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Grind Particle Size Modulates Pyrazine Profile, Bioactive Content, and Sensory Quality of Filter Coffee

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Abstract

Filter coffee, prepared by percolation of hot water through ground coffee, is among the most widely consumed brewing methods globally. Despite considerable research on the chemical and sensory properties of various coffee types, the specific influence of grind particle size on filter coffee quality remains poorly characterized. This study investigated the effects of three grind settings on the aroma profile, total phenolic content, antioxidant activity, and sensory properties of filter coffee prepared from 100% Ethiopian Arabica (*Coffea arabica*) beans of the Yirgacheffe origin, roasted at 210°C. Grind particle sizes, verified by laser diffraction analysis, were determined as 1740 µm (medium-fine), 2250 µm (medium), and 2340 µm (medium-coarse). Gas chromatography mass spectrometry (GC-MS) analysis revealed that pyrazine compounds were most abundant in the medium-fine fraction (1740 µm), indicating that finer particle size promotes greater extraction of Maillard-derived roast volatiles. Sensory evaluation showed that medium-fine ground coffee received the highest overall acceptability and aroma intensity scores among panelists. In contrast, medium-coarse ground coffee (2340 µm) yielded the highest total phenolic content and antioxidant capacity as assessed by DPPH and ABTS radical scavenging assays, suggesting preferential extraction of phenolic compounds at coarser particle sizes. Grind particle size was identified as a critical variable governing the chemical, visual, and organoleptic profile of filter coffee.

Keywords: *Filter coffee, grind particle size, Ethiopian Arabica, pyrazines, sensory evaluation*

1.INTRODUCTION

Coffee is one of the most widely consumed beverages worldwide and represents a major agricultural commodity with substantial economic and cultural importance. Originating from Ethiopia and subsequently spreading through the Arabian Peninsula and Europe, coffee has become an integral part of daily life across diverse societies. Global coffee consumption continues to increase daily, driven not only by its stimulating effects but also by consumers' growing appreciation of specialty coffees and differentiated brewing methods (International Coffee Organization, 2024). Among commercially traded coffee species, *Coffea arabica* accounts for approximately 60–70% of global production and is particularly valued for its complex aroma profile, balanced acidity, and desirable sensory characteristics (Farah, 2019).

The quality of a coffee beverage is determined by a combination of factors, including botanical origin, cultivation conditions, post-harvest processing, roasting degree, grinding conditions, and brewing method. During roasting, numerous chemical reactions occur, especially Maillard reactions, Strecker degradation, and caramelization, leading to the formation of hundreds of volatile compounds responsible for coffee aroma and flavor (Buffo & Cardelli-Freire, 2004; Toledo et al., 2016). Among these compounds, pyrazines, furans, aldehydes, ketones, and sulfur-containing molecules are considered key contributors to the characteristic roasted, nutty, caramel-like, and floral notes associated with coffee beverages (Mayer et al., 2000; Caporaso et al., 2018).

Filter coffee, prepared by passing hot water through ground coffee retained in a paper or metal filter, is among the most popular brewing techniques worldwide. Its popularity stems from its ease of preparation, relatively clean flavor profile, and ability to highlight the intrinsic sensory properties of coffee beans. Compared with espresso or Turkish coffee, filter coffee generally produces a beverage with lower suspended solids and a lighter body while preserving a wide range of aroma-active compounds (Caporaso et al., 2014). As consumer interest in specialty coffee continues to grow, optimization of brewing parameters has become increasingly important for both industry professionals and home brewers.

Among brewing variables, grind particle size plays a critical role in determining extraction efficiency and beverage quality. Particle size directly influences the available surface area of coffee grounds, thereby affecting mass transfer rates and the extraction of volatile and non-volatile compounds into the brew (Ren et al., 2024). Finer particles generally provide greater surface area and faster extraction kinetics, whereas coarser particles may result in slower extraction and altered chemical composition of the final beverage (Andueza et al., 2003; Ren et al., 2024). Consequently, grind size can influence not only aroma intensity and flavor perception but also phenolic composition, and antioxidant properties of coffee infusions.

Coffee is recognized as an important dietary source of bioactive compounds, particularly chlorogenic acids and other phenolic constituents, which contribute significantly to its antioxidant capacity (Vignoli et al., 2011). The extraction of these compounds is highly dependent on brewing conditions, including water temperature, contact time, and particle size distribution. Previous studies have demonstrated that modifications in grinding and brewing parameters can alter the concentration of antioxidants and volatile compounds in brewed coffee (Petracco, 2005; Cordoba et al., 2020). However, despite the extensive literature on coffee chemistry and brewing technologies, the specific effects of grind particle size on the combined aroma, physicochemical, antioxidant, and sensory characteristics of filter coffee remain insufficiently understood.

Therefore, the aim of the present study was to investigate the influence of three grind particle sizes on the quality characteristics of filter coffee prepared from Ethiopian Arabica beans originating from the Yirgacheffe region. The effects of particle size on volatile aroma composition, total phenolic content, antioxidant activity, and sensory properties were comprehensively evaluated. Understanding the relationship between grind size and coffee quality may provide valuable insights for optimizing brewing practices and improving consumer satisfaction.

2. MATERIAL and METHODS

2.1 Materials

In this study, 100% Ethiopian Arabica (*Coffea arabica*) coffee beans grown in the Yirgacheffe region of Ethiopia were used. Roasted coffee beans at 210°C were directly ground and used for further analysis without storage.

2.2 Grinding and Particle Size Analysis

Coffee grinding was performed using a Comandante C40 Nitro Blade manual grinder (Comandante GmbH, Germany), which is widely recognized in specialty coffee research and practice for its high grinding consistency and precision. The grinder is equipped with nitrogen-alloy–hardened stainless-steel burrs, which provide high mechanical stability and sharp cutting performance while minimizing heat generation during grinding. This is particularly important, as excessive heat during grinding can potentially alter the volatile composition of coffee and negatively affect aroma quality (Illy & Viani, 2005).

The Comandante C40 operates with a stepped adjustment system, allowing precise control of grind settings in 40 discrete click positions. This feature enables reproducible and homogeneous particle size distributions, making it suitable for experimental studies where extraction consistency is critical (Comandante GmbH, 2023). In the present study, three different grind settings were selected: 22 clicks (medium-fine), 28 clicks (medium), and 32 clicks (medium-coarse) (Figure 1).

22 28 32

Figure 1. *Comandante C40 Nitro Blade manual grinder and ground samples*

To verify the actual particle size distribution corresponding to each grind setting, a laser diffraction particle size analyzer was used. The laser diffraction measurement was performed on a Mastersizer 3000 (Malvern Instruments Ltd., Malvern, UK) (Xu et al., 2015). The analyzer is composed of an optical unit, a dispersion unit, and a measurement cell. The measurement range was 0.01–3500 µm. The device was operated by the selected predefined measurement sequence (CUMERLAB, Çukurova University, Türkiye).

2.3 Preparation of Filter Coffee Brews

In this study, the Pour Over technique was adopted as the filter coffee brewing method, and the experiments were carried out using a Hario V60 (Hario Co., Ltd., Tokyo, Japan) brewing apparatus. Before the brewing process, a paper filter (Hario V60 02, white) was moistened with purified water at 93°C and placed in the brewing funnel; this step both preheated the filter and removed any potential paper-related odors. 15.0 g of each coffee sample was weighed using a precision balance (±0.01 g) and transferred to the filter. Purified water heated to 93 ± 1°C was used as the brewing water; 230 ml of water was poured evenly and controllably over the coffee surface to perform the extraction. The total brewing process was completed in an average of 11 minutes, and the same protocol was applied in all experiments to ensure reproducibility. The resulting filter coffee samples were cooled to room temperature before the analyses began (Ayseli et al., 2021).

2.3 Analysis of Filter Coffee Brews

2.3.1 Extraction of Aroma Compounds

The aroma extraction method for coffee samples was the liquid-liquid extraction method proposed by Amanpour and Selli (2016). Dichloromethane, the most suitable solvent for separating volatile compounds from coffee, was used for the extraction of aroma compounds. 50 ml of the room-temperature coffee sample was added to a 500 ml Erlenmeyer flask, and 60 ml of dichloromethane and the internal standard (4-nonanol, 41.5 µg) were added. The mixture was shaken for 1 hour under nitrogen gas at 4°C. Following this, the mixture was centrifuged (Kubota, Osaka, Japan) for 15 minutes at 5500 rpm at 4°C. Impurities were removed from the samples by filtration using glass wool and sodium sulfate solution. The solution, transferred to a volatile flask, was heated in a 50°C hot water bath to remove the dichloromethane. The resulting aroma extract was transferred to small glass vials and directly injected into the GC-MS.

2.3.2 GC-FID and GC-MS Conditions

Quantitative identification and determination of aroma compounds were performed simultaneously on a “Shimadzu Nexis GC-2030” gas chromatograph and a connected “Shimadzu GC-MS-QP2020 NX” mass spectrometer. In this system, the column output is equally divided into three parts using a special separator (Dean switch-Agilent), with the first part going to FID and the second part to MSD. Thus, the sensitivity of the analysis is increased by performing the quantitative determination and identification process simultaneously. Separation of aroma compounds was performed using a DB-WAX capillary column (30 m x 0.25 mm x 0.5µm). The instrument was programmed to maintain a constant temperature of 220 °C (injector), 250 °C (detector), and 60 °C (column) for 20 minutes, then increasing by 2 °C per minute to 220 °C, and subsequently by 3 °C per minute to 245 °C. The sample injected was 2 µL. Helium was used as the carrier gas. The helium flow rate was 1.5 ml/min, and the detector and injector temperatures were 250 °C. The mass spectrometer was set at an ionization energy of 70 eV, an ion source temperature of 250 °C, and a quadrupole temperature of 120 °C, with scans performed at 1-second intervals between 29-350 mass/charge (m/e). Peak identification was performed by injecting a standard solution for compounds with a standard and comparing the mass spectra of non-standard compounds with mass spectra from aroma compounds libraries (Wiley 7.0, NIST-98, and Flavor, 2L) in computer memory. Each analysis was performed in triplicate (Dagli et al., 2022).

2.3.3 Total Phenolic Content

The total phenolic content (TPC) of the coffee samples was determined according to the method of Guclu and Selli (2022). 1 mL of each coffee extract was mixed with 60 mL of pure water, 5 mL of Folin-Ciocalteu solution, and 15 mL of sodium carbonate solution and left to stand at room temperature for 2 hours. Then, the samples were measured at a wavelength of 765 nm using a UV-Vis spectrophotometer (Agilent Technologies, Santa Clara, California, USA). The amount of phenolic compound, was calculated from the standard curve equation prepared with gallic acid. TPC values were determined in mg gallic acid equivalent (GAE)/L.

2.3.4 Antioxidant Activity Analyses

Antioxidant activity values of the samples were determined by two different methods: DPPH and ABTS. The DPPH (2,2-diphenyl-1-picrylhydrazyl) value, which represents the ability to inhibit free radicals, was determined by measuring the change in the reaction over time in methanol at a wavelength of 515 nm using a UV-vis spectrophotometer (Guclu and Selli, 2022). For the ABTS method, 7 mM ABTS (2,2′-azino-bis-(3-ethyl-benzothiazoline-6-sulfonic acid) (Sigma Aldrich, Poole, UK)) was mixed with 2.45 mM potassium bisulfate and incubated in the dark for 12-16 hours. The solution was then diluted with 80% methyl alcohol and an absorbance of 0.70 ± 0.01 was obtained at 734 nm using a UV-Vis spectrophotometer (Kelebek et al., 2020). Subsequently, the extract was mixed with 0.1 mL of buffer solution, and the absorbance value was measured at 734 nm after 30 minutes using a spectrophotometer (Kelebek et al., 2020). Absorbance values were calculated based on Trolox equivalent (TE) standard calibration graphs and the results are expressed in µmol TE/L.

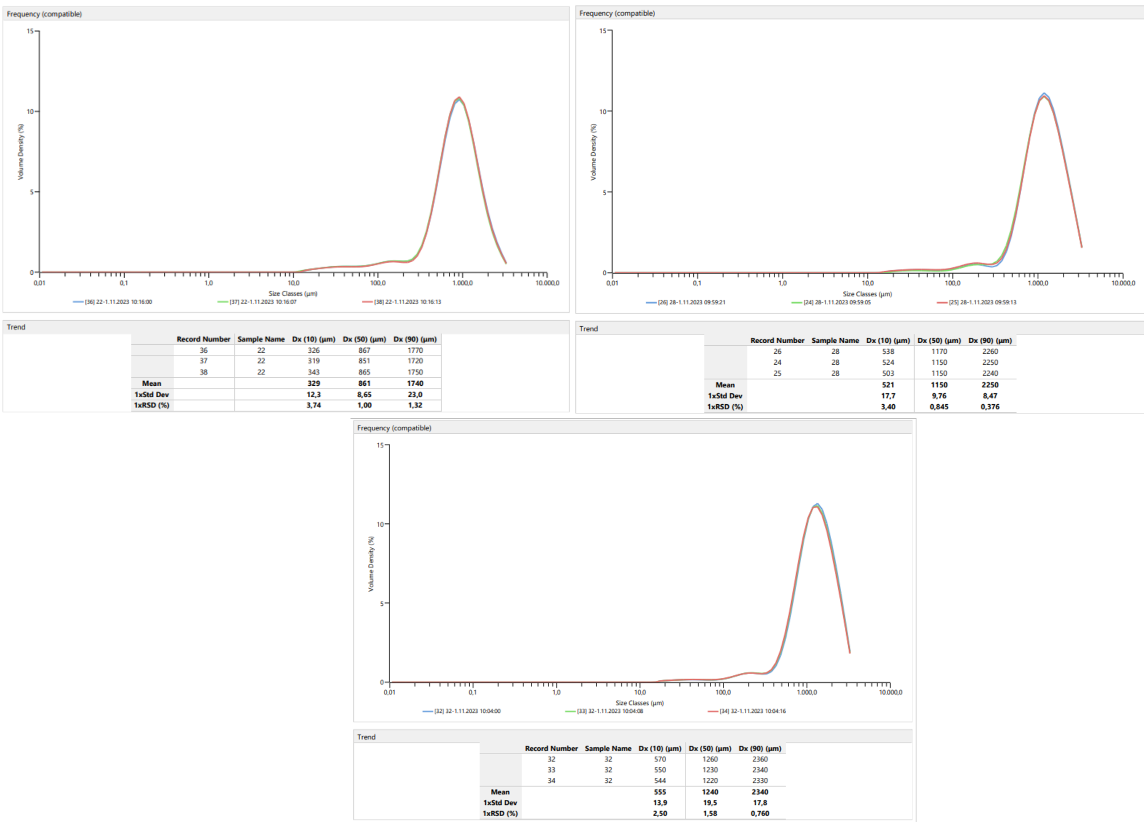
2.3.5 Sensory Analyses

Descriptive sensory analysis was applied to the sensory evaluation of coffee samples. A 100 mm flat scale was used for each predetermined characteristic, and the sensory analysis was evaluated by an experienced panel of 10 people (6 women, 4 men, ages 25-56) according to predetermined taste and aroma criteria (Altuğ and Elmacı, 2005). During the analysis, coffee samples were presented to the panelists in turn, and they were asked to score the samples on a 100 mm scale according to various characteristics of the samples. Statistical analysis was performed using one-way analysis of variance (ANOVA), followed by Duncan's multiple range test to determine significant differences among the means. Differences were considered statistically significant at $p < 0.05$.

3. RESULT and DISCUSSION

3.1 Particle Sizes of Ground Filter Coffee

In this study, coffee grinding was performed using a Comandante C40 Nitro Blade hand grinder (Comandante GmbH, Germany). This grinder is characterized by its nitrogen alloy reinforced stainless steel blades and 40-step precision adjustment system, which allows for a repeatable and homogeneous particle size distribution. The nitrogen alloy blade structure minimizes excessive heat generation and blade wear during grinding, preventing thermal degradation of coffee compounds; thus, preserving the chemical integrity of the bean. In the filter coffee brewing experiments, grinding was applied at 22, 28 and 32 click settings. The particle size distributions for the grinding settings were analyzed using laser diffraction and the resulting frequency distribution curves are presented in Figure 2. According to the analysis results, the average particle size was determined as 1740 µm at 22 click setting, 2250 µm at 28 click setting and 2340 µm at 32 click setting. When Figure 2 is examined, it is seen that the distribution curves exhibit a unimode and relatively symmetrical structure in all three grinding settings. It is noteworthy that as the number of clicks increases, the peak of the curve shifts to higher particle size values, and the peak width increases in parallel. This indicates that the particle population is spread over a wider size range in coarse grinding settings, which is consistent with the typical distribution patterns reported in filter coffee brewing methods. In the literature, the appropriate particle size range for filter coffee is generally defined as 500–1400 µm (Illy & Viani, 2005); however, it is reported that larger particle sizes are also successfully used in gravity-based techniques such as Pour Over and V60. Cordoba et al. (2020) showed that particle sizes in the range of 800–1600 µm have a decisive effect on extraction efficiency in filter coffees prepared with the V60 method, and that the total soluble solids concentration (TDS) decreases as the size increases. The fact that the particle size values obtained in the present study are above this range can be attributed to the use of a long brewing time of 11 minutes; since larger particles exhibit slow extraction kinetics, long contact times are required to ensure sufficient extraction efficiency (Andueza et al., 2003).



	Record Number	Sample Name	Dx (10) (µm)	Dx (50) (µm)	Dx (90) (µm)
	36	22	326	867	1770
	37	22	319	851	1720
	38	22	343	865	1750
Mean			**329**	**861**	**1740**
1xStd Dev			**12,3**	**8,65**	**23,0**
1xRSD (%)			**3,74**	**1,00**	**1,32**

	Record Number	Sample Name	Dx (10) (µm)	Dx (50) (µm)	Dx (90) (µm)
	26	28	538	1170	2260
	24	28	524	1150	2250
	25	28	503	1150	2240
Mean			**521**	**1150**	**2250**
1xStd Dev			**17,7**	**9,76**	**8,47**
1xRSD (%)			**3,40**	**0,845**	**0,376**

	Record Number	Sample Name	Dx (10) (µm)	Dx (50) (µm)	Dx (90) (µm)
	32	32	570	1260	2360
	33	32	550	1230	2340
	34	32	544	1220	2330
Mean			**555**	**1240**	**2340**
1xStd Dev			**13,9**	**19,5**	**17,8**
1xRSD (%)			**2,50**	**1,58**	**0,760**

Figure 2. *Particle size distribution of filter coffee samples*

Uman et al. (2016) emphasized that the type of grinding mill and blade geometry play a decisive role in the homogeneity of particle size distribution. They reported that conical blade mills offer a narrower and more repeatable distribution profile compared to planer blade models. In this context, the conical blade structure of the Comandante C40 used in the study may have contributed to the formation of the relatively symmetrical and unimode distribution curves observed in Figure 2. On the other hand, Gloess et al. (2013) comparatively examined the effect of blade quality and heat transfer on particle morphology in coffee samples prepared with different grinders; they confirmed the contribution of blade hardness to homogeneous cutting. Particle size is known to be more than just a physical parameter; it is a fundamental variable that directly determines the chemical composition, aroma profile, and bioactive compound content of coffee (Angeloni et al., 2023). Therefore, evaluating particle size data obtained by laser diffraction together with the findings on total phenolic compound content, antioxidant capacity, and volatile compound profile presented in the following sections is critically important for understanding the integrated effect of grinding conditions on filter coffee quality.

3.2 Total Phenolic Content and Antioxidant Activity of Filter Coffee

Coffee contains a wide range of bioactive compounds, primarily phenolic acids, tocopherols, melanoidins, and caffeine, which are key determinants of the beverage's high antioxidant capacity (Nicoli et al., 1997; Alves et al., 2010). Maillard reactions and caramelization processes during roasting also contribute to the formation of new bioactive structures that enhance this capacity. These antioxidant components are extensively investigated for their potential impact on human health due to their ability to reduce oxidative damage caused by free radicals. In this study, the antioxidant capacity of filter coffee samples ground at different particle sizes was determined using the DPPH and ABTS methods, while the total phenolic compound (TPC) content was determined using the Folin-Ciocalteu method. DPPH analysis was performed at 515 nm and ABTS analysis at 734 nm using a UV-Vis spectrophotometer (Shimadzu UV-1201, Kyoto, Japan) (Ludwig et al., 2012; Cheong et al., 2013).

According to the results obtained, the DPPH radical scavenging capacity was determined as 3704; 4342 and 13449 μmol TE/L at 22, 28 and 32 click grinding settings, respectively. The antioxidant capacity values measured by the ABTS method were determined as 5750; 6565 and 13972 μmol Trolox/L for the same grinding settings, respectively. TPC content was measured as 936, 1898, and 2665 mg GAE/L at 22, 28, and 32 click settings, respectively, and a parallel increase was observed in both antioxidant parameters (Figure 3).

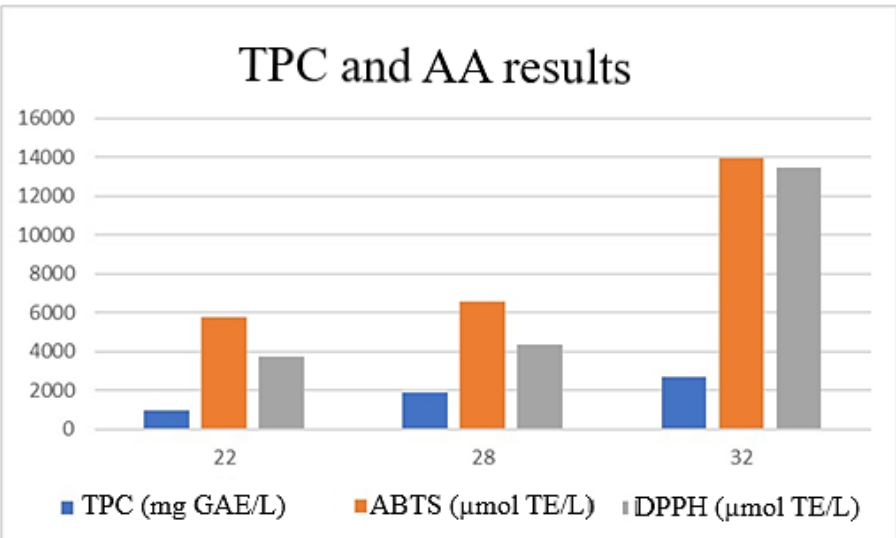


***Figure 3**. Total phenolic and antioxidant activity results of filter coffee brewed with different particle sizes*

The increase observed in TPC content and antioxidant capacity with increasing particle size can be explained by the extraction dynamics in the brewing process. In finely ground coffee (22 clicks), the high surface area significantly restricts the water flow rate; this limits the passage of compounds through the filtrate due to excessive extraction and flow resistance. In contrast, with a larger particle size (32 clicks), the more regular and faster passage of water through the coffee bed facilitates the effective transport of phenolic compounds and antioxidant structures to the filtrate. Compared to the literature, the antioxidant capacity values obtained in this study are higher than those in previous studies. Daniel and Workneh (2017) determined the antioxidant capacity of Yirgacheffe coffee extract as 0.791 µmol Trolox/L and the TFC content as 80.51 mg GAE/g using the ABTS method. Niseteo et al. (2012) reported ABTS values of 9.24–14.23 and 49.34 mmol Trolox/L in espresso and instant coffee, respectively; Ludwig et al. (2012) determined a value of 102.9 µmol Trolox/g in filter coffee. Hečimović et al. (2011) found the ABTS capacity of 15.64 mmol Trolox/L in medium roast coffee; they reported that the antioxidant capacity increased with increasing roasting degree from light roast to medium roast, and tended to decrease in dark roast. Lu et al. (2023) determined the TFC content in Arabica coffee as 83.09 mg GAE/g. The high values obtained in the present study can be attributed to the combined effect of the Yirgacheffe origin of the beans used, the post-harvest processing method applied, the roasting degree, and the grinding conditions.

3.3 Pyrazine Content of Filter Coffee

In this study, volatile aroma compounds of filter coffee samples ground at different particle sizes were extracted using the purge and trap method and then analyzed by gas chromatography-mass spectrometry (GC-MS) (Sides et al., 2000; Czerny et al., 2008). Examining the analysis results, it is seen that pyrazines are the compound group that contributes most significantly to the aroma profile of filter coffee samples in all three grinding settings. The distribution of pyrazine compounds according to grinding setting is presented in Figure 4. Pyrazines are heterocyclic nitrogenous compounds that are directly associated with roasted, nutty, peanut, and earthy aromas in coffee (Semmelroch & Grosch, 1996; Sanz et al., 2002). These compounds are mainly formed through the pyrolysis of hydroxyamino acids and the condensation of reducing sugars with amino acids in the Maillard reaction process; It can also be naturally synthesized as a secondary compound in fermented foods and some vegetables. More than 80 pyrazine derivatives have been identified in roasted coffee so far, among which 2-methylpyrazine, 2,3-dimethylpyrazine, 2,5-dimethylpyrazine, 2-ethylpyrazine and 2-ethyl-3-methylpyrazine are among the most frequently reported compounds (Buchbauer et al., 2000).

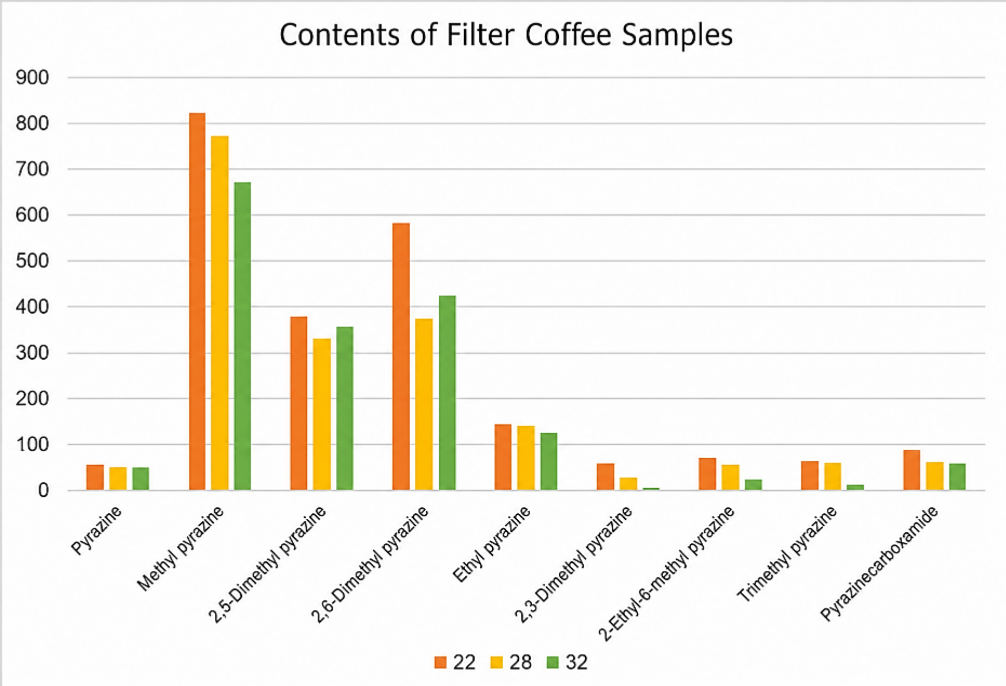


Figure 4. *Pyrazine contents of samples*

As shown in Figure 4, the total concentration of pyrazine compounds was found to be significantly higher at the finest grinding setting of 22 clicks; as the number of clicks increased, i.e., as the particle size increased, a systematic decrease in pyrazine content was observed. This finding indicates that fine grinding facilitates the transfer of volatile compounds to the extract phase through the increased surface area. Indeed, as particle size decreases, the greater breakdown of cellular structures accelerates the release of volatile compounds stored in the vacuole and intracellular matrix, increasing the contact surface with the brewing water and thus improving extraction efficiency (Andueza et al., 2003; Baggenstoss et al., 2008). However, brewing time is also thought to have an independent effect on pyrazine content; long contact times can lead to partial degradation of thermally unstable pyrazine derivatives. These findings are generally consistent with previous studies. Andueza et al. (2003), in their study comparing coffee samples prepared at different grind levels, showed that the concentration of pyrazine compounds increased significantly at the finest grind level and that these compounds directly contributed to the formation of nutty and caramel-like aromas in coffee. Ayseli et al. (2021), in their study examining the aroma compounds of coffee samples at different roasting levels, emphasized that pyrazines are the most effective group of compounds on coffee aroma and that the intensity of the heat treatment applied plays a decisive role in the formation of these compounds. Petisca et al. (2013), in their analysis performed using solid-phase microextraction technique, identified 105 volatile compounds in ground coffee beans; they reported that pyrazine and ketone compounds stood out as the dominant group. Ho et al. (2013) detected furfural, pyrrole, benzaldehyde, furfuryl alcohol, pyrazine, acetic acid, and 2,3-dimethylpyrazine as aroma-active compounds in brewed coffee. This trend is also confirmed in more recent studies; Caporaso et al. (2018), in their studies comparing different brewing methods, determined that pyrazines are among the compounds with the highest odor activity (OAV) value in filter coffee.

Consequently, the findings from this study reveal that the grind particle size has a statistically significant effect on the amount of pyrazine compounds transferred to the filter coffee extract, consistent with existing data in the literature. Given the low detection thresholds of pyrazines, for example, approximately 60 µg/L for 2-methylpyrazine and 0.09 µg/L for 2-ethyl-3-methylpyrazine (Flament, 2001), it is considered that even small concentration differences in these compounds can significantly alter the aroma intensity perceived by the consumer.

3.4 Sensory Characteristics of Filter Coffee

The sensory quality of coffee is among the most critical factors determining consumer preferences, and objectively evaluating this quality requires the application of structured sensory analysis methods. In this study, the sensory characteristics of filter coffee samples ground at different particle sizes were determined using a flavor profile test. The flavor profile test is a sensory evaluation method widely accepted in the food science literature, applied by trained panelists within the framework of predefined reference criteria (Meilgaard et al., 2001). The evaluations were carried out by a group of 10 trained panelists on 100 mm linear scales; each sample was examined within two separate profiles, independently of each other, in terms of flavor and aroma characteristics.

In the flavor profile evaluation, coffee samples were evaluated using a 10-point scale based on nine criteria: color/appearance, full-bodied taste, aroma, sourness, metallic taste, bitterness, sweetness, persistence, and overall impression/liking. The results are presented in radar diagram format in Figure 5. When the radar diagram is examined (Figure 5), it is seen that coffee samples ground at 22 and 28 click settings received similar scores in the vast majority of criteria; however, the sample ground at 32 click settings exhibited significantly lower scores in terms of negative sensory characteristics such as sourness, metallic taste, and bitterness. This finding indicates that the large particle size limits the extraction of undesirable taste components and contributes to obtaining a cleaner sensory profile. Indeed, the effect of grinding particle size on the perception of sourness and bitterness of coffee has been reported before; it has been shown that organic acids and chlorogenic acid degradation products pass into the extract phase at a higher rate in fine grinding (Cordoba et al., 2020; Gloess et al., 2013).

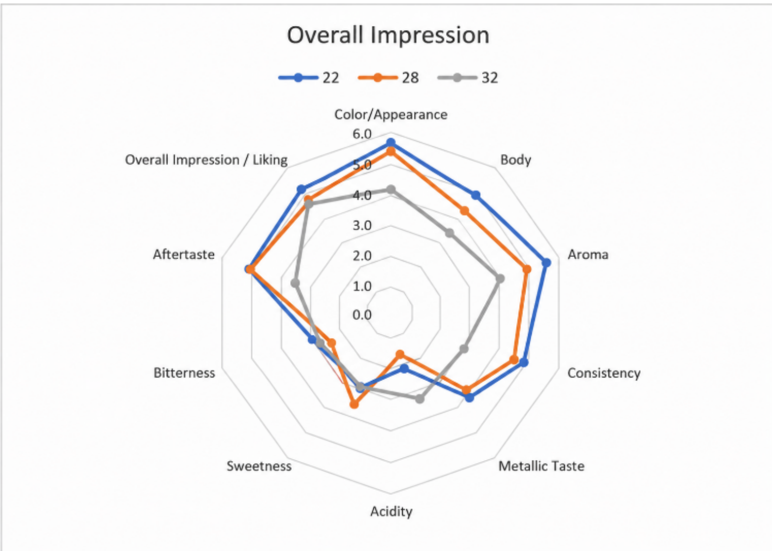


Figure 5. *Overall impression on filter coffee samples with different grinding sizes*

When evaluated in terms of the general impression/liking criterion, it was determined that the filter coffee sample ground at 22 click settings received a statistically significantly higher score compared to the other samples ($p < 0.05$). This result can be explained by the fact that fine grinding positively affects aroma intensity and body through increased extraction efficiency. Similar findings have been reported in the literature by Andueza et al. (2003); the researchers emphasized that coffees obtained with smaller particle sizes had higher overall liking scores, but this effect could turn into overextraction beyond a certain threshold. In the present study, the 22-click setting appears to have provided optimum aroma intensity without exceeding this threshold. The aroma profiles of the coffee samples were examined in terms of nine aroma characteristics: sweet/caramel, roasted/nutty, fruity, sourness/acidity, bitterness, spice, earthy, smoky, and overall impression/liking; the results are presented as a radar diagram in Figure 6. A trend parallel to the flavor profile was observed in the aroma profile evaluation; the coffee sample ground at 22 clicks received the highest score in terms of overall impression/liking. This sample, which exhibits a significant superiority, particularly in the "sweet/caramel-like" and "roasted/hazelnut" descriptions, is considered to be directly related to its richer profile in terms of pyrazines, furans, and Maillard reaction products, which are the main compounds responsible for the formation of these aromas. Indeed, the pyrazine analysis results presented in the previous section also revealed the highest pyrazine concentration at the 22-click setting, and these findings are consistent with each other. The decisive role of pyrazines in coffee aroma and the contribution of these compounds to nutty and caramel-like aroma notes have been extensively documented in many studies (Semmelroch & Grosch, 1996; Flament, 2002; Ayseli et al., 2021).

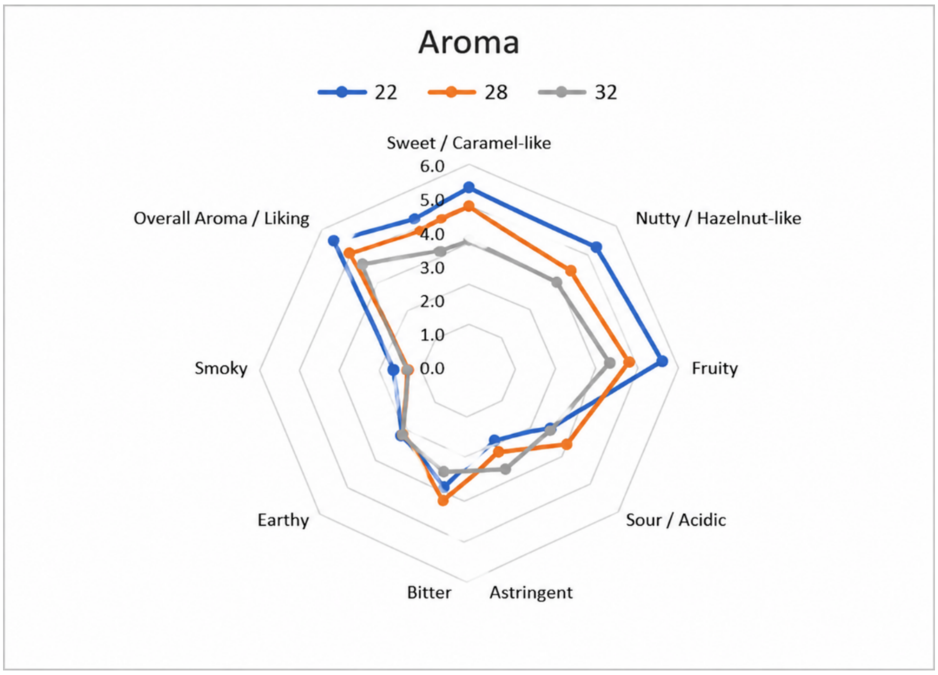


Figure 6. *Aroma evaluation of filter coffee samples with different grinding sizes*

On the other hand, the low scores obtained by the sample at the 22-click setting in terms of "earthy" and "smoky" aroma characteristics indicate that the potential of this grind setting to produce undesirable aroma notes is also limited. Earthy and smoky notes are generally associated with phenolic compounds such as guaiacol and 4-ethyleneguaiacol, which are typically formed at high roasting temperatures or long extraction times (Czerny et al., 2008). The longer water-coffee contact time in coarse particles at 32 click setting may have somewhat increased the extraction of these compounds, which could explain the relatively higher perception of earthy and smoky notes in this sample.

Studies in the literature that include sensory analyses performed using the V60 method also support these findings. Kement et al. (2021) examined consumer evaluations of coffees prepared using the V60 method with coffee beans of Ethiopian and Colombian origin; they determined that Ethiopian coffees stood out in terms of fruity, sour, and floral notes, while Colombian coffees were characterized by sour, fruity, and roasted notes. The researchers reported that the rate of consumers recognizing the origin flavors remained at approximately 60%, emphasizing the relationship between consumer perception and bean origin. The fact that the fruity and floral aroma of Yirgacheffe-origin Ethiopian Arabica used in the present study emerged more distinctly with a fine grind at 22 clicks is consistent with these literature findings. Uman et al. (2016), in their studies examining the effect of grinder type and particle size on the sensory profile of coffee, revealed that a more homogeneous particle distribution was associated with consistent and high sensory quality. In this context, it is considered that the homogeneous particle distribution provided by the Comandante C40 grinder may have supported the high sensory scores observed at the 22-click setting. Studies based on Specialty Coffee Association (SCA) protocols indicate that a brewing ratio of 18–22 g/240 ml and medium-fine particle sizes are recommended for optimal filtration quality, and in this framework, the 22-click setting can be considered a grinding parameter consistent with SCA recommendations (Batali et al., 2020).

In conclusion, both flavor and aroma profile evaluations reveal that filter coffee ground at the 22-click setting is significantly superior to other samples in terms of the desired sensory characteristics; this finding indicates that particle size should be considered in an integrated manner with its effects on pyrazine extraction, phenolic compound content, and antioxidant capacity.

4. CONCLUSION

In this study, the pyrazine profile, total phenolic compound content, antioxidant capacity, and sensory characteristics of filter coffee samples prepared from 100% Arabica (*Coffea arabica*) coffee beans grown in the Yirgacheffe region of Ethiopia, roasted at 210°C and prepared at three different grinding settings (22, 28, and 32 clicks), were comprehensively examined. The findings clearly show that grinding particle size has statistically significant effects on the chemical and sensory quality parameters of filter coffee. In the volatile aroma compound analysis, pyrazine compounds were determined to be the dominant aroma group in all three grinding settings; the total pyrazine concentration was found to be significantly higher at the finest grinding setting of 22 clicks compared to other samples. This finding is consistent with the hypothesis that small particle size increases cell structure breakdown, facilitating the passage of volatile compounds into the extract phase. Considering the low detection threshold values of pyrazines, this increase observed at the 22 click setting is considered to have a direct determining role in the sensory profile of the coffee.

Regarding total phenolic compound content and antioxidant capacity, an inverse relationship was observed with particle size; the highest values were determined in the sample ground to 32 clicks. The significantly higher antioxidant capacity, measured by DPPH and ABTS methods, and the total phenolic compound content at the 32-click setting were explained by the more regular flow of brewing water at larger particle sizes and the more efficient transport of phenolic structures to the extract phase. This finding indicates that filter coffee ground to 32 clicks exhibits a more advantageous profile from a functional beverage perspective in terms of bioactive compound density.

Sensory analysis results revealed that coffee ground to 22 clicks scored higher than other samples in terms of overall impression/liking, aroma intensity, sweet/caramelized, and roasted/nutty aroma characteristics. In contrast, the fact that the 32-click setting showed the lowest values in terms of negative sensory characteristics such as sourness, metallic taste, and bitterness indicates that coarse grinding limits the extraction of undesirable components. When these findings are evaluated as a whole, it is concluded that the 22-click setting is the optimum grinding parameter in terms of sensory quality; while the 32-click setting provides functional superiority in terms of bioactive compound content. The data obtained from this study show that the grinding particle size affects filter coffee quality in a multi-parameter framework, not a one-dimensional one; it draws attention to the fact that consumer preference and health perspectives may highlight different grinding settings. Future studies investigating the interaction of other brewing variables such as water temperature, brewing time, and coffee-to-water ratio with particle size; and also examining the behavior of phenolic compounds under in vitro digestion conditions through bioavailability analyses will provide valuable contributions to deepening the knowledge in this field.

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DECLARATION OF CONFLICTING INTERESTS

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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