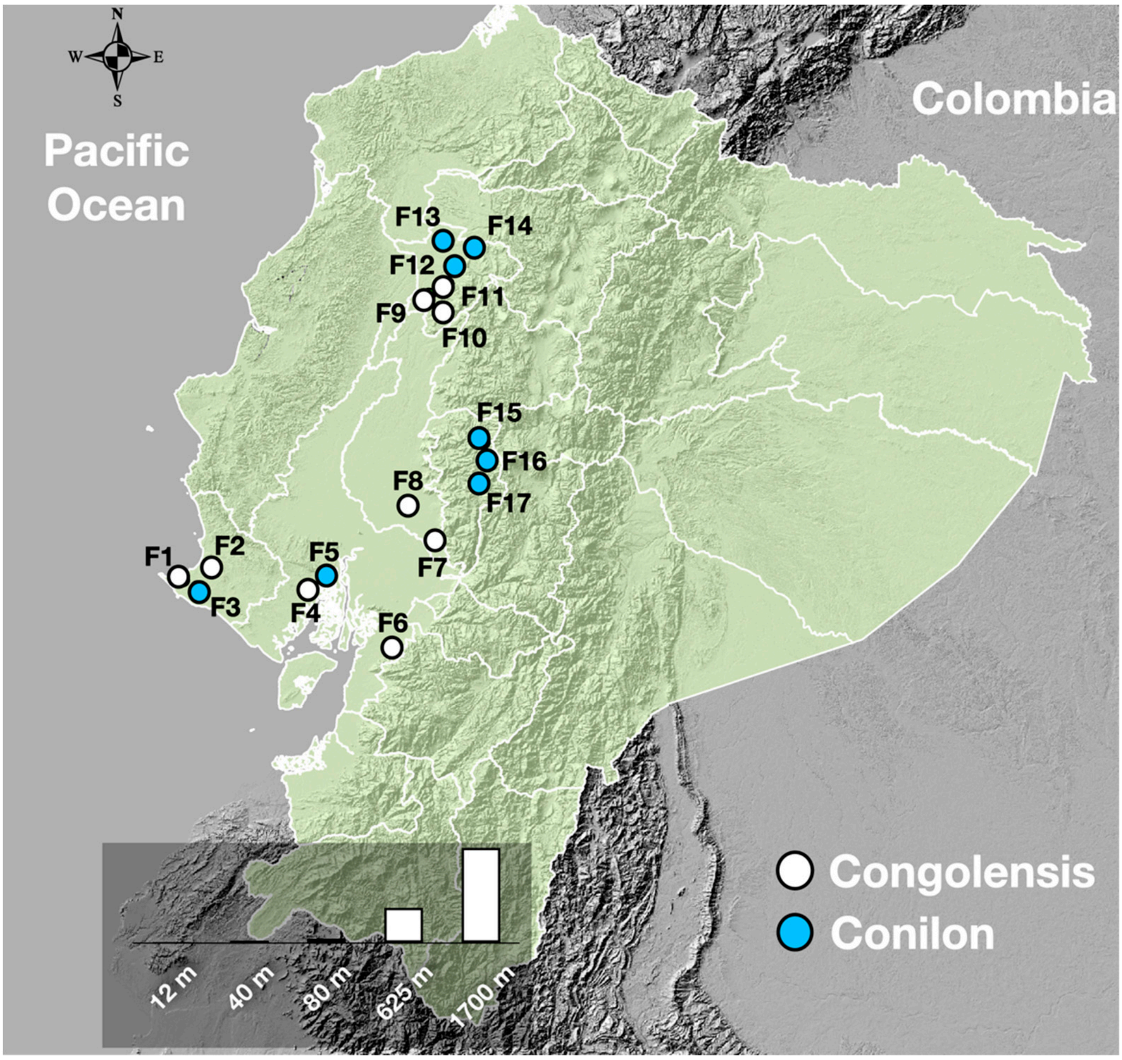

Figure 1. Sampling points in Ecuador.

In the honey (semi-dry or pulped natural) approach, the coffee skin and pulp are removed using a pulping machine. The seeds were dried under the sun with the mucilage still around them. The parchment layer is removed with a hulling machine [43].

In all the above processes, to separate the unripe, overripe, and damage cherries and to get rid of dirt, soil, twigs, and leaves, the gathered cherries were first manually sorted and cleaned. This was accomplished with a sizable sieve and manual winnowing. In all processes, the drying step was conducted under the sun in specially designed canopies, in wooden boxes (150 × 70 × 30 cm) with plastic mesh covers, and at room temperature until the grains' moisture content reached 10%.

2.3. Preparation of Coffee Samples

In a coffee roaster (Fresh Roast SR540, China), each coffee sample was roasted at 210–220 °C (American medium roast) [44]. This took up to 10 min. The roasting level was measured by the Agtron/SCAA roast classification colour disc at number 55. After the roasting process, the coffee samples were cooled and stored at room temperature. Roasted coffee beans were ground into a fine powder (Shardor conical burr coffee grinder, CG9406-UL2, USA). This step was performed before the sensorial analysis.

2.4. Sensorial Analysis

Five tasters performed the sensory analysis at each altitude. Therefore, there were a total of twenty-five tasters, as there were five distinct elevations. The training was conducted by video conference in accordance with COVID-19 social distance requirements. The sensory analysis was carried out by a panel accredited by the Coffee Quality Institute (CQI). We worked with the cupping protocol established by the Specialty Coffee Association (SCA), which establishes ten quality parameters for *C. canephora* (fragrance/aroma, flavour, aftertaste, salt/acidity, bitter/sweet, body, balance, and overall score) [37,45].

The cupping test of coffee beans was carried out referring to the standards and protocols for fine *C. canephora*. The cup quality components observed included the attributes of fragrance/aroma, flavour, aftertaste, salt/acidity balance, bitter/sweet balance, mouthfeel, cup uniformity, cup balance, cleanliness, and overall score. Fragrance is the smell of the ground coffee when it is still dry, aroma is the odour of the coffee after it has been infused with hot water, and aftertaste is the vapours that stay in the mouth after consuming the coffee. Balance is the evaluation of how well the flavour, aftertaste, acidity, and body harmonize with one another. The attribute overall is a reflection of the panellist's personal appraisal [45].

Panellists assessed each sensory attribute with a score of 6.00 to 6.75 (good), 7.00 to 7.75 (very good), 8.00 to 8.75 (excellent), and 9.00 to 10.00 (outstanding) [46]. The final score was obtained by adding up the scores for each attribute. If the value was >80 on a scale of 100, it was categorized as fine *C. canephora*; higher scores could classify the coffee as specialty grade (80 to 100 points) or commercial grade (<79 and below).

2.5. Statistical Analysis

The observational data were analysed by descriptive and inferential statistics using R-project and R-studio with the ggplot2 package [47,48]. The effects of altitude (Factor A) and post-harvest process (Factor B) on the sensory attributes (response variables) fragrance/aroma, flavour, aftertaste, sweetness, body, acidity, balance, and overall score were studied using ANOVA and Tukey's range test. The interactions altitude*variety and altitude*process were also included. Since the two coffee varieties are not found at the same altitudes, statistical tests were conducted individually for each.

3. Results

3.1. Effect of Post-Harvest Processes and Altitude on Coffee Cupping

According to Figure 2, all congolensis and conilon samples from different altitudes (12, 40, 80, 625, and 1700 m.a.m.s.l.) and post-harvest processes scored above 7.00 points, indicating that the panel of assessors rated them as very good and excellent in terms of aroma/flavour, aftertaste, salt/acidity, bitter/sweet balance, mouthfeel, body, cup balance, and overall score. The defects reached a score of 0 points in all cases. All the samples scored a maximum of 10 points for each of the variables clean-cup and uniformity, which were added to the total scores of the other sensory variables (Figures 3 and 4).

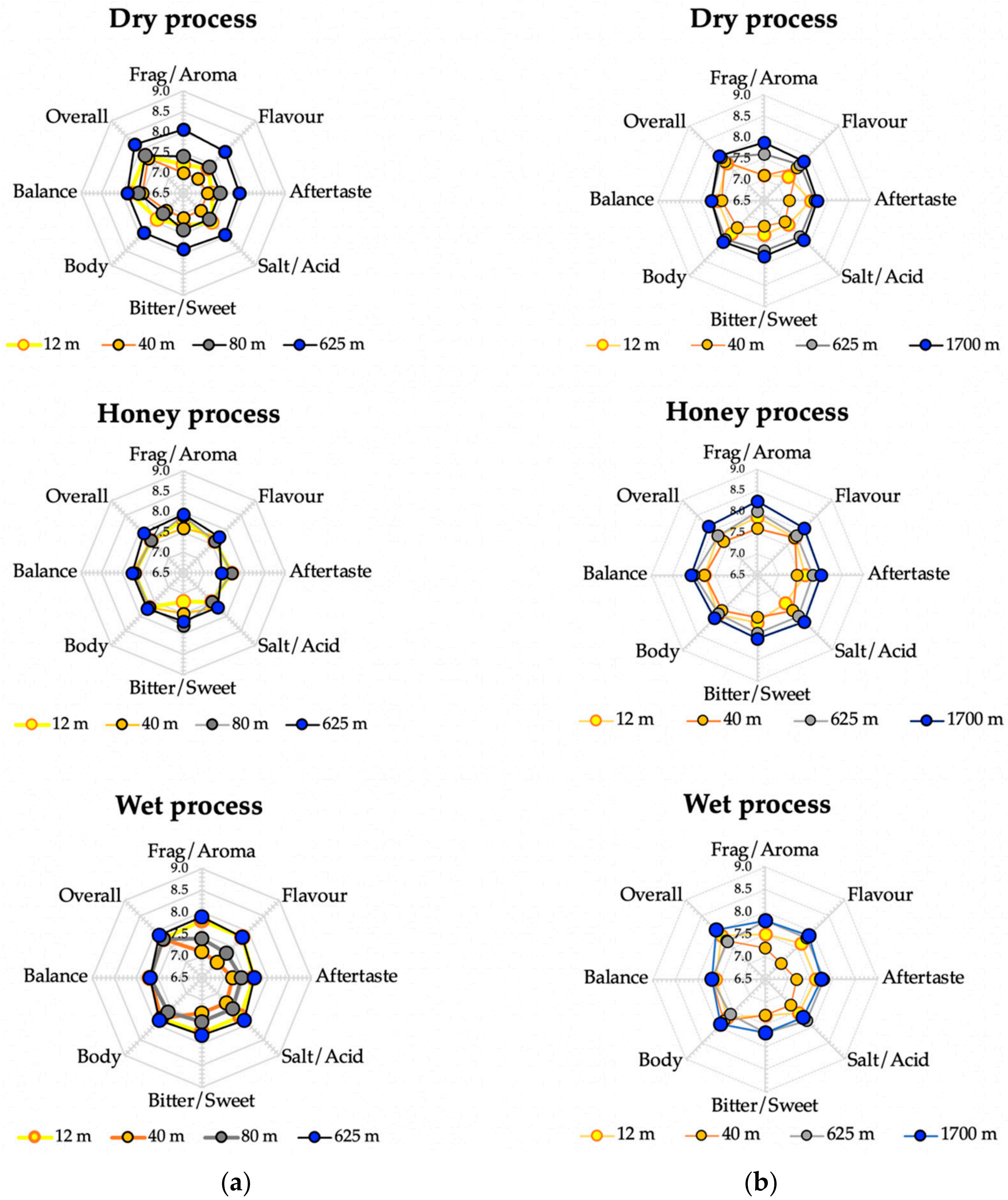

Figure 2. Average score of sensory profile evaluated by protocol cupping SCA (5 Q-Graders). Different altitudes: (**a**) congolensis; (**b**) conilon.

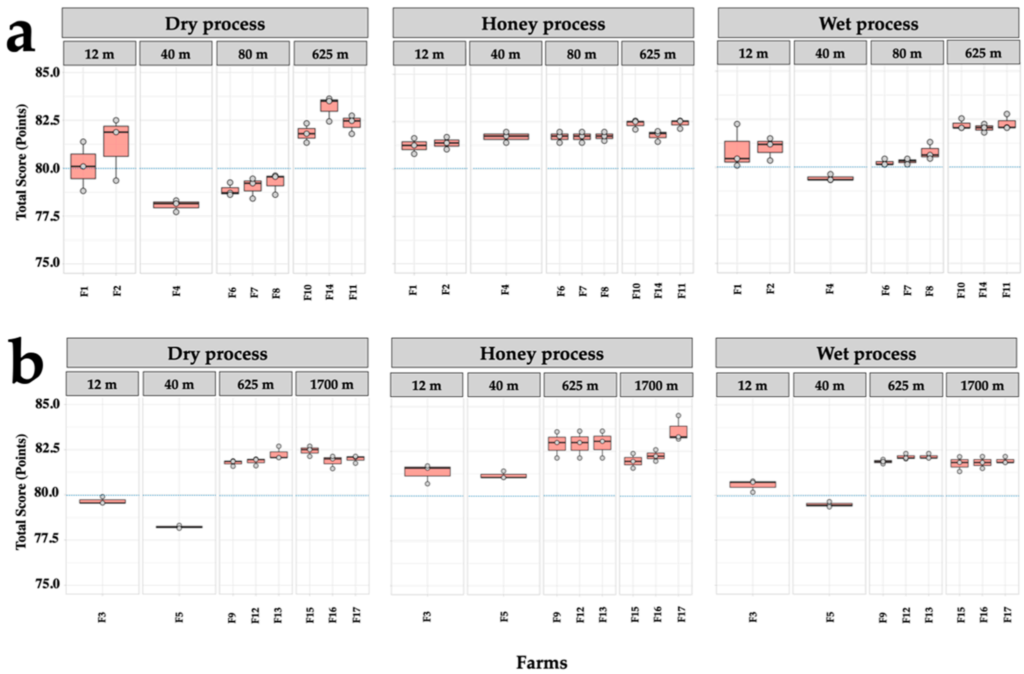

Figure 3. Total score of congolensis 100-point scale at different altitudes and different post-harvest processes, where: (**a**) congolensis; (**b**) conilon.

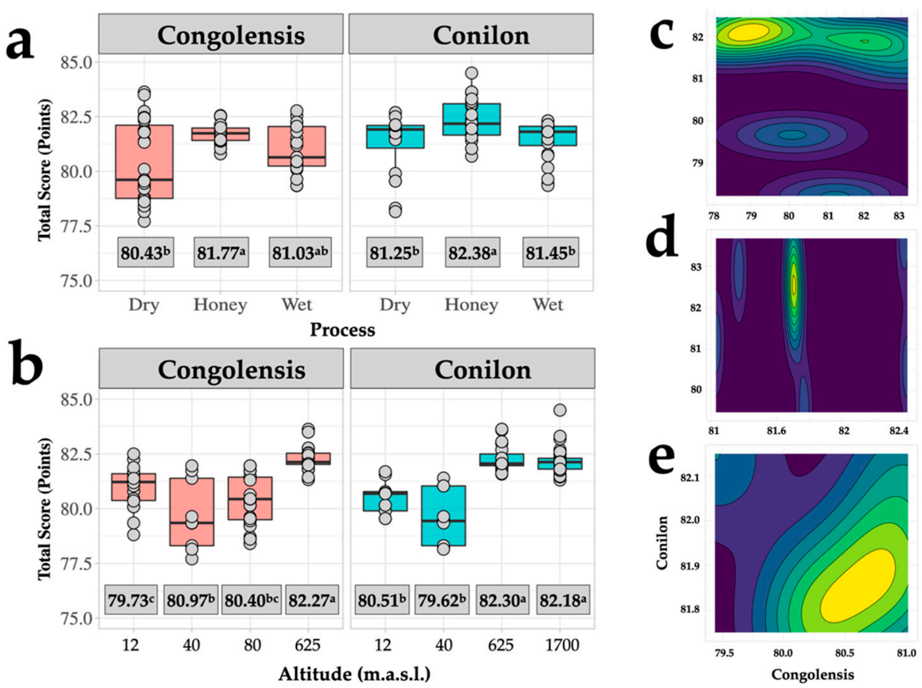

Figure 4. Total score of congolensis and conilon for (**a**) post-harvest processes; (**b**) altitudes. Contour plots of total scores for (**c**) dry; (**d**) honey; and (**e**) wet processes. Inside the Figure 4a,b, identical letters in superscripts indicate non-significant differences.

At a 12–40 m altitude, after the three post-harvest processes, coffee cupping produced significantly different attribute scores ($p < 0.05$), with a maximum value of 7.80 points (rated 'very good') for fragrance/aroma. At this altitude, dry processing reached the lowest scores, up to 7.0 points for fragrance/aroma, flavour, aftertaste, salt–acid, bitter–sweet, and body for both conilon and congolensis. The average grade for honey processing was an excellent 8.0 (Figure 2).

At an 80 m altitude, congolensis coffee's cupping results revealed an improvement in flavour, sweetness, and aroma but not in aftertaste or acidity (Figure 2). All post-harvest processes improved the quality of the cup, but dry processing did not. Conilon plantations were not present in our study at this height.

At an altitude of 625 m, for both conilon and congolensis, all three post-harvest processes improved the ratings of all attributes with nearly no statistically significant difference ($p > 0.05$) among them (Table 2).

Table 2. Summary of F-values from analysis of variance (ANOVA) for congolensis according to sensory attributes.

Source of Variation	Df	Frag/Aroma	Flavour	Aftertaste	Acidity	Sweetness	Body	Balance	Overall
Process	2	40.19 (***)	14.45 (***)	25.50 (***)	23.27 (***)	14.34 (***)	18.06 (***)	2.00 (ns)	42.90 (***)
Altitude	3	39.37 (***)	22.54 (***)	21.88 (***)	28.59 (***)	30.93 (***)	16.17 (***)	15.97 (***)	58.06 (***)
Process:Altitude	6	6.40 (***)	3.61 (***)	5.37 (***)	2.09 (.)	14.23 (***)	6.01 (***)	10.54 (***)	13.16 (***)

Df = Degrees of freedom. Significance codes: 0 (***) 0.001 (**) 0.01 (*) 0.05 (.) 0.1 (−) no significance (ns).

At 1700 m, only samples from conilon were tested, because congolensis plantations were not found at that altitude. Nonetheless, all conilon cup coffee characteristics had excellent score values at higher altitudes.

After dry-processing, congolensis obtained a very good grade for fragrance/aroma, flavour, aftertaste, salt–acid, bitter–sweet, and body from samples grown at elevations ranging from 12 to 80 m; meanwhile, at a 625 m altitude, the average overall attribute score was excellent (Figure 2). After honey and wet processing, congolensis obtained very good grades in all sensory attributes, with an average overall attribute score of excellent for samples growing at a 625 m altitude.

Conilon received very good scores after all three post-harvest processes in all the categories of fragrance/aroma, flavour, aftertaste, salt–acid, bitter–sweet, and body; besides this, conilon had an average overall attribute score of 'excellent' between 625 and 1700 m.

The effects of dry, honey, and wet post-harvest processes on congolensis coffee cupping were significantly different (Table 2). For congolensis, a significant difference ($p < 0.05$) was found across all sensory attributes when coffee beans were post-harvested by different means at different altitudes. Congolensis and conilon were not found in all altitudes, and thus the coffee variety did not offer a meaningful response and did not interact significantly with either the altitude or the post-harvest processing factors.

As altitude increased, particularly above 625 m, congolensis coffees from the dry, honey, and wet processes improved in most sensory qualities. When comparing post-harvest congolensis samples at higher altitudes (Table 3), there was no difference in sensory attributes ($p > 0.05$) except for acidity, sweetness, and balance.

Table 3. Summary of means from Tukey's HSD test for congolensis.

Altitude	Process	Frag/Aroma	Flavour	Aftertaste	Acidity	Sweetness	Body	Balance	Overall
12 m	Dry	7.53 (a)	7.51 (a)	7.41 (a)	7.51 (a)	7.52 (a)	7.64 (a)	7.64 (a)	7.85 (a)
	Honey	7.76 (a)	7.72 (a)	7.56 (a)	7.62 (a)	7.58 (a)	7.69 (a)	7.70 (a)	7.95 (a)
	Wet	7.58 (a)	7.55 (a)	7.47 (a)	7.59 (a)	7.56 (a)	7.68 (a)	7.69 (a)	7.89 (a)
40 m	Dry	7.06 (b)	7.13 (b)	7.10 (b)	7.13 (b)	7.16 (c)	7.20 (b)	7.46 (a)	7.53 (c)
	Honey	7.80 (a)	7.70 (a)	7.69 (a)	7.61 (a)	7.76 (a)	7.72 (a)	7.70 (a)	8.00 (a)
	Wet	7.20 (b)	7.34 (ab)	7.30 (b)	7.47 (a)	7.30 (b)	7.50 (ab)	7.52 (a)	7.70 (b)
80 m	Dry	7.34 (c)	7.33 (c)	7.22 (c)	7.27 (b)	7.28 (c)	7.28 (c)	7.50 (b)	7.65 (c)
	Honey	7.81 (a)	7.70 (a)	7.69 (a)	7.61 (a)	7.76 (a)	7.72 (a)	7.70 (a)	8.00 (a)
	Wet	7.44 (b)	7.50 (b)	7.51 (b)	7.52 (a)	7.52 (b)	7.50 (b)	7.64 (a)	7.83 (b)
625 m	Dry	7.80 (a)	7.78 (a)	7.70 (a)	7.67 (b)	7.72 (b)	7.70 (a)	7.68 (b)	8.04 (a)
	Honey	7.89 (a)	7.85 (a)	7.75 (a)	7.83 (a)	7.84 (a)	7.75 (a)	7.88 (a)	8.05 (a)
	Wet	7.83 (a)	7.78 (a)	7.70 (a)	7.82 (ab)	7.77 (ab)	7.70 (a)	7.68 (b)	8.04 (a)

Identical letters per sensory attribute indicate non-significant differences.

The effects of dry, honey, and wet post-harvest processes on conilon coffee cupping were significantly different (Table 4). For conilon, a significant difference ($p < 0.05$) was found across all sensory attributes when coffee beans were post-harvested by different means at different altitudes. Nevertheless, the interaction process:altitude was not significant ($p > 0.05$) for the attribute balance.

Table 4. Summary of F-values from analysis of variance (ANOVA) for conilon according to sensory attributes.

Source of Variation	Df	Frag/Aroma	Flavour	Aftertaste	Acidity	Sweetness	Body	Balance	Overall
Process	2	61.29 (***)	16.17 (***)	12.27 (***)	9.61 (***)	16.97 (***)	4.48 (*)	19.80 (***)	44.29 (***)
Altitude	3	77.60 (***)	35.42 (***)	73.98 (***)	62.36 (***)	44.84 (***)	12.80 (***)	14.27 (***)	104.63 (***)
Process:Altitude	6	6.35 (***)	3.64 (***)	5.38 (***)	4.29 (**)	4.56 (***)	2.55 (*)	1.43 (ns)	6.17 (***)

Df = Degrees of freedom. Significance codes: 0 (***) 0.001 (**) 0.01 (*) 0.05 (.)tHR 0.1 (—) no significance (ns).

In Table 5, Tukey's test determines where the significant difference ($p < 0.05$) exists among all sensory attributes at different altitudes. From the post-hoc test results, there were statistically significant differences between the honey, wet, and dry processes for fragrance/aroma, flavour, acidity, and overall score at lower altitudes (12 to 80 m). However, up to 1700 m, there were no significant differences—for example, for flavour, aftertaste, acidity, sweetness, or body—except for fragrance/aroma, balance, and overall score.

Table 5. Summary of means from Tukey's HSD test for conilon according to sensory attributes.

Altitude	Process	Frag/Aroma	Flavour	Aftertaste	Acidity	Sweetness	Body	Balance	Overall
12 m	Dry	7.10 (c)	7.36 (b)	7.58 (a)	7.30 (b)	7.37 (a)	7.68 (a)	7.56 (a)	7.75 (b)
	Honey	7.81 (a)	7.62 (a)	7.65 (a)	7.54 (a)	7.62 (a)	7.77 (a)	7.66 (a)	7.95 (a)
	Wet	7.43 (b)	7.60 (a)	7.58 (a)	7.54 (a)	7.51 (a)	7.70 (a)	7.63 (a)	7.85 (a)
40 m	Dry	7.10 (b)	7.13 (b)	7.10 (b)	7.16 (a)	7.16 (b)	7.30 (a)	7.46 (a)	7.55 (c)
	Honey	7.70 (a)	7.70 (a)	7.54 (a)	7.47 (a)	7.66 (a)	7.72 (a)	7.70 (a)	7.93 (a)
	Wet	7.23 (b)	7.34 (ab)	7.30 (b)	7.49 (a)	7.30 (b)	7.50 (a)	7.52 (a)	7.71 (b)
625 m	Dry	7.71 (b)	7.72 (a)	7.70 (b)	7.72 (b)	7.70 (b)	7.76 (a)	7.70 (b)	8.01 (b)
	Honey	7.95 (a)	7.85 (a)	7.81 (a)	7.85 (a)	7.83 (a)	7.81 (a)	7.89 (a)	8.12 (a)
	Wet	7.79 (b)	7.75 (a)	7.72 (ab)	7.77 (b)	7.75 (ab)	7.76 (a)	7.70 (b)	8.02 (b)
1700 m	Dry	7.72 (b)	7.74 (a)	7.73 (a)	7.68 (a)	7.68 (a)	7.70 (a)	7.66 (b)	8.01 (b)
	Honey	7.98 (a)	7.85 (a)	7.80 (a)	7.79 (a)	7.76 (a)	7.77 (a)	7.80 (a)	8.09 (a)
	Wet	7.91 (a)	7.76 (a)	7.73 (a)	7.77 (a)	7.70 (a)	7.75 (a)	7.72 (ab)	8.01 (b)

Identical letters per sensory attribute indicate non-significant differences.

Tukey's test is applied in Table 5 to evaluate where there is a significant difference ($p < 0.05$) among all sensory qualities at different elevations. According to the post-hoc test results, there were statistically significant differences in fragrance/aroma, flavour, acidity, and overall score at lower elevations in all processes (12 to 80 m). However, there were no significant differences ($p > 0.05$) in flavour, aftertaste, acidity, sweetness, and body up to 1700 m, although there were differences in fragrance/aroma, balance, and overall score.

3.2. Effect of Post-Harvest Processes and Altitude on Total Score

The effects of higher altitude on coffee cupping are shown in Figure 3. It shows the total cupping scores for coffee congolensis and conilon harvested at various elevations (12, 40, 80, 625, and 1700 m.a.m.s.l.) applying dry, honey, and wet post-harvest methods. The results show that each altitude and processing method gives the coffee a unique cup profile.

Samples of congolensis and conilon grown under 80 m were identified as commercial grade. However, there were some exceptions for honey- and wet-processed samples from 12 and 40 m which were regarded as speciality grade. Above a 625 m altitude, all samples from all three processes were classified as speciality grade. Thus, the higher the altitude, the higher the coffee's sensory quality [32,49–51].

Figure 4 shows the effect of post-harvesting processes and altitudes on the accumulative total score of all 17 farms; also, it shows the post-hoc test to evaluate where there is a significant difference ($p < 0.05$) among all processes and different elevations. The mean values indicate that congolensis and conilon samples grown under 40 m received scores below 80 points, which are regarded as commercial grade coffee. According to contour plots, conilon was perceived to have the best sensory attributes at high altitudes using honey processing. In general, the wet-processed congolensis and conilon samples have a tastier profile than dry-processed ones.

4. Discussion

At an altitude of 12–40 m, fragrance/aroma, flavour, aftertaste, salt–acid, bitter–sweet, and body scores were all as low as 7.0 points for dry-processed conilon and congolensis (Figure 2). The results showed that the flavour, sweetness, and scent of congolensis coffee improved at 80 m but not the aftertaste or acidity. *C. canephora* grown under 800 m has a high bitterness, astringency, strength, body, grassy flavour, and a low aromatic value [25,27,32,45,52,53]. According to the present results, for both congolensis and conilon, acidity was an attribute with the lowest scores up to 7.0 points. At this altitude, it is feasible that a high humidity led to fermentation, and therefore fragrance/aroma and flavour are more likely reduced.

According to the findings of this study, the overall score of the two coffee species at higher altitudes exceeds 80 points, indicating that they belong to speciality grade. At higher altitudes, sweetness, smoother taste, and cup quality increases in *C. canephora* [39]. Caramel, brown sugar, fruity, almond, apricot, very sweet, coconut bullet, and fruity are the flavour characteristics that are most prevalent [54]. This increase in sensory attributes is related with the coffee plant's slow growth and a higher precipitation index. Due to the slower maturation rate at higher elevations, photoassimilates (sucrose, polyols, and amino acids), which are associated with a flavourful aroma, accumulate in greater concentrations in the coffee tree's leaves and fruits [26,55,56]. Furthermore, the slower ripening process allows a greater production of phenolic compounds and more intensely flavoured beans than those grown in lower areas, or under full sunlight [49,57].

The dry process produces a less aromatic but full body coffee cup, but it depends on the variability of climatic conditions which results in an inconsistency of drying [58,59]. Furthermore, drying temperatures above 40 °C for parchment and 45 °C for cherries have a noticeable impact on the quality of the final cup of coffee. Excessive drying would occur if air flow, relative humidity, and pressure are not managed, causing a great deal of water to evaporate off the bean's surface [60]. During the drying process, coffee beans remain viable with metabolic activities to produce a wide variety of free amino acids from proteins, and low-molecular-weight sugars (i.e., glucose, fructose, and mannose); however, the germination process is inhibited [57,61]. The inhibition of germination is related to low coffee cup quality, and this is related to the accumulation of gamma-amino butyric acid (GABA) [26]. On the contrary, during the wet process, germination occurs immediately after depulping. The most likely metabolic events in living seeds are related to germination, which enhances coffee cup quality [57,62]. Therefore, the characteristics of coffee produced by dry and wet processing remain distinct.

The wet processes herein tested produced coffees with more flavour and acidity but with less body than those samples from the dry-processing method, according to our results. In the wet coffee-processing methods, fermentation occurs in water at more controlled temperatures which produce lower levels of undesirable flavours [26]. Thus, the washed coffee is often associated with better cup quality. Wet-processed coffees have a better aroma with a pleasantly higher acid content, resulting in higher acceptance [24,57]. Besides this, in the wet method, sugars and pectins present in the mucilage allow microorganisms' growth, thus playing an important role in coffee flavour [63].

The hypotheses established as the premise of this study should be accepted in the context of the information presented herein.

5. Conclusions

Crop altitude and post-harvest processes influence perceived coffee cupping. Our results indicate that the greater the altitude, the higher the quality of the coffee, and that wet-processed coffees are preferred. Altitude had a strong impact on the physicochemical qualities and consequently the organoleptic quality of the coffee, representing the key element that influenced the coffee sensory quality. Congolensis and conilon received high average scores for fragrance/aroma, flavour, aftertaste, salt/acidity, bitter/sweet balance, mouthfeel, body, cup balance, and overall score. Honey processing produced the highest fragrance/aroma, flavour, aftertaste, salt/acidity, bitter/sweet, body, balance, and overall ratings for all congolensis and conilon samples from varied altitudes. Conilon outperformed congolensis in all qualities using the dry, honey, and wet procedures. At a 12–40 m altitude, congolensis had the lowest fragrance/aroma and flavour values in all post-harvest processes. Higher altitude coffees exhibit the highest scent strength and quality. Wet-processed congolensis and conilon samples possessed a more flavourful character than dry-processed samples. Dry processing results in a hard coffee, whereas wet processing results in a better-quality coffee with less body, higher acidity, and more aroma than dry processing. As a result of arabica's increased sensitivity to temperature fluctuations, *C. canephora* might benefit in this scenario. As a result, more information on the *C. canephora* market is needed, particularly regarding customer characteristics and purchasing patterns. This study suggests that any *C. canephora* cultivar has the potential to produce high-quality coffee; nevertheless, flavour profiles will vary depending on growing conditions.

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Capítulo 3

Post-harvest effects on physical quality and tasting notes of robusta coffee

Abstract

La calidad del café es un rasgo complejo influenciado por factores como las condiciones atmosféricas, sombra, humedad, altitud, prácticas de cultivo y procesamiento post-cosecha. Estos factores afectan al tamaño y la forma de los granos, así como a la densidad, color y otros parámetros de calidad. Aunque la calidad del café está bien estudiada en algunas especies, como Coffea arabica, hay información limitada sobre la especie Coffea canephora. Por tanto, este estudio tiene como objetivo evaluar la calidad física y sensorial (notas de cata) de los grupos genéticos Conilón y Robusta de diferentes altitudes en Ecuador. En este estudio se realizaron análisis físicos y organolépticos de muestras obtenidas de tres altitudes diferentes (12, 625 y 1700 m.s.n.m.). Las muestras de granos se sometieron a tres métodos de procesamiento posterior a la cosecha (seco, húmedo y miel), y se preparó un tueste americano medio. Los catadores registraron características favorables (por ejemplo, chocolate, cítricos) y desfavorables (amargo, herbáceo) para el análisis estadístico. El estudio encontró que se observaron mejores puntuaciones de calidad en términos de tamaño de los granos y notas de cata para las muestras de café obtenidas a altitudes de hasta 625 metros y procesadas con los tres métodos de procesamiento post-cosecha. Además, la contribución a la calidad física y en taza del café no fue significativamente diferente entre Conilón y Robusta. El estudio también encontró que los métodos de procesamiento post-cosecha y la altitud afectaron significativamente a la retención de granos en el tamiz. Este estudio concluyó que la calidad del café se relaciona principalmente con el tamaño de los granos y la ausencia de defectos, ya que estas características están relacionadas con el gusto, el sabor y el precio. El sabor del café está influenciado por la composición química de los granos, variedad de los granos, prácticas agrícolas y condiciones post-cosecha, como la fermentación, secado, almacenamiento y el tueste. Por tanto, es necesario comprender las complejidades de la producción de café y considerar cuidadosamente diversos factores para producir café de alta calidad. Deben seguirse las directrices internacionales para la aplicación de buenas prácticas de fabricación y los criterios de certificación y trazabilidad para gestionar la calidad y la seguridad del café.

Palabras clave: Daño en los granos, Defectos de los granos, Robusta, Conilón, Calidad de los alimentos, Análisis sensorial

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POSTHARVEST EFFECTS ON THE PHYSICAL QUALITY AND SENSORY CHARACTERISTICS OF *COFFEA CANEPHORA*

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ABSTRACT

Background. Coffee quality is a complex trait influenced by many factors, including atmospheric conditions, shade, humidity, altitude, cultivation practices, and post-harvest processing. These factors ultimately affect bean size and shape, as well as density, color, and other quality parameters. Although coffee quality is well-studied in some species, such as *Coffea arabica*, there is limited information about the species *Coffea canephora*. Therefore, this study aims to evaluate the physical and sensory quality (tasting notes) of the genetic groups Conilon and Robusta from different altitudes in Ecuador.
Materials and methods. In this study, physical and organoleptic analyses were conducted on samples obtained from three different altitudes (12, 625, and 1,700 m.a.s.l.). The bean samples were subjected to three post-harvest processing methods (dry, wet and honey), and American medium roast was prepared. Cuppers recorded favorable (e.g., chocolate, citrus) and unfavorable (bitter, herbaceous) characteristics for statistical analysis.
Results. The study found that better quality scores in terms of bean size and tasting notes were observed for coffee samples obtained at altitudes up to 625 meters processed with all three post-harvest processing methods. Furthermore, there was no significant difference between the contribution of these factors to the physical and cup quality of coffee made from Conilon and Robusta. The study also found that post-harvest processing methods and elevation significantly affected screen retention.
Conclusion. This study concluded that coffee quality is primarily related to bean size and lack of defects, as these characteristics are closely linked to taste, flavor, and price. Coffee flavor is directly influenced by the chemical composition of the beans, which is determined by the cultivar of the beans, farming practices, and post-harvest processing conditions such as fermentation, drying, storage, and roasting. Therefore, an understanding of the complexities of coffee production and a careful consideration of various factors are necessary to produce high-quality coffee. International guidelines for applying good manufacturing practices and criteria for certification and traceability should be followed to manage the quality and safety of coffee.

Keywords: bean damage, bean defects, *Robusta*, *Conilon*, food quality, sensory analysis

INTRODUCTION

While Arabica coffee (*Coffea arabica*) is often seen as superior, Robusta coffee (*Coffea canephora*) has several unique qualities that make it a valuable and versatile coffee species. Robusta's stronger flavor, higher caffeine content, and resilience to drought and heat make it ideal for a variety of applications, including blending

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with Arabica coffee to create high-quality coffee products with desirable flavor profiles (Schwan and Fleet, 2014; Chindapan et al., 2019; Byrareddy et al., 2021; Portela et al., 2022). Although Arabica is renowned for its aroma and acidity (Campuzano-Duque et al., 2021), research on Robusta coffee processing parameters is essential to unlock its full potential (Hameed et al., 2018; Kittichotsatsawat et al., 2021). In terms of processing, research has shown that semi-dry processing can produce coffee with more complex and desirable flavor profiles than dry processing (Wulandari et al., 2022; Silva et al., 2022; Girma and Sualeh, 2022). This is because semi-dry processing allows some of the sugars in the coffee cherries to ferment, which can lead to the development of more complex flavors (Nadaleti et al., 2022; Aswathi et al., 2023). Coffee brews processed using the semi-dry and wet methods scored higher as specialty coffee than those processed using the dry method. The dry method produced coffee with a medium fruity body, fresh medium acidity, and chocolate and caramel flavors, while the wet and semi-dry methods produced coffee with citrus and fruity flavors (Cortés-Macías et al., 2022; Linda et al., 2023). By gaining a comprehensive understanding of how various processing methods impact the flavor profile, it becomes feasible to develop more efficient processes for the production of premium *Robusta coffee* products that cater to consumer preferences and demands.

The final cup quality is intricately linked to critical variables such as coffee genotype, bean size, the presence of damaged beans, and the choice of pre- and post-harvest processing methods (Folmer, 2017; Velásquez and Banchón, 2022). Smaller coffee bean sizes are generally regarded as inferior in some countries, do not qualify as specialty coffee, and are priced lower. Furthermore, defective coffee beans account for up to 20% of total coffee production and significantly reduce the quality of coffee beverages worldwide (Ramalakshmi et al., 2007; Belay et al., 2014). The size of coffee beans is a key factor in determining their density and flavor, and the presence of damaged beans can impact the overall quality and taste of the coffee, affecting both coffee yield and the quality of the brewed cup (Luna González et al., 2019; Tassew et al., 2021). The coffee industry is seriously threatened by a variety of pests, and the predominant global menace is the coffee berry borer (CBB), scientifically referred to as *Hypothenemus hampei*, which is renowned for causing substantial damage to coffee crops, resulting in significant yield losses (Johnson et al., 2020). Various factors can influence the extent of CBB damage. For instance, reduced shade tree diversity in *C. canephora* leads to higher CBB infestation rates, as it decreases natural predator diversity (Ayalew et al., 2022; Oliva et al., 2023). Conversely, the presence of shade trees increases bird populations, resulting in a 50% reduction in CBB infestation rates in *C. arabica* and an improvement in coffee quality (Chain-Guadarrama et al., 2019). In general, declining biodiversity in agroforestry systems disrupts ecological interactions, reducing pest control services and impacting crop quality (Torrez et al., 2023). These physical attributes are essential considerations for coffee producers and roasters striving to achieve the best results in their coffee production processes (Belay et al., 2014; Hameed et al., 2018; Bastian et al., 2021).

Ecuadorian historical records trace the introduction of *C. canephora* genetic material back to 1951. Originating from Costa Rica and falling within the “Robusta” category (with a genetic group referred to as putative SG2), this genetic material gradually extended its presence to several coastal provinces and the northern areas of the Ecuadorian Amazon. Subsequently, in 1987, Ecuador imported genetic material of the “Conilon” type (putative SG1) from Brazil (Leroy et al., 2014; Loor Solórzano et al., 2017). In Ecuador, scientists developed a breeding program to improve *C. canephora* coffee plants. In 1998, the National Institute of Agricultural Research of Ecuador (INIAP) identified elite coffee plant clones that are now recommended for commercial planting under the conditions of the northern Ecuadorian Amazon. Crop altitude and post-harvest processing methods are known to have a significant influence on the cupping quality of Ecuadorian coffee plant clones (Velásquez et al., 2022), with altitude being the primary factor, but more information is needed about their effects on specific clones. In this context, it is pertinent to explore the connections between the sensory attributes of coffee cup quality derived from Ecuadorian Robusta and Conilon clones, the altitudes at which they are cultivated, and the physical characteristics of the beans. In these terms, this study’s novelty lies in its categorization of flavor attributes into positive and negative factors, providing a nuanced evaluation of taste profiles and enhancing our comprehension of the sensory characteristics associated with Robusta and Conilon. Accordingly, the aim of this research was to determine how bean size, bean defects, and post-harvest processing methods influence the sensory qualities (taste notes) of Robusta and Conilon beans. The expected outcome of this research is a set of recommendations on the optimum green coffee bean post-harvest methods for farmers at three different altitudes.

MATERIALS AND METHODS

Sampling

The fruits of *C. canephora* genetic groups Robusta and Conilon were gathered from six different Ecuadorian plantations located at various altitudes (Table 1).

Post-harvest processing method

Three different post-harvest processing methods were applied: dry, wet and honey. In the dry method, the entire crop of mature cherries was sun-dried for 12 days, until the requisite 10% water content was reached (Evangelista et al., 2014). The cherries were exposed uniformly to the sun's rays and constantly scraped to prevent fermentation. The unwanted outer layers were removed manually. After drying, the cherries were milled to remove the fruit and the parchment encasing the seed. In the wet process, the pulp and mucilage from ripe coffee cherries were removed using approx. 30 L of water per kilogram of beans for 24 hours. Proteolytic enzymes (Granozyme, Ecuador) were used to break down the mucilage for 2 days. The remaining mucilage was washed off. The parchment coffee was cleaned and dried under the sun (Pereira et al., 2020). In the honey (semi-dry or pulped natural) approach, the coffee skin and pulp were removed using a pulping machine. The seeds were dried under the sun with the mucilage still around them. The parchment layer was removed with a hulling machine (Wulandari et al., 2021).

In all the above processes, to separate the unripe, overripe, and damaged cherries and to get rid of dirt, soil, twigs, and leaves, the gathered cherries were first manually sorted and cleaned.

Physical analysis

For the physical analysis, a quantity of 300 grams of coffee was subjected to a sorting process employing screens with a mesh size number ranging from 14 to 18 (Tassew et al., 2021). The weight of the coffee retained in each sieve was measured and the corresponding percentage was documented (Ameyu, 2016).

In a defects analysis, Specialty Grade (1) coffee should have no more than five complete defects in a 300-gram sample, and primary defects (full black, full sour, pod cherry, large stones, large and medium sticks) are not allowed. Additionally, a tolerance of up to 5% above or below the advertised screen size is permitted (SCA, 2022).

Premium Grade 2 allows a maximum of 8 complete defects in 300 grams, with no restrictions on primary defects, and samples may contain up to three quakers (SCA, 2022).

Table 1. Features of the coffee farms where the fruit samples were gathered

Farm	Province	Coord.	Altitude m.a.m.s.l.	Precipitation[1] mm	Temperature[2] °C	Variety
F1	Santa Elena	2°13′36″S 80°51′30″W	12	487	26°C	Robusta
F2	Santa Elena	2°13′36″S 80°51′30″W	12	487	26°C	Conilon
F3	Santo Domingo	0°15′15″S 79°10′19″W	625	4 000	23°C	Robusta
F4	Santo Domingo	0°15′15″S 79°10′19″W	625	4 000	23°C	Conilon
F5	Bolivar	1°36′S 79°00′W	1 700	4 355	23°C	Robusta
F6	Bolivar	1°36′S 79°00′W	1 700	4 355	23°C	Conilon

[1, 2] Annual mean values for precipitation and temperature are provided.

Preparation of coffee samples (roasting and grinding, beverage preparation)

The roasting process aimed to achieve an American medium roast, a commonly preferred level for Robusta coffee. In a coffee roaster (Fresh Roast SR540, China), each coffee sample was roasted at 210–220°C (American medium roast). This took up to 10 min. To determine the roast level, the Agtron/SCAA E10/E20 color disc with the number 54 was employed as a standard tool. After the roasting process, the coffee samples were cooled and stored at room temperature. For a consistent grind size, the Shardor conical burr coffee grinder was used, producing grounds in the 0.3 to 0.5 millimeter range suitable for pourover brewing (Shardor conical burr coffee grinder, CG9406-UL2, USA). Pourover brewing was selected due to its ability to offer precise control over essential brewing parameters like water temperature and contact time. The amount of ground coffee was 8.75 grams per 150 mL of hot water (90°C).

Sensorial analysis

Five tasters performed the sensory analysis of fruits originating from each altitude. As there were three distinct altitudes, there were a total of fifteen tests. A panel of experts certified by the Coffee Quality Institute (CQI) conducted the sensory study. All of the panellists went through 120 hours of descriptive panel training with a variety of food products (di Donfrancesco et al., 2019). The attribute terminology employed was based on the coffee´s aroma, flavour, and aftertaste, according to the coffee taster´s flavour wheel (SCA, 2022).

Cuppers of coffee recorded odour/flavor attributes in two categories: positive flavour attributes such as chocolate, lemon grass, cocoa, citrus, aromatic, apple, cherry, passion fruit, floral, berries, sweet, vanilla, brown sugar, honey, toffee, pistachio, kiwi, or creamy; and negative flavor characteristics such as rubbery, fermented, coarse, burned caramel, wood, bitter, vinegar, astringent, cereal, dry, mashed, grass, butter, rancid, a little juicy, overripe, silky, loose, straw, vegetables, aged cheese, undercooked, leafy, or unripe (Andueza et al., 2007; Seninde and Chambers, 2020; Pinsuwan et al., 2022).

Numeric scores were assigned to each odor/flavor attribute or tasting note on a scale from 1 to 10, reflecting the intensity of each characteristic as described by the cuppers. Subsequently, the data allowed for the calculation of the percentage of positive and negative tasting notes. A comprehensive statistical analysis was conducted to discern significant differences in tasting notes between coffee species and altitudes.

Statistical analysis

The observational data were analysed by descriptive and inferential statistics using R-project and R-studio with the ggplot2 package (R Core Team, 2022; Wickham, 2016). The effects of physical characteristics, defects, altitude, and post-harvest treatments on the sensory attributes (response variables) were studied using ANOVA and Tukey's range test. Since the two Robusta varieties are not found at the same altitudes, statistical tests were conducted individually for each variety.

RESULTS AND DISCUSSION

Screen size

Figure 1 shows the percentage of Conilon and Robusta coffee beans retained on screens 12–18, with the size distribution of the beans described as follows: screen 12 (caracol) for small beans, screen 14 (terceras) for medium beans, and screens 16–18 (segundas and superior) for large beans. Small caracol beans and terceras beans are two of the smallest coffee bean sizes. According to the results (Fig. 1), small caracol beans were found to make up less than 4% of the total coffee beans at any altitude and for any post-harvest process, while terceras beans made up less than 14% of the total coffee beans at any altitude.

At lower altitudes, there were no notable variations in the 12 screen size of Conilon coffee beans, regardless of the post-harvest processing method employed. Nevertheless, when it comes to both Robusta and Conilon 14 screen size beans, a marked difference emerges: the dry processing method yielded up to 15% screen retention, whereas the other methods exhibited a comparatively lower level of retention. At 12 m altitude, Robusta beans had significantly higher screen 18 retention (62%) than Conilon beans (12%). There were no significant differences in screen 18 retention based on the post-harvest processing method for Conilon beans, but there were significant differences for Robusta beans (Table 2).

Table 2. Summary of F-values from ANOVA for physical and defects analysis

Source of variation	Df	Conilon			Robusta		
		12 m	625 m	1700 m	12 m	625 m	1700 m
Processing method	2	44.8 (***)	5.4 (*)	0.7 (–)	103.6 (***)	5.3 (*)	3.0 (.)
Screen 12/18	1	39.0 (***)	3.1 (–)	83.9 (***)	0.5 (–)	240.1 (***)	680.0 (***)
Processing method: Screen	2	5.6 (*)	14.6 (**)	4.2 (.)	1122.5 (***)	34.1 (***)	13.5 (***)
Defects							
Category-1	2	13.8 (***)	5.5 (*)	2.1 (–)	2.1 (–)	5.7 (*)	4.8 (*)
Category-2	2	2.1 (–)	0.2 (–)	3.1 (.)	0.1 (–)	1.4 (–)	1.4 (–)
Tasting notes							
Processing method	2	85.0 (***)	58.1 (***)	0.6 (ns)	385.6 (*)	513.1 (***)	74.1 (***)

Df = Degrees of freedom. Significance codes: 0 (***) 0.001 (**) 0.01 (*) 0.05 (.) 0.1 (–) no significance (ns)

At higher altitudes, according to Figure 1, Conilon beans from elevations up to 625 m had over 40% screen retention for screen 15–18. Coffee beans above mesh 15 are known as *medium or excelso* (SCA, 2022). At the same 625 m altitude, samples from honey processing screen retention achieved screen 18. Coffee beans above mesh 18 are known as *large*, *superior* or *supremo*. For Robusta processed using the wet-method, major screen retention occurred at screen 18, and for samples processed using the honey-method they reached major screen retention for screen 15 above 625 m. At 1,700 m altitude, screen 15 was obtained with all post-harvest methods (Fig. 1). According to the current study and previous sources, bean size increases significantly at higher elevations (Tassew et al., 2021). According to Table 2, screen retention

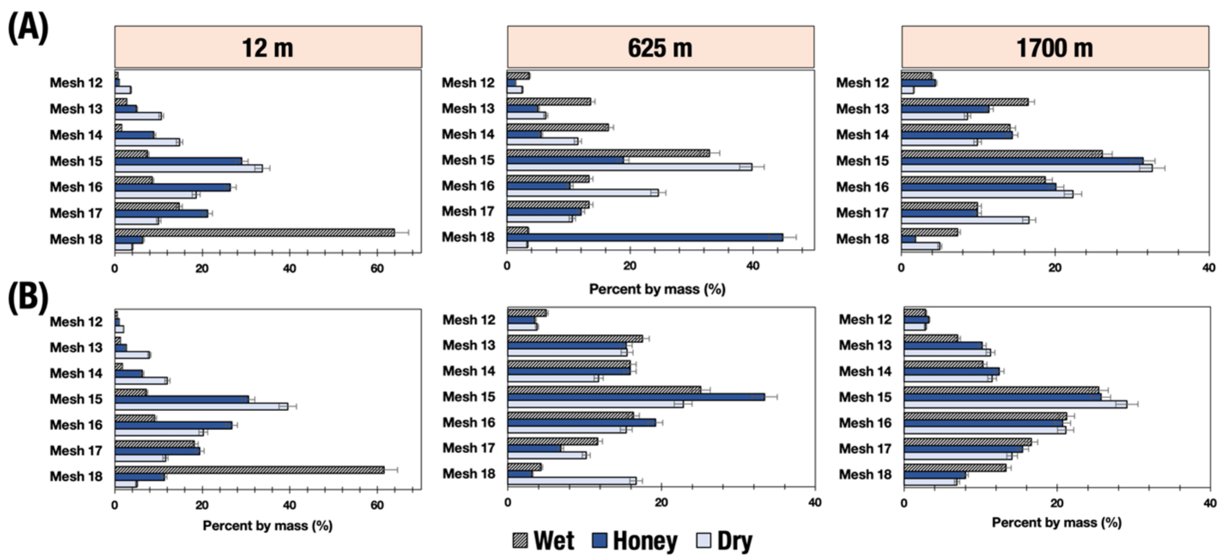

Fig. 1. Percentage of Conilion (A) and Robusta (B) beans from screens 12–18 originating from three altitudes and three post-harvests processes

was affected significantly ($p < 0.05$) by post-harvest processing and elevation. However, at altitudes up to 1,700 meters, the screen sizes from the different post-harvest processes were not statistically different ($p > 0.05$), especially for congolensis samples. In all cases (Fig. 1), there was a size variance of more than 5% among the 350-gram samples; thus, none of the coffee samples from any of the environments and post-harvest treatments would be considered *specialty*.

In addition to assessing the influence of bean size on coffee cup quality, this study also explored potential distinctions between Conilon and Robusta coffee varieties, revealing that the majority of the beverage's cup quality characteristics are independent of the coffee bean variety (Fig. 1, Table 2). Based on the findings of the present study investigating the effects of altitude and post-harvest processing methods on the size of beans in Robusta and *Conilon coffee* samples, there is a significant correlation between higher elevations and increased bean size. Additionally, this study emphasized the significant impact of processing methods and altitude on screen retention for both types of coffee. These findings align with previous research on coffee varieties like Catura, Rume Sudan, and Blue Mountain, which often produce smaller beans associated with reduced cup quality (Njoroge, 1998). This emphasizes the importance of careful selection of the appropriate cultivar, variety, or even coffee species to attain the desired quality. It is worth noting that high-quality coffee typically comprises a blend of flat and caracol beans, incorporating large, medium, and small beans retained above screen size 14 (Hoffmann, 2018; Luna González et al., 2019). Previous studies have shown that coffee beans of screen size 15 have lower acidity, sweetness, and taster scores than those of any other size, with a significant difference in the final score of more than four points compared to the smaller screen size 13 or the larger sizes 17 and 18 (Luna González et al., 2019). Larger beans, often grown at altitudes exceeding 1,000 meters above sea level, tend to yield better-tasting coffee due to their extended maturation period on the tree, which allows for more comprehensive development (Papadopoulos, 2008). Furthermore, notable seasonal variations in the impact of climate on coffee bean size and defects were observed, with reduced rainfall in the late growing season associated with smaller beans, while diminished rainfall during the early growing season had the opposite effect (Kath et al., 2021).

Defects

In the current research, it was observed that all Robusta and Conilon variants exhibited defects falling within categories 1 and 2. The analysis of variance (ANOVA) results presented in Table 2 indicate that post-harvest processing had a more pronounced impact on the cupping quality of congolensis and conilon variants at lower altitudes. Additionally, it was noted that bean screen size had a more significant effect on higher elevations, with an observed association between larger bean sizes and altitude. Table 2 suggests that small caracol beans and terceras beans are relatively rare, regardless of the altitude at which Conilon and Robusta coffee beans are grown and the post-harvest processing method. The significance of bean size during the roasting process is attributed to the softening of the bean's cellulose structure and the accumulation of pyrolysis byproducts, establishing bean size as a factor closely intertwined with the coffee's ultimate cup quality (Papadopoulos, 2008). Previous research has indicated that the sensory attributes of coffee brews are notably influenced by both peaberry and flat bean shapes, along with the fermentation process in both wet and semi-dry methods (Luna González et al., 2019). This is attributed to microbial activity during fermentation, which results in the production of diverse end-metabolites, subsequently exerting a substantial influence on the chemical composition of processed coffee (Wulandari et al., 2021; Cortés-Macías et al., 2022).

The flavour quality of brew coffee is an important factor that is linked to the presence of defective coffee beans. According to SCA, *specialty* coffee would not allow defects of category 1. Insect pests have devasting effects on the coffee plant, leading to the production of small low quality berries (Njoroge, 1998). After the threshing stage, defective beans become visible, and these must be identified and eliminated by physical analysis to prevent imbalances in the organoleptic properties of the coffee (Barrios Rodriguez et al., 2020). Higher rainfall during harvest was associated with an increased chance of coffee bean defects like mouldy beans and insect damage (Kath et al., 2021).

Table 3 shows the results of the Tukey HSD test, highlighting variations in cupping quality and

Table 3. Summary of means from Tukey HSD test for physical analysis

Process	Conilon			Robusta		
	12 m	625 m	1,700 m	12 m	625 m	1,700 m
Weight distribution for mesh 15/18						
Wet	14.0 (a)	27.7 (a)	6.9 (a)	34.4 (a)	19.8 (a)	19.6 (a)
Dry	52.3 (b)	39.3 (a)	32.2 (b)	23.5 (b)	18.0 (ab)	18.6 (a)
Honey	27.6 (c)	7.9 (b)	28.4 (b)	20.9 (b)	15.1 (b)	17.5 (a)
Defects of Category 1						
Wet	4.5 (a)	4.0 (a)	3.5 (a)	3.0 (a)	1.5 (a)	2.5 (a)
Dry	2.5 (b)	2.7 (ab)	1.7 (a)	2.3 (a)	0.8 (ab)	1.0 (ab)
Honey	1.0 (b)	1.0 (b)	1.5 (a)	1.5 (a)	0.2 (b)	0.5 (b)
Defects of Category 2						
Wet	3.7 (a)	3.2 (a)	2.7 (a)	3.3 (a)	0.7 (a)	1.5 (a)
Dry	2.0 (a)	2.7 (a)	2.0 (a)	2.5 (a)	0.5 (a)	0.8 (a)
Honey	1.5 (a)	2.5 (a)	0.7 (a)	2.3 (a)	0.5 (a)	0.5 (a)
Tasting notes						
Wet	44.8 (a)	15.4 (a)	5.7 (a)	22.2 (a)	14.0 (a)	6.8 (a)
Dry	54.8 (b)	27.8 (b)	5.6 (a)	35.6 (b)	17.8 (a)	13.4 (a)
Honey	43.4 (a)	14.8 (a)	5.7 (a)	44.8 (c)	42.6 (b)	6.6 (b)

[a,b] Identical letters indicate non-significant differences.

physical characteristics among Conilon and Robusta processed at various altitudes and subjected to different post-harvest processes. According to Table 3, the full defects (Category 1 + Category 2) did not reach a total of 8.0, which means that the samples are categorized as premium coffee (SCA, 2022). For this premium category, primary defects are permitted. A coffee is considered *specialty* when the number of Category 1 defects of green coffee beans is 0 (e.g., full black, sour, fungus damaged, foreign matter, and severe insect damage), and the number of Category 2 defects is ≤5 (e.g., immature/unripe, withered, broken, and floater defects) (SCA, 2022). The study found that all coffee samples from congolensis and conilon had defects, which are associated with lower flavor quality. Specialty coffee does not allow Category 1 defects. Insect pests can lead to the production of small, low-quality berries. Defective beans must be identified and eliminated to maintain the coffee's sensory properties. The Robusta and Conilon samples in the study were categorized as *premium coffee*, which permits some primary defects.

Tasting notes

Figures 2 and 3 summarize the percentages of positive and negative tasting notes of cup samples prepared from beans of various altitudes using the different post-harvest processes. The results show that the most negative tasting notes came from coffee made from low altitude beans. The organoleptic qualities of canephora coffees were determined to be influenced more by altitude than by processing conditions.

For Conilon and Robusta processed by all three methods, the statistical analysis (Tables 2 and 3) revealed that the honey and wet processes contributed more to coffee cup quality at high altitudes ($p < 0.05$).

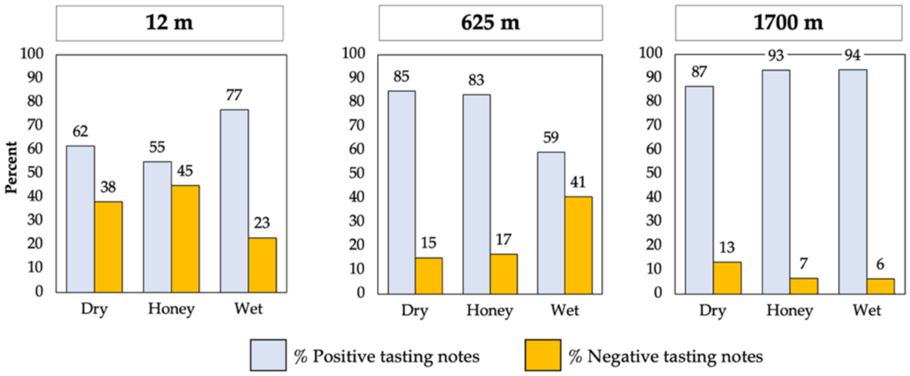

Fig. 2. Percentage of positive and negative tasting notes for Robusta cultivated at different altitudes

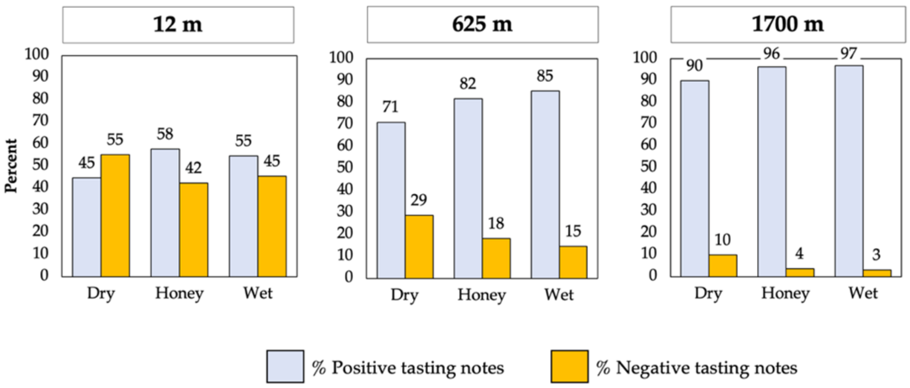

Fig. 3. Percentage of positive and negative tasting notes for Conilon cultivated at different altitudes

Figures 4 and 5 show the average scores for negative tasting notes on a scale from 1 to 10 for Robusta and Conilon coffees cultivated at different altitudes. Negative tasting notes were more prevalent at low elevations than at high altitudes, particularly for Conilon. Wet and honey processes had a favorable effect on the removal of unpleasant flavor notes in both species. Previous studies found that the best treatment for coffee beans was a combination of honey processing, 175ºC roasting temperature, and 15 minutes roasting time (Wulandari et al., 2021). This treatment resulted in high overall acceptance for the brewed aroma, brewed taste, brewed bitterness, ground fineness, and brewed viscosity; ground aroma, brewed acidity, and brewed sweetness were slightly less accepted (Wulandari et al., 2021).

The beverage´s astringent and musty taste and bitterness are due to the concentration of chlorogenic acid, and the proportions of several compounds present in the raw coffee bean; the presence of these acids indicates low product quality (Silva et al., 2022). Light-roasted coffees that emphasize the delightful acidity of a cup of coffee have flavours of citrus, fruit, and flowers (lime, tangerine, orange, raspberry). Dark-roasted coffees are associated with tasting notes of chocolate, caramelized sugars, almonds, smoke, malt, and molasses. Off-flavours like onion taste and butyric and propionic acids adversely affect the quality of coffee beans (Haile and Kang, 2019; Santosa et al., 2021).

The effect of full black, floater, broken, and insect damage defects on coffee cup quality is related to microbial growth, which gives coffee a stinky, dirty,

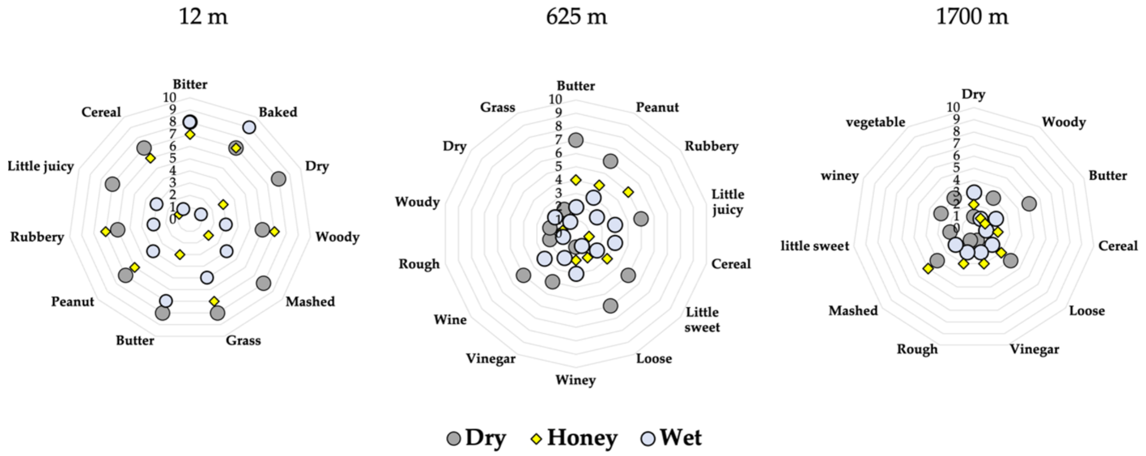

Fig. 4. Average scores for negative tasting notes on a scale from 1 to 10 for Robusta coffee cultivated at different altitudes

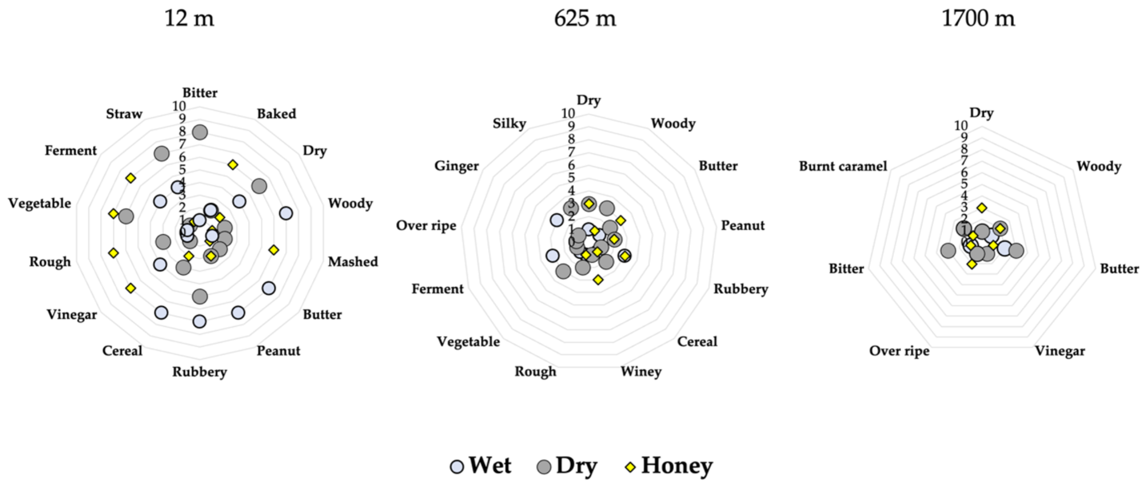

Fig. 5. Average scores for negative tasting notes on a scale from 1 to 10 for Conilon coffee cultivated at different altitudes

mouldy, sour, and phenolic flavour (Franca et al., 2005). Fungus damage affects cup quality by delivering a fermented, mouldy, earthy, dirty, and phenolic flavour (SCA, 2022).

Figures 6 and 7 present the average scores assigned to positive tasting notes, rated on a scale from 1 to 10, for Robusta and Conilon coffee. Notably, the data reveals a greater abundance of positive tasting notes for coffee grown at higher elevations. It is important to highlight that this altitude-driven distinction proved to be more influential than the effects of different processing conditions. In this context, the current findings diverge from those of other studies that claim various post-harvest and processing treatments have an impact on the sensory quality of ground and brewed coffee (Wulandari et al., 2021).

A numerical scoring system, ranging from 1 to 10, quantifies sensory descriptions, enabling easy comparative analysis. Calculating the percentages of positive and negative notes succinctly presents flavor trends for

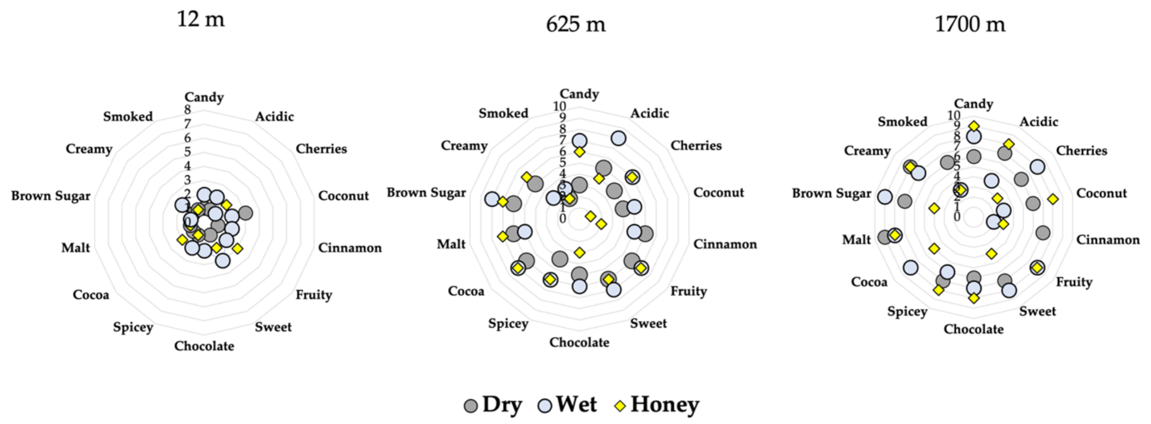

Fig. 6. Average scores for positive tasting notes on a scale from 1 to 10 for Robusta coffee cultivated at different altitudes

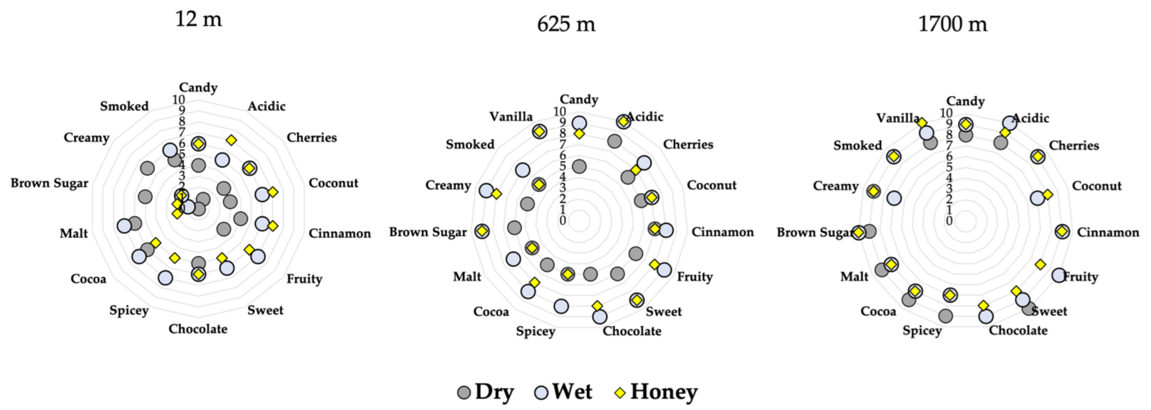

Fig. 7. Average scores for positive tasting notes on a scale from 1 to 10 for Conilon coffee cultivated at different altitudes

coffee species and altitudes, providing an overview of dominant taste traits. In this context, the study revealed that beans from low altitudes exhibited the most pronounced effects related to defects in coffee tasting notes. Altitude notably influenced the organoleptic qualities of robusta coffees more than processing conditions. No significant difference emerged between the the effect of processing method on coffee cup quality for Conilon and the same effect for Robusta. Defects such as full black, floater, broken, insect damage, and fungus damage detrimentally affected cup quality by introducing unpleasant flavors. Varied roasting levels were correlated with distinct tasting notes, spanning from citrus and fruit to chocolate and caramelized sugars.

CONCLUSION

This study investigated the impact of altitude and post-harvest processing methods on bean size, defects, and final cup quality in canephora coffee. The study found that higher altitudes correlated with larger beans, and that processing methods and altitude significantly affected bean screen retention for both coffee varieties. Among both Conilon and Robusta coffees processed using all three post-harvest processes methods, it was observed that the honey and wet processing methods had a more significant impact on the quality of the coffee when cultivated at higher altitudes. Screen retention was significantly affected by post-harvest processing and elevation. However, at altitudes up to 1,700 meters, the screen sizes were not statistically different for the three post-harvest processes, especially for the Congolensis samples. Large coffee beans are generally considered to be of higher quality, but this is not always the case. The findings of this study are aligned with previous research on other coffee varieties, which often produce smaller beans associated with reduced cup quality. To manage the quality and safety of coffee, international guidelines have been developed for the application of good manufacturing practices throughout the entire production and distribution chains, along with criteria for certification and traceability. This work provides insights into the complexities of Robusta coffee production and highlights the need for careful consideration of pre- and post-harvest processing factors in order to produce high-quality coffee.

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Discusión

En el presente estudio, los resultados mostraron que el sabor, la dulzura y el aroma del café Robusta (Congolensis) mejoraron a partir de los 80 metros sobre el nivel del mar; sin embargo, no así el sabor residual (after-taste) o la acidez (Velásquez et al, 2022). El café robusta cultivado a menos de 800 metros presenta alta amargura, astringencia, fuerza, cuerpo, sabor herbáceo y bajo valor aromático (Schwan y Fleet, 2014; Folmer, 2017; Louzada y Rizzo, 2021; Worku et al., 2018; Gebrekidan et al., 2019; Zakidou et al., 2021). De acuerdo con los presentes resultados, tanto para Robusta (Congolensis) como para Conilón, la acidez fue un atributo con los puntajes más bajos hasta 7.0 puntos. A 800 metros, es factible que la alta humedad conduzca a la fermentación y, por lo tanto, es más probable que la fragancia/aroma y el sabor se reduzcan. En general, el puntaje general de los dos grupos genéticos de café en altitudes más altas superó los 80 puntos, lo que indica que pertenecen al grado de especialidad. En zonas geográficas más altas, la dulzura, el sabor más suave y la calidad de la taza de robusta aumentan (Figueiredo, Borém, Ribeiro, Giomo, y Malta, 2018). Caramelo, azúcar moreno, afrutado, almendra, albaricoque, dulce, coco y afrutado son las características de sabor que fueron más frecuentes (Ferreira et al., 2021).

El aumento en los atributos sensoriales está relacionado con el lento crecimiento de la planta de café y un mayor índice de precipitación. Debido a la tasa de maduración más lenta en elevaciones más altas, los fotoasimilados (sacarosa, polioles y aminoácidos), que están asociados con un aroma sabroso, se acumulan en mayores concentraciones en las hojas y frutos del cafeto (Bastian et al., 2021; Sunarharum, Williams, y Smyth, 2014; Velásquez et al, 2021). Un proceso de maduración más lento permite más efectos en una mayor producción de compuestos fenólicos y granos aromatizados más intensos que los cultivados en áreas más bajas o bajo plena luz solar (Avelino et al, 2007; Joët et al., 2010).

El método de procesamiento en seco da como resultado una taza de café con menos aroma pero un cuerpo robusto, influenciado por la variabilidad de las condiciones climáticas, lo que a su vez provoca inconsistencias en el proceso de secado (Banti y Abraham, 2021; Firdissa et al, 2022).

Según los resultados de la presente investigación, los procesos secos sí permiten la producción de café de especialidad, con muestras de café de ambos grupos genéticos Robusta (Congolensis) y Conilón, tomadas de altitudes por encima de 625 metros. Durante el proceso de secado, los granos de café siguen siendo viables con actividades metabólicas para producir una amplia variedad de aminoácidos libres a partir de proteínas y azúcares de bajo peso molecular (es decir, glucosa, fructosa y manosa); sin embargo, el proceso de germinación se inhibe básicamente por el proceso de secado (Joët et al., 2010; de Melo Pereira et al., 2019).

En el marco de esta investigación, se concluyó que los granos de café de los grupos genéticos analizados aumentan significativamente en tamaño a medida que se incrementa la altitud. Este incremento en el tamaño de los granos se atribuye al hecho de que las plantas de café tienen un mayor período de maduración a zonas geográficas elevadas. Dado que los granos de mayor tamaño suelen ofrecer un sabor superior, los cafés cultivados a mayor altitud son generalmente considerados de mayor calidad. Adicionalmente, el presente estudio revela que el método de procesamiento post-cosecha ejerce un impacto significativo en el tamaño de los granos (Velásquez y Banchón, 2022). Como se corrobora en otros estudios, los granos de café procesados mediante el método húmedo tienden a ser más grandes que aquellos procesados por el método seco (Luna González, Macías Lopez, Taboada Gaytán, y Morales Ramos, 2019). Además, se observaron diferencias notables en la calidad de la taza de café entre las variedades Conilón y Robusta.

Los granos de café de mayor tamaño tienden a ofrecer un sabor más refinado, con notas de dulzura y acidez destacadas, mientras que los granos más pequeños tienden a mostrar perfiles de sabor más amargos y herbáceos (Papadopoulos, 2008; Hoffman, 2018; Luna González et al., 2019). En consecuencia, los granos de café uniformes suelen ser preferidos por los consumidores.

Los patógenos tienen un impacto directo en la producción de café, así como en la calidad de la taza. La Roya del Cafeto (Coffee Leaf Rust en idioma Inglés) es causada por el hongo Hemileia vastatrix (Hv), y es una enfermedad devastadora que conduce a una defoliación de hasta el 50% y pérdidas de rendimiento de hasta el 50%, específicamente más en C. arabica en lugar de Robusta (Salcedo-Sarmiento et al., 2021; Documet et al, 2022). El Hv contribuye a la degradación de los azúcares en los granos, lo que afecta la calidad de la taza, tornando la bebida en un sabor leñoso, herbáceo y terroso.

Conclusiones

- Los resultados obtenidos permiten establecer que existen una relación directa entre la altitud de cosecha del café Robusta y los métodos post-cosecha de beneficio por vía húmeda, semihúmedo honey y por vía seca; estos factores tienen un efecto significativo sobre la calidad física del grano y organoléptica de la bebida de café Robusta.
- El café Arábica sembrado a más de 1000 metros sobre el nivel del mar tiene mejores características aromáticas, bajo amargor, buena acidez y cuerpo; mientras que el café Robusta sembrado a menos de 800 metros sobre el nivel del mar tiene alto amargor, sabor herbáceo, bajo valor aromático y astringencia.
- La posición geográfica del cultivo y los procesos post-cosecha influyeron en la degustación del café. La altitud fue el elemento clave que influyó en la calidad sensorial del café. Robusta (Congolensis) y Conilón recibieron puntajes promedio altos para fragancia/aroma, sabor residual, sal/acidez, equilibrio amargo/dulce, cuerpo, equilibrio y general. El procesamiento honey produjo las calificaciones más altas de fragancia/aroma, sabor residual, sal/acidez, amargo/dulce, cuerpo, equilibrio y general para todas las muestras de Robusta (Congolensis) y Conilón de muestras tomadas de variadas altitudes.

- Se evaluó el efecto de que los métodos de procesamiento para influir en los atributos físicos y organolépticos de los cafés robusta. No hubo diferencia significativa entre Conilón y Robusta (Congolensis) en la contribución a la calidad física y de taza del café. No hubo diferencia significativa entre Conilón y Robusta (Congolensis) en la contribución a la calidad física y de taza del café.
- Las muestras de Conilón superó a Robusta (Congolensis) en todas las calidades organolépticas utilizando los procesamientos secos, honey y húmedo. A una altitud de 12-40 m, las muestras de Robusta (Congolensis) tuvieron los valores más bajos de fragancia/aroma y sabor. Las tazas de café preparadas con granos provenientes de mayor altitud tienen la mayor calidad olfativa. Las muestras de Robusta (Congolensis) y Conilón procesadas en húmedo tienen un carácter más sabroso que las muestras procesadas en seco. El procesamiento en seco da como resultado un café fuerte, mientras que el procesamiento húmedo da como resultado un café de mejor calidad con menos cuerpo, mayor acidez y más aroma que el procesamiento seco.
- El presente estudio sugiere que cualquier cultivar Robusta tiene el potencial de producir café de alta calidad; sin embargo, los perfiles de sabor variarán dependiendo de las condiciones de crecimiento.
- Los procesos húmedos producen bebidas con más sabor y acidez, pero con menos cuerpo que las muestras del método de procesamiento seco.
- La modulación del aroma y sabor del café mediante el tueste es un desafío para las tendencias futuras. Para ello, se requiere un conocimiento profundo del proceso de tostado.
- El café Robusta ganaría más participación en el mercado en términos de controlados procesos de post-cosecha. Por tanto, cualquier cambio novedoso en estos procesos afectaría positivamente las características sensoriales. En este sentido, la industria del café debería ofrecer más productos en términos de amargor u otros perfiles sensoriales porque la

percepción de un sabor amargo juega un papel clave en la preferencia del consumidor. Por lo tanto, comprender el impacto de los parámetros de procesamiento en la química del café traerá nuevos escenarios al mercado.

- Las muestras de café obtenidas de altitudes de hasta 625 metros y procesadas con tres procesos post-cosecha tuvieron mejores puntajes de calidad en términos de tamaño del grano y notas de catación.
- Para gestionar la calidad y seguridad del café, se han desarrollado directrices internacionales para la aplicación de buenas prácticas de fabricación a lo largo de todas las cadenas de producción y distribución, junto con criterios de certificación y trazabilidad.

Conclusions

- The findings support the conclusion that the harvest altitude of Robusta coffee is directly correlated with the post-harvest methods, including wet, semi-wet honey, and dry processing. These variables exert a notable influence on both the physical attributes and organoleptic qualities of the resulting Robusta coffee beverage.
- Arabica coffee planted at more than 1000 meters above sea level has better aromatic characteristics, low bitterness, good acidity and body; while Robusta coffee planted at less than 800 meters above sea level has high bitterness, herbaceous flavor, low aromatic value and astringency.
- The geographical position of the crop and the post-harvest processes influenced the cupping of the coffee. Altitude was the key element influencing the sensory quality of the coffee. Robusta (Congolensis) and Conilon received high average scores for fragrance/aroma, residual flavor, salt/sweetness, bitter/sweet balance, body, balance and overall. Honey processing produced the highest scores for fragrance/aroma, residual flavor, salt/sourness, bitter/sweet, body, balance, and overall for all Robusta (Congolensis) and Conilon samples from samples taken from varied altitudes.
- The effect of altitude and processing methods on the physical qualities of Robusta (Congolensis) and Conilón coffee samples was evaluated. It was determined that altitude was more influential than processing methods in influencing the physical and organoleptic attributes of Robusta coffees. There was no significant difference between Conilon and Robusta (Congolensis) in the contribution to physical and cup quality of coffee. There was no significant difference between Conilon and Robusta (Congolensis) in the contribution to the physical and cup quality of coffee.
- Conilon samples outperformed Robusta (Congolensis) in all organoleptic

qualities using dry, honey and wet processing. At an altitude of 12-40 m, Robusta (Congolensis) samples had the lowest fragrance/aroma and flavor values. Cups of coffee prepared with beans from higher altitudes had the highest olfactory quality. Wet-processed Robusta (Congolensis) and Conilon samples have a more flavorful character than dry-processed samples. Dry processing results in a strong coffee, while wet processing results in a better quality coffee with less body, higher acidity and more aroma than dry processing.

- The present study suggests that any Robusta cultivar has the potential to produce high quality coffee; however, flavor profiles will vary depending on growing conditions.
- Wet processing produces beverages with more flavor and acidity, but with less body than samples from the dry processing method.
- The nuanced modulation of coffee aroma and flavor during roasting poses a challenge for future trends in the industry. Meeting this challenge necessitates a profound understanding of the roasting process.
- Robusta coffee would gain more market share in terms of controlled post-harvest processes. Therefore, any novel change in these processes would positively affect the sensory characteristics. In this sense, the coffee industry should offer more products in terms of bitterness or other sensory profiles because the perception of a bitter taste plays a key role in consumer preference. Therefore, understanding the impact of processing parameters on coffee chemistry will bring new scenarios to the market.
- Coffee samples obtained from altitudes of up to 625 meters and processed with three post-harvest processes had better quality scores in terms of bean size and cupping notes.
- To manage the quality and safety of coffee, international guidelines have been developed for the application of good manufacturing practices throughout the production and distribution chains, together with certification and traceability criteria.

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