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REVIEW ARTICLE

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

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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

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

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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:

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

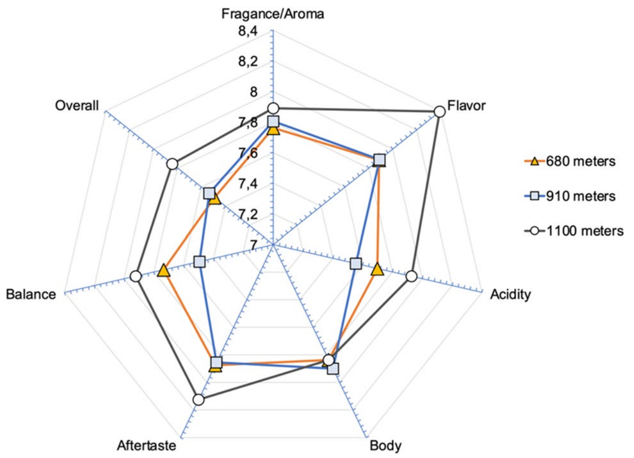

Fig. 1 Sensory analysis of Arabica coffee harvested at different altitudes from Brazil. Adapted from Barbosa et al. 2020

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)

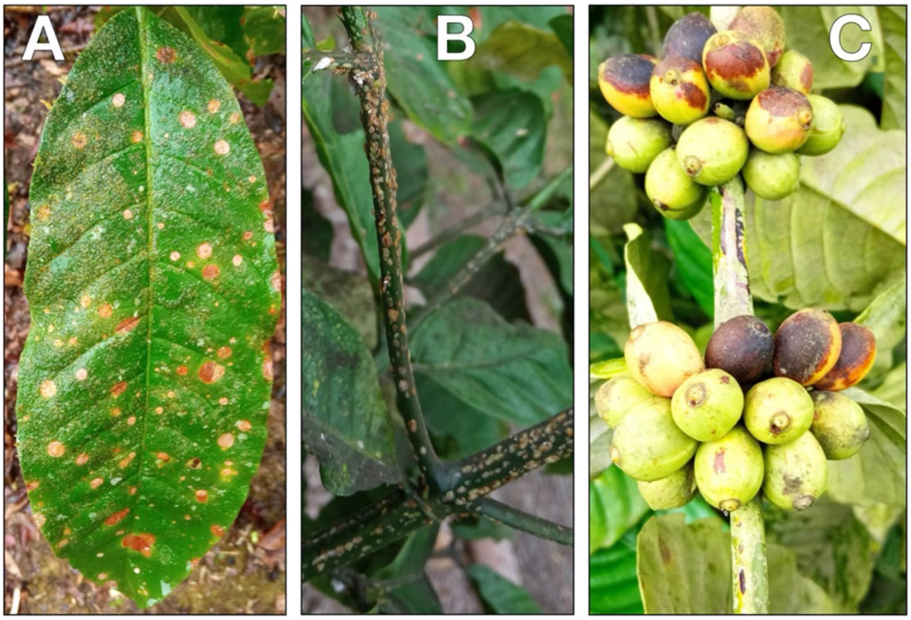

Fig. 2 Robusta coffee plant pathogens from Ecuadorian crops: **A** Leaf spots produced by *Mycena citricolor*; **B** the coffee green scale *Coccus viridis*; **C** fungal plant pathogen *Mycosphaerella coffeicola*

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

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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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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