frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 29 January 2025
DOI 10.3389/fsufs.2025.1497350

Sensory characterization of the Ethiopian germplasm of *Coffea arabica* L. conserved in the Colombian Coffee Collection

Juan Carlos Arias-Suárez[1]*, Luisa Fernanda López-Monsalve[1], Rubén Darío Medina-Rivera[2] and Claudia Patricia Flórez-Ramos[1]

[1]Department of Plant Breeding, National Coffee Research Center (Cenicafé), Manizales, Colombia, [2]Department of Biometrics, National Coffee Research Center (Cenicafé), Manizales, Colombia

Check for updates

OPEN ACCESS

EDITED BY
Matteo Balderacchi,
Consultant, Gazzola, Italy

REVIEWED BY
Fitri Fitri,
Hasanuddin University, Indonesia
Muhammad Ikhsan Sulaiman,
Syiah Kuala University, Indonesia

*CORRESPONDENCE
Juan Carlos Arias-Suárez
✉ juancarlos.arias@cafedecolombia.com

RECEIVED 16 September 2024
ACCEPTED 15 January 2025
PUBLISHED 29 January 2025

CITATION
Arias-Suárez JC, López-Monsalve LF, Medina-Rivera RD and Flórez-Ramos CP (2025) Sensory characterization of the Ethiopian germplasm of *Coffea arabica* L. conserved in the Colombian Coffee Collection. *Front. Sustain. Food Syst.* 9:1497350. doi: 10.3389/fsufs.2025.1497350

The sensory quality of coffee (*Coffea arabica* L.) has become increasingly important and is considered the best way to increase the competitiveness and profitability of the sector. Given the narrow genetic base cultivated, the use of its genetic resources conserved in germplasm banks is particularly relevant, especially for germplasm collected in Ethiopia, the country from which coffee originated and the center of its diversity of profiles. However, the potential benefits of using these resources is unknown. Therefore, the objective of this study was to characterize the sensory quality of the Ethiopian germplasm conserved in the Colombian Coffee Collection (CCC) to determine its variability and potential for use. The sensory qualities of drinks from 378 accessions of CCC were characterized. The results showed that 34% of the accessions evaluated presented sensory descriptors different from those of the traditional varieties. For the Global Impression attribute, the highest scores were associated with citrus, spice and floral notes. Additionally, prospecting rather than the area of origin of the germplasm influenced its sensory diversity, possibly due to the established objectives of the collection. The conserved germplasm exhibited important sensory variability, which is linked to rare descriptors in traditional varieties. Characterization activities of genetic resources, such as those conducted in this study, add value and serve as an initial step toward their application in breeding. The results obtained allow the selection of genotypes with distinct sensory profiles, which can be incorporated into genetic improvement programs aimed at developing future varieties with these attributes.

KEYWORDS

genetic resources, plant breeding, coffee organoleptic quality, sensory variability, coffee breeding

Introduction

In the coffee market, consumer preferences have changed over time; coffee has transitioned from serving as just a stimulating drink to engendering the search for particular characteristics. This trend reflects the life cycle of many products, as consumers and producers continue to specialize and innovate as the industry matures (Nadelberg et al., 2017). This approach has the potential to maintain and improve the economic viability of crops (Nadaleti et al., 2022b), thus justifying genetic improvement programs.

Given the narrow genetic base that gives rise to the crop (Salojärvi et al., 2024) obtaining significant advances is possible only if genetic diversity is available. In this context, genetic availability and knowledge are fundamental (Krieg et al., 2017). In this sense, Ethiopia is the center of origin and diversity for *Coffea arabica* L., which is widely recognized for its quality and diversity of sensory profiles. Furthermore, the genetics and contrasting environments where it is produced play important roles in its profiles (Davis et al., 2018). The influence of genetics, which is of interest for plant breeding, is seen in the Ethiopian genotypes used in other regions; while they were initially distributed to meet other objectives, they currently stand out for their quality (Dulloo et al., 2021). Additionally, Ethiopia is widely recognized for producing profiles with unique and distinctive flavors, such as Yirgacheffe, where intense notes of fruits, nuts, citrus, and chocolate are characteristic (Davis et al., 2018).

In Ethiopia, numerous studies have explored the existing sensory diversity of its genotypes (Dessalegn et al., 2008; Kitila et al., 2011; Tessema et al., 2011; Merga et al., 2022) and demonstrated their potential. However, in general terms, these studies involve a low number of genotypes, and their use is restricted. Other regions also have numerous evaluations related to sensory quality at either small (di Donfrancesco et al., 2019; Osorio et al., 2021) or large scales (Quintero et al., 2016; Ogutu et al., 2022); these include the evaluation of germplasm collections (Malta et al., 2021; Nadaleti et al., 2022a). In these studies, the same narrow genetic base that gives rise to the currently cultivated coffee has generally been explored; though conclusions indicate that important advances could be achieved through genetic improvement (Nadaleti et al., 2022a), these findings may not be significant.

Outside of Ethiopia, diversity is restricted to that conserved in germplasm banks, which are made up of accessions from different collections; the establishment of these banks was motivated by the economic importance of the species and threat of loss (Davis et al., 2019). The most representative of these banks, in terms of both number and origin, were those developed in Ethiopia by the Food and Agricultural Organization (FAO) between 1964 and 1965 (Food and Agricultural Organization, 1968) and by Office de la Recherche Scientifique et Technique Outre-mer (ORSTOM now Institut de Recherche pour le Développement - IRD) in 1966 (Charrier, 1978). They were distributed to different regions of the world, including Colombia (Krishnan et al., 2021), and used to strengthen germplasm banks and genetic improvement programs. In Colombia, the genetic resources of *C. arabica* are conserved in the Colombian Coffee Collection (CCC), which supports the genetic improvement program of the National Coffee Research Center (Cenicafé). The genotypes of these surveys have been used for various purposes, thus demonstrating their potential; however, their sensory variability has been poorly explored, both in Colombia and in other producing countries, possibly because of the economic and technical costs involved in carrying out such studies (Montagnon et al., 2012).

Considering that quality is a competitive trait of the coffee sector and that genetic resources are used as the main tool for this purpose, the objective of this study was to sensorially characterize the Ethiopian germplasm of *C. arabica* conserved in the CCC to determine its variability and potential use in obtaining varieties.

Materials and methods

Study area

The germplasm of Ethiopian origin preserved in the CCC is stablished at the Naranjal Experimental Station of Cenicafé in Chinchiná, Colombia, which is located at 04° 59´ N latitude and 75° 39´ W longitude at an altitude of 1,381 m above sea level. The average climatic characteristics are as follows: 21.4°C temperature, 2,782 mm^{-1} annual precipitation and 77.5% relative humidity. The experimental lots for the characterization of sensory quality in each of the accessions were stablished at this same experimental station.

Plant material

For the sensory characterization, samples of 393 Ethiopian accessions, which came from the surveys carried out by the FAO (308) and ORSTOM (74) between 1,654 and 1966, and other samples (17) of probable Ethiopian origin were used (Table 1). According to the available passport information obtained from the documents of these surveys (Food and Agricultural Organization, 1968; Charrier, 1978), the accessions were grouped into eight of the 16 Ethiopian coffee areas proposed by Davis et al. (2018).

Experimental design and sample setup

The characterized accessions were established in 10 experimental lots under full sun exposure, each represented by between 8 and 16 plants, obtained from open-pollinated seeds taken from a single genotype of each accession. For each of them, the plants were distributed in a completely random design within the experimental lot. Additionally, within each experimental lot, an equal number of

TABLE 1 The origins of the samples were classified according to the zoning method proposed by Davis et al. (2018).

Position in Ethiopia	Zone	Area	FAO	ORSTOM	Total
West Rift Valley	North	Amhara	15		15
	Southwest	Illubabor	6	2	8
		Jimma-Limu	140	3	143
		Tepi	48	13	61
		Kaffa	43	32	75
		Bench Maji	36	18	54
East of the Rift Valley	Southeast	Sidamo	20		20
Other accessions	N/A	N/A			17
Total			308	68	393

plants of the traditional varieties of *C. arabica*, Typica and/or Bourbon were included, which were used as reference controls.

Collection, processing and preparation of the sample

The peak harvest of the second and third productive years, considered the highest volume, was used to obtain a sample of 500 grams of dry parchment coffee. In the established plants of each accession, between 3 and 4 kilograms of coffee cherries were collected that were in grades 5–6 of maturity according to the chromacafé® color scale (Peñuela-Martínez et al., 2022). In the collected sample, due to density, fruits with filling problems or affected by insects were discarded, and the processing was carried out wet, starting with the mechanical removal of the exocarp. The samples were fermented for 12 to 14 h under the environmental conditions of the zone, after which the mucilage was removed through 3 or 4 successive washes with clean water. Due to density, fruits with filling deficiencies were removed, and fruits with mechanical or insect damage were visually separated. The samples were placed in parabolic dryers on perforated plastic meshes located at least one meter from the ground, allowing ventilation. The samples were kept in motion, thus ensuring that they dried at the same rate, until a humidity between 10 and 12%, which was established through a Kett PM-450 moisture content determinator, was reached. The samples were packed in 12-gauge plastic bags, sealed and stored in a cold room at 10–12°C and a relative humidity between 60 and 70% for 50–60 days prior to sensory analysis.

Sensory analysis

Given the volume of samples, the sensory evaluation was carried out in five periods, where between 55 and 91 accessions were evaluated, comprising accessions collected in at least four geographical areas and including at least one of the varieties in all cases as a control. Similarly, to guarantee a standardized roasting and preparation process for the samples, the methodology described in the Colombian Technical Standard (NTC) No. 4883 was used (Instituto Colombiano de Normas Técnicas y Certificación, 2000). The analysis was carried out by the Quality Office of Almacafé in Bogotá (Colombia), which assesses quality through the use of an ascending ordinal scale from degrees 0 to 10 in intervals of 0.5, where the typical assessment for Colombian coffee is located in the center of the scale (5–6.5). Nine sensory attributes were assessed: Fragrance/Aroma (Frag/Arom), Flavor (Fla), Residual Flavor (ResFla), Acidity (Acid), Body (Bod), Balance (Bal), Uniformity (Uni), Clean Cup (CleCup) and Sweetness (Swe). Unlike other evaluation scales used, where the sum of the scores obtained for each attribute defines its quality, in this scale, a tenth attribute is assigned by the taster, called Global Impression (GloImp), which takes into account all the sensory characteristics and attempts to summarize the potential for quality. Each evaluation session was carried out by at least three certified Q-Grader tasters, where the median was used for the final qualification of the sample for each of the attributes. Additionally, a sensory descriptor was assigned for the attributes Frag/Arom, Fla. and ResFla, as well as for the GloImp.

Information analysis

The accessions that obtained GloImp scores lower than 4 were not included in the analysis since, at the scale used, they generally reflect the possible presence of defects (e.g., immature). The quality values assigned to each of the attributes were used to determine the sensory variability of the Ethiopian germplasm through the K-means clustering method. This method was defined based on a comparative analysis of clustering methods (Hierarchical, K-means, and Partitioning Around Medoids, PAM) utilizing the clValid function in R. To ensure comparability between variables, the data were scaled in advance using the scale function. The range of cluster numbers evaluated was from 2 to 10, and both stability criteria and internal indices were employed to validate the quality of the clusters. The most appropriate clustering method was determined using the summary() function, based on the data structure.

Using this groups, heat maps were generate with the 10 sensory attributes, identifying associations between clusters and descriptors for the attributes of Frag/Arom, Fla., ResFla and GloImp. Additionally, a simple correspondence analysis (SCA) was performed using PROC CORRESP in SAS V9.4 to explore the relationship between the categorical variables of GloImp and Main Group, as well Frag/Arom and Main Group. The variable Area was include as a supplementary variable, allowing it to be projected in the correspondence space without affecting the construction of the main dimensions. The analysis included the calculation of the chi-squared statistic to evaluate the significance of the associations observed between the categories of the variables.

Results

Sensory quality

The characterization carried out allowed us to determine the existing sensory variability in the Ethiopian germplasm conserved in the CCC, from the points of view of both quality assessment and associated descriptors. The control varieties Typical and/or Bourbon presented values within the range associated with the standard quality (5.0–6.5) for the scale used for all attributes, so the variation due to the time of establishment, environmental condition or management was not taken into account. This process enabled the sensory results obtained from the evaluated accessions to be compared. Similarly, 5% of the accessions presented GloImp values lower than four, possibly due to defects caused by deficiencies in the production and preparation process prior to their analysis. Due to the impossibility of associating the presence of this type of descriptor with the experimental management or characteristics of the accession, they were withdrawn from the analysis. The results of the characterization of 378 accessions are shown.

According to the scores of the quality sensory variables, the accessions were grouped into six quality clusters (Figure 1) where according to the evaluation scale used, cluster VI had a direct relationship with GloImp, an attribute utilized by the tasters to summarize the sensory potential of a particular genotype.

Among the formed clusters, an increase in the ratings for the attributes Fla., ResFla, Bod, Bal, CleCup, Swe, and GloImp is observed. In the case of the attributes Acid and Uni, the values did not change

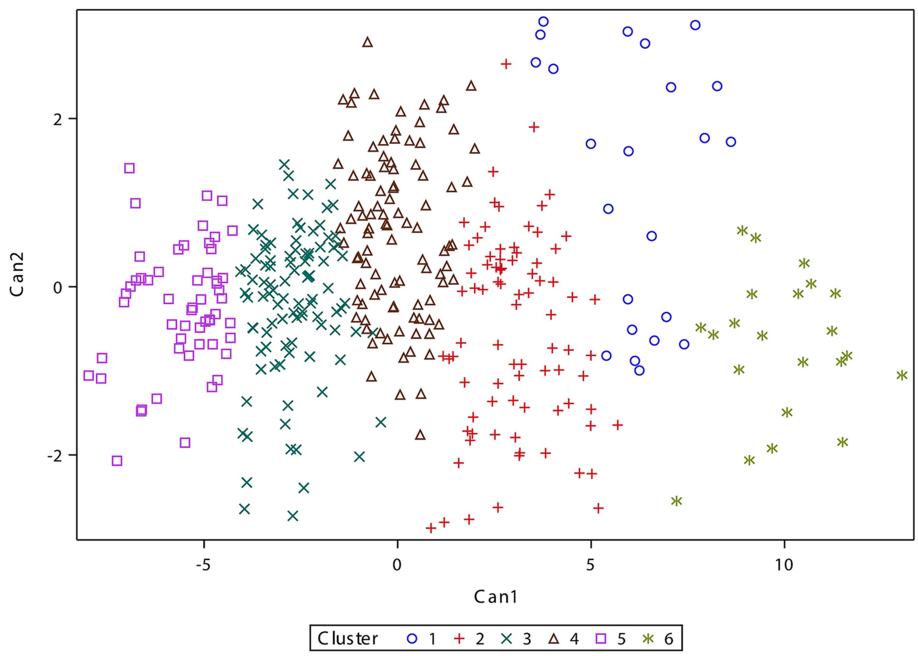

FIGURE 1
Distribution of the 378 accessions conserved in the Colombian Coffee Collection in six quality clusters according to the values assigned to the ten analyzed attributes. The sensory value increases from left to right.

TABLE 2 Distribution of accessions for each established cluster and higher frequency of quality assessments (> 50%) for each of the attributes.

Cluster	N. Accessions	Assessment in each common attribute for at least 50% of the accessions									
		Frag/ Arom	Fla	ResFla	Acid	Bod	Bal	Uni	CleCup	Swe	GloImp
V	51	4.5–5.0	4.0–4.5	4.0–4.5	4.5–5.0	4.0–4.5	4.0–4.5	4.5–5.0	4.0–4.5	4.5–5.0	4.0–4.5
III	104	5.0–5.5	5.0–5.5	4.5–5.0	5.0–5.5	4.5–5.0	5.0–5.5	5.0–5.5	4.5–5.0	5.0–5.5	5.0–5.5
IV	96	5.0–5.5	5.5–6.0	5.5–6.0	5.5–6.0	5.0–5.5	5.5–6.0	5.5–6.0	5.5–6.0	5.5–6.0	5.5–6.0
II	84	6.5–8.0	6.0–6.5	6.0–6.5	5.5–6.0	6.0–6.5	6.0–6.5	6.5–7.0	6.0–6.5	6.0–6.5	6.5–7.0
I	21	4.5–5.5	7.0–7.5	7.0–7.5	6.5–7.0	6.5–7.0	6.5–7.0	7.0–8.0	6.5–7.0	6.5–7.0	7.5–8.0
VI	22	8.0–8.5	8.0–8.5	8.0–8.5	7.5–8.0	7.5–8.0	8.0–8.5	7.5–8.0	7.5–8.0	7.0–7.5	8.0–8.5

between clusters IV and II, and I and VI, respectively, while between clusters II and I, the values for Frag/Arom attribute exhibited and inverse behavior (Table 2).

Cluster V comprised 77% of the accessions that, according to their GloImp, were considered poor quality or lower than the standard of Colombian coffee, and two that, despite being classified as such, presented a low rating in the Frag/Arom attribute. Clusters III and IV accounted for 53% of the accessions evaluated, including the control varieties, with GloImp values between 5.0 and 6.5, a range considered standard for Colombian coffee. Clusters II, I and VI, made up 33.5% of the accessions, representing, in this order, the highest sensory values observed in the germplasm. These values were differentiated from each other by the valuations of some of their attributes. The genotypes in cluster II presented high values of the Frag/Arom attribute (46% ≥7), which was greater than that observed for the control varieties; however, the values in GloImp (82%) were slightly greater than the considered standard.

Clusters I and VI include accesions considered to have the highest sensory value; however, they are mainly differentiated by the Frag/Arom attribute. While accessions in cluster VI show high qualifications for this attribute, those in cluster I exhibit scores comparable to those of cluster V, which is regarded as of lower quality. Figure 2 illustrates the differences among the quality clusters established for each of the attributes evaluated. A color scale with a hue toward red indicates lower scores for the different attributes, while tones toward yellow indicate higher scores.

The sensory information obtained revealed greater variability in the accessions collected by the FAO survey than in those collected by the ORSTOM survey for two fundamental reasons: the distribution of the accessions in the clusters and the contribution of the collection areas to their conformation (Table 3).

10.3389/fsufs.2025.1497350

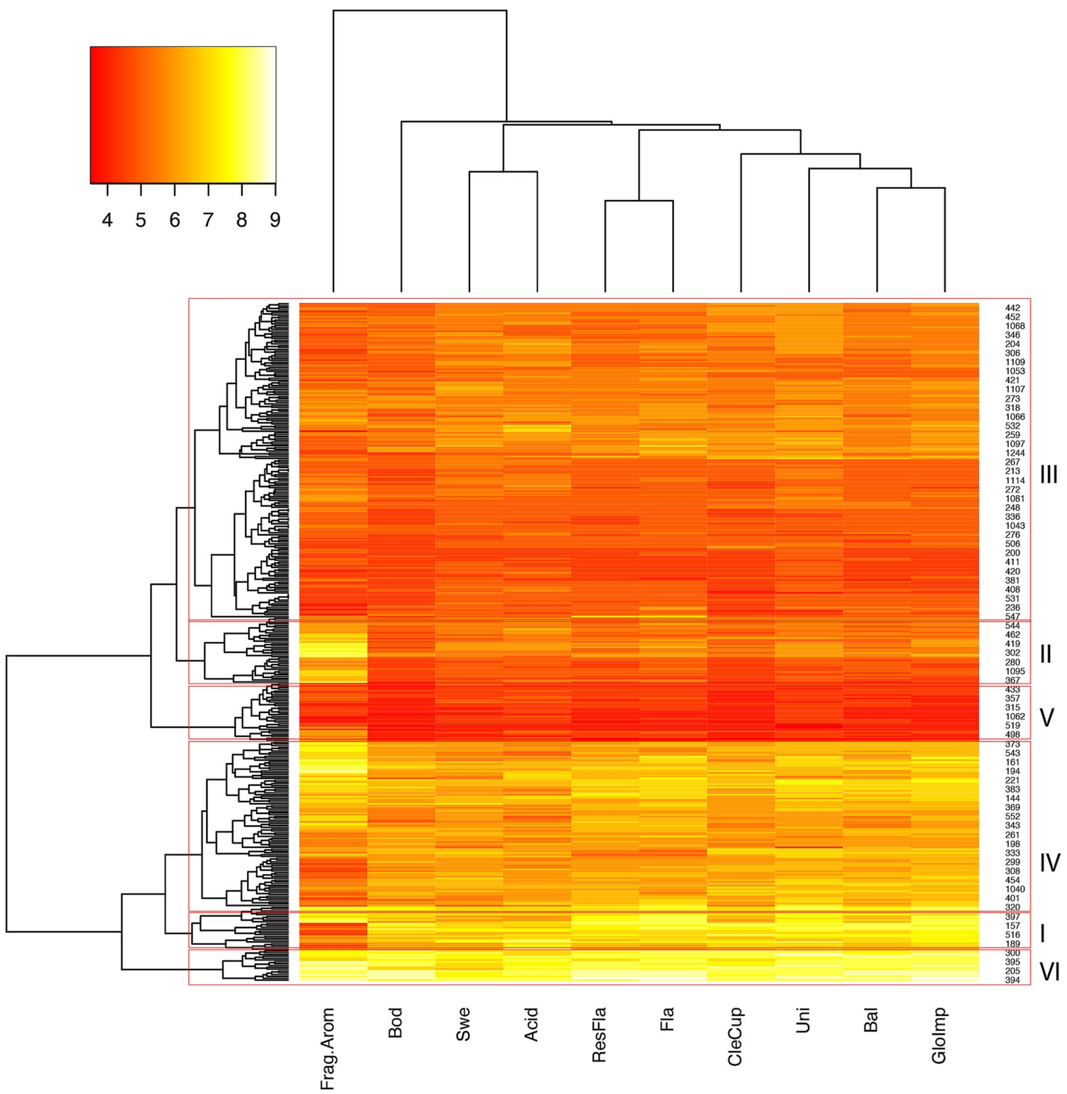

FIGURE 2
Heatmap with the values assigned to ten sensory attributes for the six clusters associated with the sensory qualities of the 378 Ethiopian accessions. The control varieties Typica and Bourbon are located within clusters III and IV.

First, the accessions from the FAO survey contributed to all the established clusters, with the lowest percentages being for clusters I and VI, both of which were less than 7.2%, while for the others, the percentages were between 16.6% (V) and 27.6% (III). In the case of the accessions collected by the ORSTOM survey, cluster I was not represented, while clusters V and VI comprised 7% of the accessions. Meanwhile 69.4% were distributed between clusters III and IV, representing the standard quality.

Second, for the four common collection areas with the highest representation in both surveys (Bench Maji, Jimma Limu, Kaffa and Tepi), those of FAO origin contributed to the different quality clusters, except for Tepi, which did not present accessions in cluster VI. According to the ORSTOM survey, these areas contributed to four of the six clusters. Kaffa, with accessions in III, IV, II and VI, was the only area contributing to the latter, while Bench Maji and Tepi were distributed across clusters V, III, IV and II. In addition, the accessions of unknown origin contributed to the formation of three of the six clusters; cluster II represented 56% of these accessions. Ethiopian germplasm (singular) demonstrate quality potential, as they are the most important ones collected by the FAO, not only because of their numbers but also because of the sensory diversity observed in the different collection regions.

Descriptors and their relationship with sensory quality

Eleven descriptors (cereal, herbal, nuts, chocolate, sweet, fruits, spices, citrus, floral, bitter, defect) were highlighted among the attributes Frag/Arom, Fla., ResFla and GloImp in the Ethiopian germplasm. Regarding the first attribute, the descriptors chocolate, sweet and floral were common in 87% of the accessions, while in Fla., ResFla and GloImp, the descriptors that were presented with greater frequency were sweet, citrus, floral and herbal, which were present in 84% of the accessions. Figure 3 shows the relative frequency of the

TABLE 3 Relative frequencies of accessions within each sensory quality cluster according to the survey and collection area.

Prospecting	Area	Quality clusters						% Participation
		V	III	IV	II	I	VI	
FAO	Amhara		28.6%	28.6%	42.9%			4.8%
	Bench Maji	6.1%	36.4%	27.3%	18.2%	6.1%	6.1%	11.4%
	Illubabor		33.3%	16.7%	33.3%		16.7%	2.1%
	Jimma-Limu	22.5%	23.3%	17.1%	19.4%	7.8%	10.1%	44.5%
	Kaffa	14.3%	26.2%	21.4%	21.4%	7.1%	9.5%	14.5%
	Tepi	8.3%	37.5%	31.3%	16.7%	6.3%		16.6%
	Sidamo	38.9%	16.7%	16.7%	11.1%	16.7%		6.2%
	Total	16.6%	27.6%	21.7%	20.0%	7.2%	6.9%	76.7%
ORSTOM	Bench Maji	4.5%	36.4%	36.4%	22.7%			30.6%
	Illubabor		50.0%	50.0%				2.8%
	Jimma-Limu			66.7%	33.3%			4.2%
	Kaffa		19.4%	41.9%	32.3%		6.5%	43.1%
	Tepi	14.3%	35.7%	42.9%	7.1%			19.4%
	Total	4.2%	27.8%	41.7%	23.6%		2.8%	19.1%
Other	Unknown		25.0%	18.8%	56.3%			4.2%
Grand total		13.5%	27.5%	25.4%	22.2%	5.6%	5.8%	100%

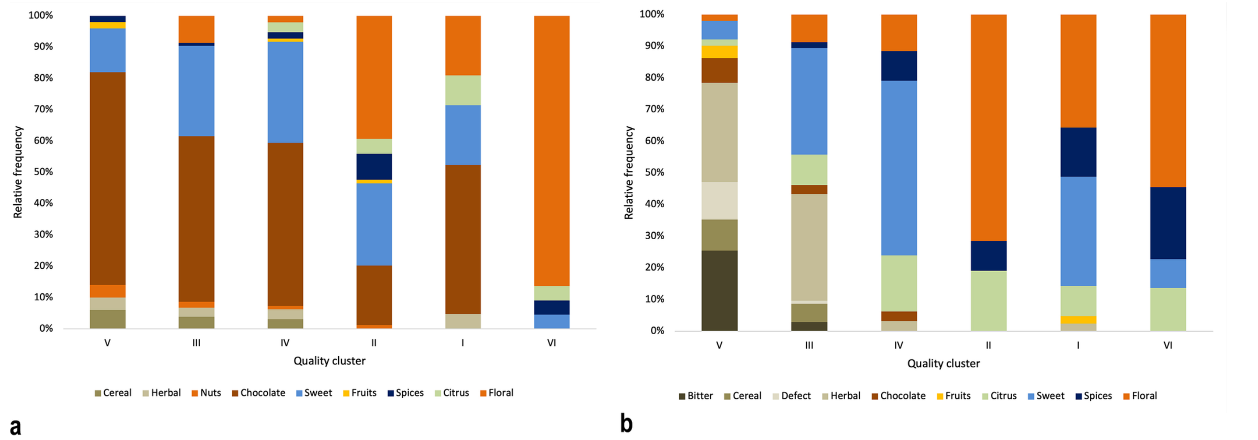

FIGURE 3
Relative frequency for eleven descriptors in the six quality clusters established for attributes **(A)**. Frag/Arom (cereal, herbal, nuts, chocolate, sweet, fruits, spices, citrus, floral) and **(B)** GloImp (bitter, cereal, defect, herbal, chocolate, fruits, citrus, sweet, spices, floral).

characteristic descriptors of the accessions that make up the quality clusters for the Frag/Arom (Figure 3A) and GloImp (Figure 3B) attributes.

For the Frag/Arom attribute, the chocolate descriptor had a strong presence in five of the six clusters, absent only in cluster VI, which comprises the accessions with the highest sensory qualification in all attributes (≥7). In addition, this cluster was characterized by a high frequency of floral descriptors, which was highlighted in 86% of the accessions, while the other descriptors presented frequencies below 5%. The descriptors cereals, herbal, fruits and spices were infrequent and were the most common only for the clusters with lower valuations (V, III, IV), while the last descriptor slightly grew in frequency with the quality associated with the cluster, increasing from 2% in cluster V to 8% in cluster II.

For the descriptors associated with the GloImp attribute, eight of the ten descriptors were distributed in all the clusters; the characteristic bitter, cereal, defect and herbal descriptors were distributed in clusters V and III, while in the other clusters, they were found at a low frequency. The sweet descriptor, highlighted in the control varieties, presented its highest frequency in the cluster III and IV and in cluster I, where it was highlighted in at least one-third of the accessions that comprised it. Similarly, just as the descriptors bitter, cereal and herbal were common in the accessions of clusters V and III, the absence of the descriptor chocolate and the presence of floral were characteristic of clusters II, I and VI.

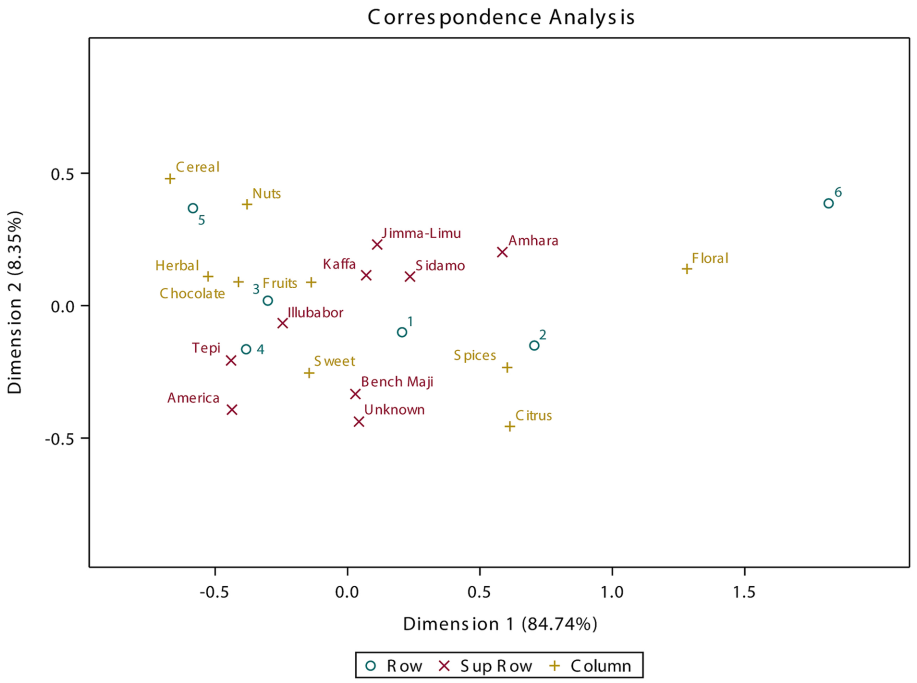

FIGURE 4
Representation of the descriptors associated with the sensory assessment of 378 accessions for the Frag/Arom attribute generated by simple correspondence analysis and its relationship with the collection area.

The simple correspondence analysis performed showed a dependence between the established quality clusters and the presence of descriptors for the attributes to which they were assigned (*p* = *0.001*). Figure 4 shows the correspondence between the Frag/Arom attribute and the quality clusters, in which the collection area was included as a complementary variable. For this attribute, the first two dimensions explained 93.1% of the variation, the first being the one with the greatest contribution (85%), where the absence of the floral and chocolate descriptors in the accessions associated with clusters V and VI, respectively, was the most important. Regarding the second dimension, the differences between the accessions that make up clusters V and IV contribute to their formation. The latter represents the intermediate step between descriptors associated with the contrasting clusters, in which the frequency of descriptors such as chocolate and cereal decreases, and the greatest presence of sweet is presented, while descriptors such as spices and floral also appear. The results of the correspondence analysis confirm what is observed in Figures 3A,B.

Of the areas of provenance that were included as complementary variables in the correspondence analysis, only Sidamo presented a representation quality of less than 40%. In the first dimension, Amhara, Tepi and the control varieties of American origin were placed, where Amhara tends to be related to clusters of greater sensory value and the prevalence of the floral descriptor. For Tepi, despite the diversity observed, the frequency in clusters III and IV and the prevalence of the sweet descriptor placed these clusters next to the American origin, where these two aspects are characteristic.

In the second dimension, the Kaffa, Jimma-Limu and Bench Maji areas were present; Kaffa and Jimma-Limu were opposite from Bench Maji, which was located next to the unknown origin. The Kaffa and Jimma-Limu areas were characterized by their variability, which contributed to the formation of clusters, especially those of higher quality (II, I, VI), as well as the main descriptors associated with them. On the other hand, the diversity of quality for the Bech Maji area is similar to that of Kaffa or Jimma-Limu; however, it differs from these due to the prevalence of the sweet descriptor and also differs from those of unknown origin. Thus, Bech Maji is located opposite to Kaffa and Jimma-Limu and close to the American origin.

Notably, for Frag/Arom, there is a strong presence of the sweet and chocolate descriptors in all the clusters, which hinders their separation; for GloImp, there is a greater association (Figure 5). The first two dimensions of the correspondence analysis between the quality clusters and the descriptors assigned to the GloImp platform explained 86.7% of inertia. Clusters V and II have the greatest contribution to the formation of the first dimension, along with seven of the ten prevalent descriptors in the characterized germplasm. In cluster V, the descriptors bitter and defect were present, the former having greatest relevance due to its presence in at least 5.3% of the accessions and 20% of the frequency in this cluster. Cluster II was located at the extreme right of the first dimension, linked to the descriptor spices, which was highlighted in only 15% of the accessions that comprised it, representing 40% of the total.

The other descriptors, located to the left and right of the first dimension, are associated with the sensory attributes of the clusters (as shown in Figure 1), resulting from the strong presence of chocolate and herbal cereal compared to other descriptors such as citrus and spices. In this sense, although the sweet and floral descriptors are part of this step, they contribute to separating the clusters related to

10.3389/fsufs.2025.1497350

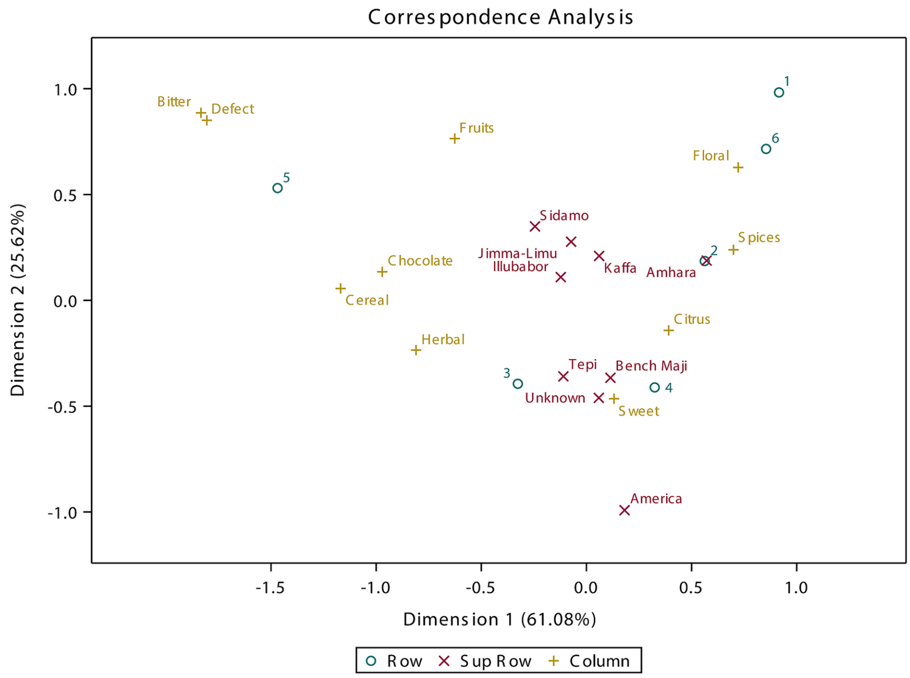

FIGURE 5
Representation of the descriptors associated with the sensory assessment of 378 accessions for the GloImp attribute generated by simple correspondence analysis and its relationship with the collection area.

standard quality (III, IV) and those with the highest sensory value (I, VI), respectively.

In the case of the provenance area, the quality of representation in the correspondence analysis was less than 0.27 for Illubabor, Sidamo and the area of unknown origin, while in the other areas, it was greater than 0.44. In this sense, for the Frag/Arom attribute, none of the attributes were associated with a higher prevalence of defects or with cluster V, which has the lowest sensory value of all the clusters. For the accessions from Amhara, although approximately 60% are within the clusters that comprise the standard quality (III, IV), the prevalence of descriptors such as floral or spices places it in the first dimension, suggesting a higher quality in the accessions of this area.

The control varieties, with sweet as the only highlighted descriptor, are located at the lower end of the second dimension, near the Bench Maji and Tepi areas. Unlike the former, these regions are particularly varied in terms of descriptors (seven and ten, respectively); however, with the sweet descriptor as the most prevalent, and because approximately 70% of the accessions are within clusters III and IV, their proximity to this origin can be explained. Furthermore, the areas of Kaffa and Jimma-Limu are far from these regions, especially due to the lower proportion of the sweet descriptor (20 and 29%, respectively) and their greater contributions to clusters II and VI.

The results of the characterization of the sensory quality of the Ethiopian accessions conserved in the CCC indicate the existence of diversity. Although there are numerous related studies, this work is the first to cover on a large scale the germplasm of Ethiopian origin available in different gene banks worldwide. Undoubtedly, the information obtained will aid in genetic improvement programs for this species to obtain varieties with specific profiles, which are important in today's demanding market characterized by diverse tastes.

Discussion

The coffee market has evolved over time, and its sensory quality has become increasingly important (Nadelberg et al., 2017). The use of the approach described in this study offers a path for potentially maintaining and possibly improving the economic viability of crops (Nadaleti et al., 2022a, 2022b). Thus, at present, this aspect has gained importance in genetic improvement programs. In this sense, the variability of profiles that Ethiopian coffee possesses has given it recognition, as its genetics play an important role (Davis et al., 2018). Outside of Ethiopia, *ex situ* germplasm from this provenance represents the greatest opportunity for significant advances in sensory quality through plant breeding (Montagnon et al., 2012). Therefore, further exploration is necessary. The results presented here confirm this fact, which is unprecedented due to two fundamental aspects: the origin and number of genotypes. First, germplasms collected by the FAO (Food and Agricultural Organization, 1968) and ORSTOM (Charrier, 1978) in Ethiopia between 1964 and 1966, which arrived in Colombia as duplicates sent from Costa Rica by CATIE and Cameroon by the IFCC, respectively, were characterized. Although these genotypes are conserved in different research centers in Latin America, Africa and Asia (Food and Agricultural Organization, 1968; Krishnan et al., 2021), where they have been evaluated and used by various genetic improvement programs, knowledge related to their sensory variability is limited. Additionally, this is the first time that sensory quality information has been collected from a considerable number of accessions, considering the economic and technical costs of this technique (Montagnon et al., 2012).

Notably, for the estimation of sensory quality, there is consensus on the role of external factors such as ecological conditions of the area and agronomic practices of the crop (di Donfrancesco et al., 2019) in either positively or negatively affecting different sensory attributes. For the accessions evaluated, this variation factor was reduced to the minimum possible by using a single environment and uniform plant age, sampling, preparation and processing, which was reflected by the grouping of the control varieties in clusters III and IV in the different evaluation periods. These methods are useful for multiple experiments (Forkman, 2013), including the sensory characterization of coffee (Nadaleti et al., 2022a), since their genetic uniformity infers that any variation is considered to be environmental. Similarly, although 5% of the accessions presented descriptors associated with defects, the low qualification in some of them may possibly be a consequence of their genetics rather than management deficiencies, a fact reflected in those genotypes of lower quality but not associated with this type of descriptor.

Numerous sensory quality studies have been conducted in various countries, including Ethiopia (Dessalegn et al., 2008; Kitila et al., 2011; Tessema et al., 2011; Merga et al., 2022). However, in general, few genotypes are used, some of which are exclusive to certain research centers or belong to the narrow genetic base cultivated (di Donfrancesco et al., 2019; Malta et al., 2021; Nadaleti et al., 2022b). One of the greatest difficulties in making comparisons among sensory results is related to the different scales used, where each actor uses their own methods (Montagnon et al., 2012). However, all of these methods include ranges for the control varieties, above which the sensory values can be considered high. Thus, the sensory characterization carried out in this study revealed both the variability of the conserved germplasm and its potential for use, given the identification of superior and/or contrasting genotypes according to the established clusters, consistent with existing reports (Tessema et al., 2011; Merga et al., 2022). Of the accessions characterized, fewer than 14% presented lower quality than expected for Colombian coffee, while one-third obtained higher grades, frequently associated with unusual descriptors. In this sense, the proportion of accessions identified as having high sensory value is important since different studies have shown that their frequency is generally low. For the largest coffee region in Colombia (Osorio et al., 2021), fewer than 3% of the samples analyzed were outstanding for their quality, similar to that observed in Ethiopia by Kitila et al. (2011) and Merga et al. (2022). Within the Germplasm Collection of the State of Minas Gerais, Nadaleti et al. (2022a) selected 10% of accessions for high-quality evaluations. In their study, although the Ethiopian germplasm was evaluated, the selected genotypes belong to the genetic base that includes the traditional or rust-resistant varieties, of which only five cases are of Ethiopian origin.

The quality of coffee can be approached from different points of view, as the characteristics sought by the consumer may differ from those offered by the industry (Giacalone et al., 2016). In this regard, when sensory diversity has been evaluated, most studies have limited themselves to assessing the attributes, while the descriptors have not been included. These are of great importance since in coffee, aromatic components are particularly important because they are the first point of contact in the sensory experience, followed by taste, as a driver of consumer preferences (Bhumiratana et al., 2011; Masi et al., 2013). Based on the frequencies of the descriptors assigned to the Frag/Arom and GloImp attributes and their relationships with the established clusters, cup quality cannot be qualified by only one of them. In this sense, fragrance and aroma are the first attributes perceived by consumers in the drink, and the presence of some descriptors may present a bias toward the general rating, either negatively (herbal) or positively (floral). In this regard, although the absence of intermediate ratings on the Frag/Arom scale suggest the possibility of differentiating clusters that group genotypes with higher sensory potential, the characteristics of cluster I highlight the need to consider all attributes. Outside of Ethiopia, traditional varieties and improved varieties belonging to the same genetic base have been characterized by the prevalence of the descriptors sweet or chocolate (Quintero et al., 2016; Osorio et al., 2021; Nadaleti et al., 2022b). In contrast, Ethiopian coffee presents a unique opportunity due to the plurality of descriptors presented. In some regions the presence of specific descriptors is indicated, such as citrus in Amhara or floral in Jimma-Limu, which is consistent in that perhaps the latter is the most common for Ethiopian coffee (Davis et al., 2018). This fact draws attention, since 40% of the accessions included the presence of these descriptors in all the quality clusters, which could indicate their independence from the environment and therefore their heritability. Thus, this attribute could possibly be intrinsic to their genetic makeup (Machado et al., 2022).

On the other hand, the southwest area of the Rift Valley has been proposed as the possible origin of *C. arabica* and, therefore, where the greatest diversity can be found (Montagnon and Bouharmont, 1996; Davis et al., 2018; Montagnon et al., 2022). In this study, this behavior was not detected, possibly due to the low representation of accessions outside this area (Sidamo, Amhara). In general, all Ethiopian provenances of the characterized germplasms, including Sidamo, where wild coffee may have been eliminated (Montagnon and Bouharmont, 1996), contributed to the formation of the different clusters. However, prospecting played a clear role in variability, measured as the contribution to the different clusters, which can be found for common collection regions. In this sense, the accessions collected by the FAO survey contributed to each of the clusters, accounting for 93.1% of the accessions in clusters III, IV and II, while those from ORSTOM did not. According to these surveys, the FAO mission was formed by an interdisciplinary team that tried to collect the greatest available diversity of *C. arabica* (Food and Agricultural Organization, 1968), a fact that was reflected in its morphology (Narasimhaswamy, 1965), and as this study shows, the sensory variability of the drink. The opposite happens to the ORSTOM Mission, carried out by the botanists Guillaumet & Hallé (Charrier, 1978) who, despite going to areas considered to have greater diversity (southwest of the Rift Valley), wanted to select genotypes with greater agronomic potential for direct use, with possible adaptation to lowlands where coffee rust was a limitation (Charrier, 1978). Therefore, the lower sensory variability observed may be a consequence of the collection objectives. The bias toward genotypes of greater agronomic interest indirectly decreased their sensory variability, although, notably, this characteristic was not a variable of interest at that time. Similarly, although in the short period of species domestication, the quality of the drink may not be a strong selection criterion, the sweet descriptor was possibly related to this process. Sensory analyses of cultivated varieties (Quintero et al., 2016; Osorio et al., 2021; Nadaleti et al., 2022a) revealed that it was the most common, and in this study, among the genotypes with some degree of selection and origins labeled as unknown. In addition, 51% of the accessions from the ORSTOM survey presented this descriptor, compared to 26% from the FAO survey. Similarly, although the passport information for the accessions of these collections indicates their possible conditions (cultivated, "wild," "semiwild"), it was not possible to establish this association with the quality or behavior described. In this regard, curiously, most of the accessions collected by ORSTOM were designated as "wild" or "possibly wild" in origin, which is not consistent with the results observed here, although they were collected from some type of plantation (Charrier, 1978). In turn, the FAO survey indicated that 33% were cultivated (Food and Agricultural Organization, 1968), but they were not associated with a specific cluster or descriptor, and were as equally diverse as those established as "wild." Furthermore, importantly, the surveys to collect the genetic resources of coffee were motivated by the knowledge of the narrow genetic base that gave rise to the cultivation and rapid destruction of primary forests in Ethiopia (Food and Agricultural Organization, 1968). This process likely partially eliminated the wild genotypes of the species (Montagnon and Bouharmont, 1996). In addition, true populations were possibly confined to small areas where the primary forest still remains, adding to the difficulty of its recognition (Charrier, 1978). Therefore, the information recorded in the passport of each accession may potentially not reflect its true condition; however, morphological selection toward traits of agronomic interest did play an important role in its variability.

Two of the Ethiopian provenances of the conserved germplasm stand out, particularly for their history: Bench Maji and Sidamo. The first is located in the Geisha district, from which the most recognized Ethiopian genotype worldwide was identified (Davis et al., 2018); this genotype was collected at the beginning of the 19th century (Pruvot-Woehl et al., 2020). In the midst of material exchanges between research centers and the need for resistance to coffee rust, it was introduced to different countries, including Panama, where it developed excellent organoleptic characteristics (Dulloo et al., 2021). This genotype stands out for its jasmine and fruits and for its sweetness (Davis et al., 2018). In turn, Sidamo does not stand out for a particular genotype, such as Bench Maji, but for including Yirgacheffe, one of the areas most recognized for producing coffee with a unique and distinctive flavor profile, frequently highlighted as "Yirgacheffe flavor" (Davis et al., 2018). In this study, the accessions from Bench Maji were distributed in all the quality clusters; sweet descriptors were the most frequent. Moreover, despite the lower representation of Sidamo (18 accessions), its accessions were distributed in five of the six established clusters, with the greatest contribution in cluster V (40%), where it was the only origin that presented a floral descriptor in this cluster.

Faced with a risk of loss (Davis et al., 2019), the conservation of coffee genetic resources both *in situ* and *ex situ* is highly relevant since these resources are tools for providing a solution to the current and potential needs of the species via plant breeding. The genetic diversity of *C. arabica* in Ethiopia has been widely recognized (Montagnon et al., 2022); however, knowledge of its diversity, which is useful for improvement, has practical value. To fulfill this purpose, characterization and evaluation activities, such as those carried out in this study, are of particular relevance for defining its use, thus adding value to its conservation. The sensory variability identified in the conserved Ethiopian germplasm can contribute to the well-being of coffee growers, with quality being a key factor for their competitiveness. In this sense, species that may be useful for this purpose have been described in the secondary gene pool (Davis et al., 2021; Bertrand et al., 2023). Their exploitation requires long and complex improvement schemes; furthermore, in addition to the limitations of their direct use, these species may detract from an overall interest in coffee. In contrast, the use of the Ethiopian germplasm, for which sensory variability is being explored for the first time, shows potential and could be used directly by coffee growers, as has been done with others from the same origin (e.g., Geisha). However, its limitations, such as susceptibility to diseases, plant arquitecture, low productivity, and lower physical bean quality, among others, restrict its use. For this reason, evaluations of other agronomic attributes that complement sensory quality are being conducted, so they can be used as selection criteria for breeding programs.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

JA-S: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing. LL-M: Data curation, Formal analysis, Methodology, Writing – review & editing. RM-R: Data curation, Formal analysis, Methodology, Visualization, Writing – review & editing. CF-R: Conceptualization, Funding acquisition, Writing – review & editing, Methodology, Visualization.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This study was supported by the National Coffee Research Center (Cenicafé) (Crossref Funder ID 100019597).

Acknowledgments

The authors want to acknowledge the valuable support provided by Dr. María del Pilar Moncada Botero and Dr. Rodrigo Alarcón for the advice provided during the execution of the field experiments and sensory analysis, respectively. Additionally, we thank the field assistants Jhon Esteban Quintero, Carlos Augusto Vera, Omar Villarreal and Gilbert Rodríguez, without whom the collection and handling of the samples would not have been possible.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Bertrand, B., Davis, A. P., Maraval, I., Forestier, N., and Mieulet, D. (2023). Potential beverage quality of three wild coffee species (Coffea brevipes, C. Congensis and *C. stenophylla*) and consideration of their agronomic use. *J. Sci. Food Agric.* 103, 3602–3612. doi: 10.1002/jsfa.12347

Bhumiratana, N., Adhikari, K., and Chambers, E. (2011). Evolution of sensory aroma attributes from coffee beans to brewed coffee. *LWT Food Sci. Technol.* 44, 2185–2192. doi: 10.1016/j.lwt.2011.07.001

Charrier, A. (1978). "Synthèse de neuf années d'observation et d'expérimentation sur les *Coffea arabica* collectés en Ethiopie par une mission ORSTOM" in Etude de la structure et de la variabilité génétique des caféiers: Résultats des études et des expérimentations réalisées au Cameroun, en Cote d'Ivoire et à Madagascar sur l'espèce Coffea arabica L. collectée en Ethiopie par une mission ORSTOM en 1966. (Paris, Francia: A. Charrier), 4–10.

Davis, A. P., Chadbrun, H., Moat, J., O'Sullivan, R., Hargreaves, S., and Lughadha, E. (2019). High extinction risk for wild coffee species and implications for coffee sector sustainability. *Sci. Adv.* 5, 1–9. doi: 10.1126/sciadv.aav3473

Davis, A. P., Mieulet, D., Moat, J., Sarmu, D., and Haggar, J. (2021). Arabica-like flavour in a heat-tolerant wild coffee species. *Nat. Plants* 7, 413–418. doi: 10.1038/s41477-021-00891-4

Davis, A. P., Wilkinson, T., Kebeweb, Z., Williams, J., Baena, S., Gole, T., et al. (2018). Coffee atlas of Ethiopia. Richmond, London: Kew.

Dessalegn, Y., Labuschagne, M. T., Osthoff, G., and Herselman, L. (2008). Genetic diversity and correlation of bean caffeine content with cup quality and green bean physical characteristics in coffee (*Coffea arabica* L.). *J. Sci. Food Agric.* 88, 1726–1730. doi: 10.1002/jsfa.3271

di Donfrancesco, B., Gutierrez Guzman, N., and Chambers, E. (2019). Similarities and differences in sensory properties of high quality arabica coffee in a small region of Colombia. *Food Res. Int.* 116, 645–651. doi: 10.1016/j.foodres.2018.08.090

Dulloo, M. E., Solano, W., Dessauw, D., Astorga, C., and Guarino, L. (2021). A methodological approach for prioritization and rationalization of field genebank accessions of coffee genetic resources: a case study of CATIE International coffee collection, Costa Rica. *Front. Sustain. Food Syst.* 5:777415. doi: 10.3389/fsufs.2021.777415

Food and Agricultural Organization (1968). FAO coffee Mission to Ethiopia 1964–65. Italia: Roma.

Forkman, J. (2013). The use of a reference variety for comparisons in incomplete series of crop variety trials. *J. Appl. Stat.* 40, 2681–2698. doi: 10.1080/02664763.2013.825703

Giacalone, D., Fosgaard, T. R., Steen, I., and Münchow, M. (2016). "Quality does not sell itself": divergence between "objective" product quality and preference for coffee in naïve consumers. *Br. Food J.* 118, 2462–2474. doi: 10.1108/BFJ-03-2016-0127

Instituto Colombiano de Normas Técnicas y Certificación (2000). NTC 4883:2000 Analisis sensorial. cafe. metodologia para analisis sensorial cuantitativo descriptivo del cafe. Available at: https://tienda.icontec.org/gp-analisis-sensorial-cafe-metodologia-para-analisis-sensorial-cuantitativo-descriptivo-del-cafe-ntc4883-2000.html (Accessed October 17, 2024).

Kitila, O., Alamerew, S., Kufa, T., and Garedew, W. (2011). Organoleptic characterization of some Limu coffee (*Coffea arabica* L.) germplasm at Agaro, southwestern Ethiopia. *Int. J. Agric. Res.* 6, 537–549. doi: 10.3923/ijar.2011.537.549

Krieg, C. P., Kassa, M. T., and von Wettberg, E. J. B. (2017). "Germplasm characterization and trait discovery" in The Pigeonpea genome. eds. R. K. Varshney, R. K. Saxena and S. A. Jackson (Cham: Springer International Publishing), 65–79.

Krishnan, S., Matsumoto, T., Nagai, C., Falconer, J., Shriner, S., Long, J., et al. (2021). Vulnerability of coffee (Coffea spp.) genetic resources in the United States. *Genet. Resour. Crop. Evol.* 68, 2691–2710. doi: 10.1007/s10722-021-01217-1

Machado, J. L., Tomaz, M. A., da Luz, J. M., Osório, V. M., Costa, A. V., Colodetti, T. V., et al. (2022). Evaluation of genetic divergence of coffee genotypes using the volatile compounds and sensory attributes profile. *J. Food Sci.* 87, 383–395. doi: 10.1111/1750-3841.15986

Malta, M. R., Oliveira, A. C. B., Liska, G. R., Carvalho, G. R., Pereira, A. A., Silva, A. D., et al. (2021). Selection of elite genotypes of *coffee arabica* L. to produce specialty coffees. *Front. Sustain. Food Syst.* 5:715385. doi: 10.3389/fsufs.2021.715385

Masi, C., Dinnella, C., Barnabà, M., Navarini, L., and Monteleone, E. (2013). Sensory properties of under-roasted coffee beverages. *J. Food Sci.* 78, S1290–S1300. doi: 10.1111/1750-3841.12211

Merga, W., Gebreselassie Abtew, W., and Garedew, W. (2022). Organoleptic quality attributes and their association with morphological traits in arabica a coffee (*Coffea arabica* L.) genotypes. *J. Food Qual.* 2022, 1–10. doi: 10.1155/2022/2906424

Montagnon, C., and Bouharmont, P. (1996). Multivariate analysis of phenotypic diversity of *Coffea arabica*. *Genet. Resour. Crop. Evol.* 43, 221–227. doi: 10.1007/BF00123274

Montagnon, C., Marraccini, P., and Bertrand, B. (2012). "Breeding for coffee quality" in Specialty coffee: Managing quality. eds. T. Oberthür, P. Läderach, J. Pohlan and J. Cock (Southeast Asia: Penang), 89–117.

Montagnon, C., Sheibani, F., Benti, T., Daniel, D., and Bote, A. D. (2022). Deciphering early movements and domestication of *Coffea arabica* through a comprehensive genetic diversity study covering Ethiopia and Yemen. *Agronomy* 12:3203. doi: 10.3390/agronomy12123203

Nadaleti, D. H. S., de Abrahão, R. J. C., Andrade, V. T., Malta, M. R., Botelho, C. E., and Carvalho, G. R. (2022a). Sensory quality characterization and selection from a *Coffea arabica* germplasm collection in Brazil. *Euphytica* 218:35. doi: 10.1007/s10681-022-02985-2

Nadaleti, D. H. S., de Rezende Abrahão, J. C., Malta, M. R., dos Santos, C. S., Pereira, A. A., and Carvalho, G. R. (2022b). Influence of postharvest processing on the quality and sensory profile of groups of *arabica* coffee genotypes. *J. Sci. Food Agric.* 102, 6899–6906. doi: 10.1002/jsfa.12051

Nadelberg, E., Polit, J. R., Orjuela, J. P., and Ranitzsch, K. (2017). Trading and transaction—market and finance dynamics. *Craft Sci. Coffee*, 205–223. doi: 10.1016/B978-0-12-803520-7.00009-8

Narasimhaswamy, R. (1965). *Coffea arabica* L. Collections from Ethiopia. *Indian Coffee*. 29, 14–30.

Ogutu, C., Cherono, S., Ntini, C., Wang, L., and Han, Y. (2022). Comprehensive analysis of quality characteristics in main commercial coffee varieties and wild arabica in Kenya. *Food Chemist* 14:100294. doi: 10.1016/j.fochx.2022.100294

Osorio, V., Pabón, J., Calderón, P. A., and Imbachi, L. C. (2021). Calidad física, sensorial y composición química del café cultivado en el departamento del Huila. *Rev. Cenicafé* 72:e72201. doi: 10.38141/10778/72201

Peñuela-Martínez, A. E., Guerrero, Á., and Sanz-Uribe, J. R. (2022). Cromacafé® Herramienta para identificar los estados de madurez de las variedades de café de fruto rojo. *AVT* 535, 1–8. doi: 10.38141/10779/0535

Pruvot-Woehl, S., Krishnan, S., Solano, W., Schilling, T., Toniutti, L., Bertrand, B., et al. (2020). Authentication of *Coffea arabica* varieties through DNA fingerprinting and its significance for the coffee sector. *J. AOAC Int.* 103, 325–334. doi: 10.1093/jaocint/qsz003

Quintero, G., Rizo, F., Piedrahita, A., Lizcano, I. E., Calderón, J. A., Ospina, O. S. G., et al. (2016). Dianóstico de la calidad del café según altitud, suelos y beneficio en varias regiones de Colombia. *Rev. Cenicafé* 67, 15–51. Available at: https://hdl.handle.net/10778/727

Salojärvi, J., Rambani, A., Yu, Z., Guyot, R., Strickler, S., Lepelley, M., et al. (2024). The genome and population genomics of allopolyploid *Coffea arabica* reveal the diversification history of modern coffee cultivars. *Nat. Genet.* 56, 721–731. doi: 10.1038/s41588-024-01695-w

Tessema, A., Alamerew, S., Kufa, T., and Garedew, W. (2011). Genetic diversity analysis for quality attributes of some promising *Coffea arabica* germplasm collections in southwestern Ethiopia. *J. Biol. Sci.* 11, 236–244. doi: 10.3923/jbs.2011.236.244