Heliyon 10 (2024) e34378

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Evaluation of physical and chemical characteristics of bean and cup quality of arabica coffee genotypes grown in Southern Ethiopia

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A R T I C L E I N F O

Keywords:
Coffee quality
Genotypic variability
Growing environment

A B S T R A C T

The study aimed to investigate physical characteristics, cup quality, and biochemical content variability among thirty South Ethiopian Arabica coffee genotypes over three locations. The results revealed the existence of statistically significant variation among genotype, location, and GEI effects for all studied traits. The overall coffee quality score for most of the tested genotypes in three locations was above 80 %. Therefore, in terms of quality, most of the tested genotypes can be used to produce specialty coffee in the study areas. A wider range of caffeine (0.52 % dwb to 1.53 % dwb) was recorded among the studied genotypes. Accordingly, the low caffeine contenting genotypes could be a promising candidate for the development of low caffeine varieties through selection and hybridization. Cluster analysis grouped genotypes into different clusters based on quality trait variation and similarity among genotypes. According to the PCA, caffeine content (0.35), chlorogenic acid (0.34), aromatic quality (0.31), trigonelline (0.29), acidity (0.28), astringency (0.28), color (0.27) in the first PCA, flavor (−0.48), and screen size (0.46) in the second PCA were the important variables contributing more to the variation, and these traits could be considered for effective parent selection in quality improvement programs. Genotype AW9648 achieved the highest score in overall quality attributes at all three locations and could be promoted as a promising candidate and best parent for hybridization in terms of quality. Hence, genotype by environment interaction was significant, the coffee quality improvement program should give due attention to incorporating genetic and environmental influences by using a multi-locational selection strategy.

1. Introduction

Coffee is the second most traded commodity and the most beloved non-alcoholic beverage in the world [1]. It is important in the lives of billions of people on the globe by giving pleasure and satisfaction to the consumer through flavor, aroma, and desirable physiological and psychological effects [2]. Although coffee is primarily consumed for its pleasant flavor and stimulating properties,

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https://doi.org/10.1016/j.heliyon.2024.e34378
Received 17 February 2023; Received in revised form 8 July 2024; Accepted 9 July 2024
Available online 10 July 2024
2405-8440/

recent investigations assert the health benefits of the beverage due to the presence of caffeine, trigonelline, and chlorogenic acids [3,4].

Coffee is a well-known pillar of the Ethiopian economy, which accounts for 34 % of its export earnings [5]. Growing, processing, trading, transporting, as well as marketing of coffee provide livelihood to about 25 million people directly or indirectly [6]. Coffee is the defining feature and sphere of Ethiopian culture, politics, economy, social life, and identity, with about 55 % of the production consumed domestically [7]. The cultural ceremony of Ethiopian coffee beverage preparation and drinking is unique and stunning.

Ethiopia is the origin and center of genetic diversity for Arabica coffee. The country has collected over 12,452 accessions from various coffee-growing ecology and maintained them in in-situ and ex-situ gene banks [6]. Different studies witnessed the existence of abundant genetic diversity among Arabica coffee genotypes [8–16]. Ethiopia has an ideal and suitable environment for the production of coffee in both quality and quantity [17]. Because of the suitable altitude, abundant rainfall, ideal temperature, fertile soil, and sufficient labor, the potential for coffee production is very high [18].

Despite the importance of coffee in Ethiopia's economy and the presence of ample genetic resources, favorable climate and soil types, cup and physical quality as well as biochemical evaluation is not yet done for most of the collections maintained in the gene bank including the south Ethiopian collection [19,20]. Therefore, an assessment of Ethiopian Arabica coffee genetic resources for quality have to be done for the development of superior-quality cultivars by exploiting the existing resources.

The diverse genetic basis for Arabica coffee and a wide range of ecological conditions in Ethiopia prevail for the production of different quality types. Ethiopian coffee is known for its unique characteristics including Sidama, Yirga Chefe, Harerige, Limu, Keffa, Gimbi, Amaro, Gujji, and Jinka coffee types. The country produces specialty coffee with a wide range of aromas and characteristic flavors. Specialty coffee currently accounts for 20 % of Ethiopia's coffee exports, and there is enormous potential to increase its share of the global market [21]. The country is privileged by a strong potential and opportunity to boost the specialty coffee market by producing the finest specialty coffee ever.

Caffeine, trigonelline, and chlorogenic acids are some of the coffee biochemical compounds that have been used to characterize coffee genotypes [22]. Different studies noted a significant variation in the caffeine, chlorogenic acids, and trigonelline contents of Arabica coffee [23,22,24]. Coffee's biochemical components affect the organoleptic characteristics that contribute to cup quality, which is a major factor in determining its market value and use [22]. As a result, the assessment of biochemical components in Arabica coffee genotypes is critical in the development of the best quality cultivar.

Green bean physical character and beverage quality assessment by a professional coffee cupper is crucial to examine the coffee quality and identify characteristic variations of the genotype. In the Ethiopian coffee research program, a coffee-cupping protocol was developed for the evaluation of *C. arabica* genotypes with specific evaluation criteria for the physical characteristics of green beans and cup quality [25]. The main bean physical characteristics are bean odor, color, and shape, whereas cup quality attributes are flavor, acidity, body, aromatic quality, aromatic intensity, astringency, bitterness, and overall cup quality. To evaluate Arabica coffee

Table 1
List of *C. arabica* genotypes evaluated for green bean physical characters, cup quality, and biochemical composition.

Serial No.	Genotypes	Source of collection
1	AW1777	South Ethiopian collection
2	AW4994	South Ethiopian collection
3	AW5994	South Ethiopian collection
4	AW7494	South Ethiopian collection
5	AW1995	South Ethiopian collection
6	AW9641	South Ethiopian collection
7	AW9644	South Ethiopian collection
8	AW9662	South Ethiopian collection
9	AW9622	South Ethiopian collection
10	AW9623	South Ethiopian collection
11	AW9628	South Ethiopian collection
12	AW7705	Sidama Collection
13	AW105	Sidama Collection
14	AW3106	Sidama Collection
15	AW4083	South Ethiopian collection
16	AW695	South Ethiopian collection
17	AW9610	South Ethiopian collection
18	AW9611	South Ethiopian collection
19	AW9617	South Ethiopian collection
20	AW9640	South Ethiopian collection
21	AW9648	South Ethiopian collection
22	AW9658	South Ethiopian collection
23	AW9660	South Ethiopian collection
24	AW4305	Sidama Collection
25	AW8105	Sidama Collection
26	AW12305	Sidama Collection
27	AW8806	Sidama Collection
28	Feyate	Standard check variety
29	Angafa	Standard check variety
30	74112	Standard check variety

genotypes physical character and beverage quality across different growing locations, the current study was conducted according to Ethiopian coffee coffee-cupping protocol [25].

One of Ethiopia's specialty coffee-producing areas is the south Ethiopian growing ecology, which contributes to more than 36 % of the national market for coffee production [26]. South Ethiopian coffee, with its unique and internationally branded spicy and floral flavor, is one of the main commercially available coffees among Ethiopian specialty coffees. Awada Agricultural Research Sub-Center, in collaboration with the Jimma Agricultural Center Coffee Research Team, collected over 700 coffee accessions from the southern Ethiopian regions (Sidama, Gedeo, Amaro, Gamo Gofa, Jinka, and Guji). These accessions are being evaluated and characterized, and 27 promising selections have been promoted for variety development. Through preliminary evaluation carried out at the Awada sub-center, these promising selections were promoted for their high yield potential, resistance to coffee berry disease, and resistance to coffee leaf rust. Even though these promising selections have been evaluated for disease resistance and yield performance, their cup and physical quality, as well as biochemical evaluation, are not yet done. In addition to this, the genotypic stability and wider adaptability in the different growing environments were not carried out. Therefore, this study was conducted with the objective of investigating the variation in green bean physical characteristics, cup quality, and biochemical content among 30 south Ethiopian Arabica coffee genotypes; assessing the effect of environment on green bean physical characteristics, cup quality, and biochemical content; and identifying the best quality coffee genotypes for the southern Ethiopian growing environment.

2. Materials and methods

2.1. Experimental sites

The field experiments were established at three research sites, namely Awada Agricultural Research Sub-Center (AARSC) ($6^0$45′46″N, $38^0$22′36″E, and 1740 masl); Shebedino trial field ($6^0$50′48″N, $38^0$27′06″E, and 1845 masl), and Wonago substation ($6^0$13′34″N, $38^0$27′06″E, and 1945 masl). All three sites are found in the south Ethiopian specialty coffee growing agro-ecology.

3. Experimental materials

A total of 30 Arabica coffee genotypes, comprising twenty-seven promising selections and three standard check varieties, were used for this experiment (Table 1). The promising selections were promoted from different south Ethiopian coffee collection batches for their resistance to coffee berry disease (CBD), resistance to coffee leaf rust (CLR), and high yield performance during a preliminary evaluation carried out at the Awada agricultural research sub-center (Table 1).

4. Experimental design

Thirty genotypes (27 selections and 3 standard check varieties) were planted in August 2015 in a population of 8 trees per plot with 3 replications and 2 m by 2 m spacing per location by using a randomized complete block design. All agronomic management practices were applied as per the recommendations per location.

The laboratory experiment was arranged in a completely randomized design (CRD) with three replications per location.

4.1. Sample preparation

During peak harvesting time in October 2021, about 8 kg of healthy and fully matured red-ripened coffee cherries were handpicked from the 30 genotypes per 3 replication per each three locations. Therefore, 90 samples were prepared per location. Prior to processing, over-mature and immature cherries and foreign materials were sorted out from all samples.

The samples were pulped on the day of harvest using a single-disc manual pulper to separate beans from the skin and pulp. The wet parchment coffee was left in the fermentation tank for 40 h to facilitate the breakdown of mucilage. After fermentation, the parchment coffee was properly washed and under gone further 24 h of soaking and washing. The fermentation process was done according to Woelore, (1993) fermentation protocols for Arabica coffee under Ethiopian conditions [27]. Following fermentation, the samples were placed on a raised mesh wire under the sun for drying. During drying, the amount of moisture in the parchment coffee was measured using a moisture tester H-E50 to keep the moisture level consistent at 10.5–11.0 % for all samples. About 500-g samples of green coffee beans per treatment were prepared and leveled for evaluation of physical character, cup quality, and biochemical content.

4.2. Bean physical character assessment

Three Q-grade certified and experienced cuppers assessed cup quality and bean physical character in the Ethiopian commodity exchange (ECX) laboratory at the Hawassa branch. All three professional and certified Q-grade coffee cuppers are permanent employees of the ECX authority at the Hawassa branch. The cup quality and physical character of the bean were assessed using Sualeh and Mekonnen's coffee-cupping protocol [25].

About 300 g of green bean sample from each of the 270 experimental units (30 genotypes x 3 locations x 3 replications) was used for assessment of screen size, shape and make, color, and odor according to Sualeh and Mekonnen's coffee-cupping protocol [25] based on scale values given in Table 2. Screen size determination was carried out using a rounded and perforated screen plate. The percentage of coffee beans retained above the screen-size holes of 14 (1/64 inch of 14) was recorded. The shape and make of coffee samples were evaluated based on 1–5 scales as very good, good, fair good, average, mixed, and small. Color was evaluated out of 15 using a 1–6 scale as bluish, grayish, greenish, coated, faded, and white. Odor was evaluated out of 10 using a 1–5 scale as clean, fair clean, trace, light, light, moderate, and strong (Table 2).

4.3. Cup quality assessment

About 100 g of green coffee beans were prepared for each of the 270 samples (30 genotypes with 3 replications at each of the 3 locations). The roaster machine probatBRZ6 was heated first to about 200 °C. Coffee samples were roasted medium roast (8 min on average) and tipped out into the cooling tray. Cold air was blown through the roasted coffee to produce rapid cooling and then stored in an airtight glass jar for about 12 h before grinding. The loose silver skins were removed with a blaster before grinding. The samples were ground using a Mahlkoing electrical grinder to medium sized grounds, placed in ceramic cups, and covered. Eight grams of coffee powder were put into each cup, which has 180 ml of capacity [25]. Then, boiling water was poured onto the ground coffee up to about halfway in the cup. Soon after, the volatile aromatic quality and intensity parameters were recorded using sniffing. Then, the content of the cup was stirred to ensure an infusion of all coffee grounds. The cup was then completely filled with boiled water at about 92^0c [25]. The brew was made and ready for panelists within 8 min at the ECX Laboratory Hawassa branch.

Cup quality analysis was carried out once the beverage cooled to around 60 °C (drinkable temperature). Three cups per sample per cupper were prepared for the tasting session. The coffee type and the replicates were arranged at random. Cup quality attributes such as aromatic quality, aromatic intensity, astringency, and bitterness were scored on a scale of 0–5, and acidity, body, flavor, and overall cup quality were scored on a scale of 0–10 [25], as shown in Table 2. Each experienced and certified Q-grade cuppers gave their independent judgment for each sample.

4.4. Caffeine, trigonelline and chlorogenic acid analysis

Analysis of caffeine, trigonelline, and chlorogenic acid was performed in the food science and nutrition laboratory of the Ethiopian Institute of Agricultural Research (EIAR). Caffeine, trigonelline, and chlorogenic acid contents were analyzed as described by Vignoli et al. (2014) [28]. Ground green coffee beans (0.5 g) were subjected to direct solvent extraction with 50 ml of distilled water (hot water, 95 °C) and stirred for 20 min on a hot plate. Then, the solvent extract was filtered through No. 4 Whatman filter followed by a 0.45 μm PTFE filter prior to injection into the HPLC having a prevail C18 (250 × 4.6 mm, i.d. 5 μm, 25 °C) column. The mobile phase was composed of 5 % acetic acid in water (v/v) (solvent A) and acetonitrile (solvent B). The injection volume was 10 μL, and the flow rate was 0.5 ml min^{-1}. Caffeine and trigonelline were detected by a UV detector at 280 and 320 nm wavelength respectively, whereas total chlorogenic acid was detected at 320 nm. Calibration curves of caffeine, trigonelline, and chlorogenic acid standards were used for the quantification of those compounds. Caffeine, trigonelline, and chlorogenic acid were identified by comparing the retention times of the caffeine standard, trigonelline standard, and chlorogenic acid standard and their concentrations calculated from peak areas using calibration equations. Calibration curves were made using the standard concentration and area of the sample, which were subsequently used to calculate the composition of the respective biochemical component using the area generated after a retention time [29].

4.5. Data analysis

The data were subjected to analysis of variance (ANOVA) for each location separately using the Statistical Analysis System (SAS 9.4 version statistical package) to examine the presence of statistically significant differences among genotypes in their performance for bean physical characteristics, cup quality, and biochemical composition traits. Combined analyses were performed to determine genotypic effects, location effects, and genotype by environment interaction effects. Levene's test was used to test the homogeneity of variances between environments to determine the validity of the combined ANOVA on the data. The mean separation was carried out

Table 2
Form completed by sensory evaluator for green bean character and cup quality.

No	Characters	Scale Value Description
Cup quality Characteristics		
1	Aromatic Quality (5)	5 (Excellent), 4 (V. good), 3 (Good), 2 (Regular), 1(Bad), 0(Nil)
2	Aromatic Intensity (5)	5 (Very strong), 4 (Strong), 3 (Medium), 2 (Light), 1 (Very Light), 0 (Nil)
3	Acidity (10)	10 (Pointed), 8 (Medium pointed), 6 (Medium), 4 (Light), 1 (Lacking), 0(Nil)
4	Astringency (5)	5 (Nil), 4 (Very light), 3 (Light), 2 (Medium), 1 (Strong), 0 (Very Strong)
5	Bitterness (5)	5 (Nil), 4 (Very light), 3 (Light), 2 (Medium), 1 (Strong), 0 (Very Strong)
6	Body (10)	10 (Full), 8 (Medium full), 6 (Medium), 4 (Light), 2 (Very Light), 0 (Nil)
7	Flavour (10)	10 (V. good), 8 (Good), 6 (Average), 4 (Fair), 2 (Bad), 0 (Nil)
8	Overall cup Quality (10)	10 (Excellent), 8 (V. good), 6 (Good), 4 (Regular), 2 (Bad), 0 (Unacceptable)
Green Bean Physical Characteristics		
1	Shape and Make (15 %)	15 (V. good), 12 (Good), 10 (Fair), 8 (Average), 6 (Mixed) 4 (Small)
2	Color (15 %)	15 (Bluish), 12 (Greyish), 10 (Greenish), 8 (Coated), 6 (Faded) 4 (White)
3	Oder (10)	10 (Clean), 8(Fair clean), 6 (Trace), 4(Light), 2(Light moderate), 0 (Strong)

Source [25]:

Table 3
Analysis of variance (mean squares) for the 18 characters of 30 Arabica coffee genotypes grown at Awada, Shebedino and Wonago.

Traits	Awada			Shebedino			Wonago			Combined				CV
	Gen	Error	CV	Gen	Error	CV	Gen	Error	CV	Gen	Loc	Gen*Loc	Error	
	(df = 29)	(df = 58)		(29)	(df = 58)		(df = 29)	(df = 58)		(df = 29)	(df = 2)	(df = 58)	(df = 178)	
SS	4.98**	0.42	0.67	2.55**	0.35	0.61	7.09**	0.84	0.95	9.66**	6.72**	2.48**	0.55	0.8
SM	2.76**	0.35	4.8	3.50**	0.19	3.5	1.46**	0.04	1.68	3.79**	0.55*	0.84**	0.19	3.5
Col	3.80**	0.89	8.56	5.75**	1.80	11.59	1.69**	0.48	6.19	7.39**	7.45**	1.92**	1.07	9.2
Od	2.37**	0.09	3.19	1.53**	0.40	6.69	2.13**	0.04	0.44	1.55**	6.32**	1.39**	0.18	4.4
RwT	13.53**	1.20	3.35	14.00**	2.05	4.28	5.19**	0.49	2.09	22.57**	17.91**	5.07**	1.25	3.4
AQ	0.99**	0.15	9.63	0.34*	0.15	10.1	0.32*	0.14	9.48	0.76**	1.25*	0.44**	0.16	10
AI	0.75**	0.21	11.58	0.28**	0.05	5.78	0.52**	0.2	11.79	0.95**	0.71*	0.29**	0.17	11
Ac	0.59**	0.16	4.88	2.09**	0.17	5.01	1.07*	0.76	10.53	0.86*	2.02**	0.87**	0.38	7.3
AS	0.29*	0.19	9.94	0.32*	0.17	9.26	0.29*	0.08	10.65	0.51*	0.21^{ns}	0.35*	0.22	11
Bit	0.59*	0.25	12.15	0.18*	0.10	7.59	0.68*	0.41	15.27	1.00**	0.41^{ns}	0.22^{ns}	0.26	12
Bod	0.17**	0.03	2.08	0.11**	0.04	2.62	0.56**	0.04	2.6	0.69**	0.07^{ns}	0.08**	0.04	2.4
Flav	1.32*	0.55	12.72	1.14**	0.23	6.03	1.98**	0.73	10.74	1.80**	0.90^{ns}	1.32**	0.66	10
OQL	0.47*	0.14	7.22	0.50**	0.13	4.64	1.75**	0.51	8.95	1.44**	1.40*	0.64**	0.33	7.2
TCQ	16.59**	4.00	4.08	1.23**	13.16	2.3	29.14**	4.69	4.45	35.98**	9.12^{ns}	11.46**	3.33	3.8
TRC	40.63**	5.16	2.78	40.49**	2.74	2.02	46.02**	4.4	2.55	100.44**	4.14^{ns}	13.35**	4.16	2.5
Tri	0.14**	0.002	1.43	0.04**	0.003	8.73	0.03**	0.001	3.4	0.06**	4.44**	0.07**	0.001	4.8
Chl	1.17**	0.002	1.13	1.08**	0.004	1.49	1.08**	0.003	1.1	0.77**	11.56**	1.28**	0.003	1.2
Caf	2.07**	0.001	2.07	0.07**	0.001	1.17	0.06**	0.000	2.29	0.10**	0.13**	0.07**	0.002	4.7

Where: Gen = Genotype, Loc = Location, Gen*Loc = Genotype by environment interaction, df = degree of freedom, *& ** = Significant at $P < 0.05$ and $P < 0.01$ respectively, ns = non-significant, CV (%) = coefficient of variation in percent; Numbers in parenthesis stands for the degree of freedom, SS = screen size, SM = shape & make, Col = color, od = odor, RawT = raw total, AQ = aromatic quality, AI = aromatic intensity, Aci = acidity, AS = astringency, Bit = Bitterness, Bod = body, Fla = flavor, OQL = overall quality, TCQ = Total Cup Quality, TRC = Total Raw and Cup quality, Tri = Trigonelline Chl = Chlorogenic acid, Caf = Caffeine.

Table 4
Mean value of 30 Arabica coffee genotypes for 18 characteristics at Awada, Wonago, Shebedino, and combined over locations.

Location	Treatment	SS	SM	Col	Od	RawT	AQ	AI	Acid	AST	Bit	Bod	Flav	OQL	TotalR	RCup	Trigo	Chlor	Caff
Awada	AW1777	95.00	12.00	9.33	8.00	29.33	4.00	3.67	8.67	4.67	4.00	8.20	9.33	8.00	50.53	79.86	1.38	4.22	0.86
Awada	AW105	97.00	11.33	12.00	8.00	31.33	4.00	4.00	8.00	4.00	3.67	8.00	8.67	8.00	48.33	79.67	0.84	3.24	0.78
Awada	AW12305	96.67	12.00	10.67	10.00	32.67	3.33	3.33	8.00	4.33	4.00	8.52	7.33	8.00	46.85	79.52	0.98	3.62	0.80
Awada	AW1995	96.00	12.00	11.33	8.00	31.33	4.33	4.00	8.00	4.33	4.00	8.30	8.67	8.67	50.30	81.63	1.39	3.43	0.60
Awada	AW3106	95.00	12.00	11.33	10.00	33.33	3.67	3.67	8.00	4.33	4.00	8.00	8.00	8.00	47.67	81.00	0.79	3.80	0.78
Awada	AW4083	96.00	12.00	10.00	10.00	32.00	4.33	4.33	8.67	4.33	4.33	8.00	7.33	8.00	49.34	81.34	0.92	4.73	1.16
Awada	AW4305	97.00	10.00	10.00	8.00	28.00	4.00	4.00	8.00	4.33	4.00	8.00	8.00	8.00	48.33	76.33	0.91	3.64	0.99
Awada	AW4994	96.33	12.00	10.00	10.00	32.00	5.00	4.67	8.00	4.67	4.33	8.00	9.33	8.00	52.00	84.00	0.98	3.99	0.90
Awada	AW5994	96.00	12.00	10.67	9.33	32.00	3.67	3.67	8.00	4.00	3.00	8.00	8.00	7.33	45.67	77.67	0.81	2.91	0.75
Awada	AW695	97.00	12.00	12.00	10.00	34.00	4.33	4.33	8.00	4.00	4.00	8.00	8.00	8.00	48.67	82.67	0.93	3.78	0.90
Awada	AW7494	97.00	12.00	10.00	10.00	32.00	5.00	5.00	8.00	5.00	5.00	7.93	8.67	8.67	53.26	85.26	0.87	3.55	0.91
Awada	AW7705	97.00	12.00	12.00	10.00	34.00	4.00	4.00	8.00	4.00	4.00	8.00	8.00	8.00	48.00	82.00	0.86	4.37	1.04
Awada	AW8105	95.67	12.00	10.00	10.00	32.00	4.00	4.00	8.00	4.33	4.00	8.10	8.00	8.67	49.10	81.10	1.24	4.12	0.96
Awada	AW8806	94.67	12.00	12.00	9.33	33.33	4.67	4.33	8.00	4.67	4.33	8.07	8.67	9.33	52.07	85.41	1.11	4.12	0.94
Awada	AW9610	98.00	12.00	11.33	10.00	33.33	4.00	4.00	8.00	4.67	4.67	8.00	8.00	8.00	49.33	82.67	1.28	3.38	0.92
Awada	AW9611	98.00	13.00	11.00	10.00	34.00	4.33	4.33	8.67	4.00	4.00	8.00	8.00	8.00	49.34	83.34	1.49	3.55	0.84
Awada	AW9617	98.00	14.00	10.00	10.00	34.00	3.67	3.67	8.00	4.00	4.00	7.93	7.33	8.67	47.26	81.26	1.02	4.12	0.82
Awada	AW9622	97.00	12.00	10.67	8.00	30.67	3.00	3.00	8.67	4.00	3.33	8.00	8.00	8.00	46.00	76.67	1.49	3.40	0.69
Awada	AW9623	97.00	12.00	10.67	10.00	32.67	4.33	4.33	8.67	4.33	4.33	8.20	7.33	8.00	49.53	82.20	1.07	3.63	0.79
Awada	AW9628	95.00	12.00	11.33	8.00	31.33	3.00	3.33	8.00	4.67	3.33	7.93	6.67	8.00	44.93	76.26	0.73	4.06	0.86
Awada	AW9640	93.00	12.00	10.00	10.00	32.00	4.67	4.33	8.45	4.67	4.67	8.10	8.00	8.00	50.88	82.88	1.09	5.01	1.05
Awada	AW9641	95.00	12.00	11.33	8.00	31.33	3.33	3.33	8.00	4.33	3.67	8.20	8.00	7.33	46.20	77.53	1.00	3.17	0.80
Awada	AW9644	96.00	12.00	10.00	10.00	32.00	4.00	3.33	8.00	4.00	4.00	8.00	8.00	8.00	47.33	79.33	1.28	3.39	0.72
Awada	AW9648	96.00	15.00	15.00	10.00	40.00	4.67	4.67	10.00	4.33	4.67	9.19	8.00	8.67	54.19	94.19	1.04	3.48	0.73
Awada	AW9658	97.00	12.00	10.67	10.00	32.67	3.67	3.67	8.00	4.00	4.00	8.20	8.00	8.00	47.53	80.20	0.90	4.11	1.03
Awada	AW9660	96.00	12.00	12.00	10.00	34.00	4.00	4.00	8.00	4.33	4.00	8.20	6.67	8.00	47.20	81.20	0.98	4.02	0.90
Awada	AW 9662	95.00	12.00	10.00	10.00	32.00	3.00	3.33	8.00	4.67	3.67	8.00	8.67	8.00	47.33	79.33	0.97	3.85	0.92
Awada	74112	94.00	12.00	10.67	10.00	32.67	5.00	4.67	8.67	4.67	4.00	8.00	8.00	8.00	51.00	83.67	1.02	3.85	0.73
Awada	Angafa	99.00	15.00	12.00	10.00	37.00	4.00	4.00	8.67	4.67	4.67	8.00	8.00	8.00	50.00	87.00	1.42	5.90	0.95
Awada	Feyate	96.00	13.00	12.33	8.00	33.33	4.67	4.67	8.67	5.00	4.67	8.10	9.33	8.00	53.10	86.43	0.93	5.00	1.53
Awada Mean		96.21	12.24	11.01	9.42	32.68	4.06	3.99	8.26	4.38	4.08	8.11	8.07	8.11	49.04	81.72	1.06	3.91	0.89
StD		1.29	0.96	1.12	0.89	2.13	0.58	0.50	0.45	0.32	0.45	0.24	0.66	0.40	2.36	3.68	0.22	0.63	0.17
CV		0.67	4.80	8.56	3.19	3.35	9.63	11.58	4.88	9.94	12.15	2.08	12.72	7.22	4.08	2.78	1.43	1.13	2.07
Wonago	AW1777	97.00	12.00	11.11	9.33	32.45	3.67	3.33	8.00	4.33	4.00	8.00	6.67	8.00	46.00	78.45	0.62	4.20	0.96
Wonago	AW105	98.00	12.00	11.56	10.00	33.56	3.67	3.67	8.00	4.33	4.33	8.00	7.33	7.33	46.67	80.22	0.71	5.61	1.06
Wonago	AW12305	92.00	12.00	11.78	10.00	33.78	4.00	4.00	8.00	4.67	4.00	9.33	8.00	8.00	50.00	83.78	0.60	4.54	0.82
Wonago	AW1995	98.00	12.00	11.55	10.00	33.55	4.00	4.00	8.67	5.00	5.00	8.00	8.00	8.00	50.67	84.22	0.63	4.89	0.90
Wonago	AW3106	96.00	12.00	11.33	10.00	33.33	3.33	3.67	8.00	4.33	4.33	8.00	7.33	8.00	47.00	80.33	0.87	5.15	0.84
Wonago	AW4083	96.00	12.33	11.11	10.00	33.44	4.00	3.67	10.00	4.67	4.67	8.00	8.00	8.00	51.00	84.44	0.66	4.36	1.02
Wonago	AW4305	97.00	11.00	9.33	10.00	30.33	3.00	2.67	7.33	3.67	3.00	8.00	6.00	5.00	38.67	69.00	0.71	3.63	0.64
Wonago	AW4994	98.00	12.00	10.89	10.00	32.89	3.67	3.67	8.00	4.00	4.00	8.00	8.00	7.33	46.67	79.55	0.68	5.02	0.85
Wonago	AW5994	98.00	13.11	11.11	10.00	34.22	3.67	3.33	8.00	4.33	4.00	8.00	6.67	8.00	46.00	80.22	0.85	4.53	0.65
Wonago	AW695	94.00	11.33	11.33	10.00	32.67	3.67	3.67	8.67	5.00	4.00	8.00	8.67	8.67	50.33	83.00	0.55	4.60	0.88
Wonago	AW7494	97.00	12.00	11.66	10.00	33.66	4.00	3.67	8.67	4.67	5.00	8.00	8.00	8.00	50.00	83.66	0.72	5.11	0.99
Wonago	AW7705	98.00	12.00	11.89	10.00	33.89	3.67	4.00	8.67	5.00	4.67	8.00	8.00	8.00	50.00	83.89	0.85	5.02	1.10
Wonago	AW8105	97.00	13.00	11.34	10.00	34.34	4.33	4.33	8.00	4.33	4.00	8.00	8.00	8.00	49.00	83.34	0.71	4.01	0.93
Wonago	AW8806	95.33	12.00	12.33	10.00	34.33	4.00	3.67	8.00	4.33	4.00	8.00	8.00	8.00	48.00	82.33	0.68	5.38	0.91
Wonago	AW9610	98.00	12.67	10.45	10.00	33.11	4.33	4.33	8.00	4.33	4.33	8.00	8.00	8.00	49.33	82.45	0.83	4.57	0.72

(continued on next page)

Table 4 (*continued*)

Location	Treatment	SS	SM	Col	Od	RawT	AQ	AI	Acid	AST	Bit	Bod	Flav	OQL	TotalR	RCup	Trigo	Chlor	Caff
Wonago	AW9611	97.00	12.33	10.78	10.00	33.11	4.33	4.00	8.00	4.33	4.00	8.00	8.67	8.00	49.33	82.44	0.87	4.45	0.78
Wonago	AW9617	97.00	12.00	10.67	10.00	32.67	4.00	4.00	8.00	4.67	4.33	8.00	8.00	8.00	49.00	81.67	0.67	4.53	0.89
Wonago	AW9622	98.00	14.00	10.67	10.00	34.67	4.00	3.67	8.00	4.00	3.67	8.00	8.00	7.33	46.67	81.33	0.73	4.59	1.13
Wonago	AW9623	96.00	12.00	11.55	10.00	33.55	4.00	4.00	8.67	4.67	5.00	8.00	8.67	8.00	51.00	84.55	0.57	3.45	0.62
Wonago	AW9628	96.00	12.00	11.55	10.00	33.55	3.67	3.33	7.33	4.33	3.33	8.00	6.67	7.33	44.00	77.55	0.60	4.57	0.99
Wonago	AW9640	96.00	11.00	10.22	10.00	31.22	4.00	3.67	8.67	5.00	3.67	8.00	9.33	8.67	51.00	82.22	0.56	3.80	0.88
Wonago	AW9641	96.00	13.67	11.11	10.00	34.78	3.67	4.00	8.00	4.33	4.33	8.00	8.00	7.33	47.67	82.45	0.57	5.01	0.97
Wonago	AW9644	97.00	13.00	11.11	10.00	34.11	4.00	4.00	8.67	4.67	4.67	8.00	8.67	8.00	50.67	84.78	0.76	5.64	1.02
Wonago	AW9648	92.67	13.00	13.22	10.00	36.22	4.33	4.33	10.00	4.33	4.33	10.00	10.00	10.00	57.33	93.55	0.69	4.65	0.94
Wonago	AW9658	96.00	12.00	9.78	8.00	29.78	4.00	3.67	8.00	4.33	4.00	8.00	7.33	8.67	48.00	77.78	0.65	4.06	0.78
Wonago	AW9660	95.00	12.00	11.33	10.00	33.33	4.00	4.00	8.00	4.33	4.00	8.00	8.00	8.00	48.33	81.67	0.76	3.67	0.71
Wonago	AW 9662	96.00	13.00	10.89	10.00	33.89	3.67	3.33	8.00	4.33	4.33	8.00	8.00	8.00	47.67	81.56	0.70	5.31	1.04
Wonago	74112	95.67	12.00	10.67	10.00	32.67	4.00	4.00	8.67	4.33	3.67	8.00	8.67	8.00	49.33	82.00	0.58	4.33	1.04
Wonago	Angafa	97.67	13.00	11.89	10.00	34.89	4.67	5.00	8.67	4.67	4.67	8.00	8.67	8.67	53.00	87.89	0.58	4.78	0.91
Wonago	Feyate	98.00	13.00	12.00	10.00	35.00	4.00	3.67	8.00	4.67	4.67	8.00	8.00	8.00	49.00	84.00	0.72	3.44	0.97
Wonago Mean		96.44	12.31	11.21	9.91	33.43	3.91	3.81	8.29	4.47	4.20	8.11	7.98	7.94	48.71	82.14	0.69	4.56	0.90
StD		96.45	12.31	11.21	9.91	33.44	3.92	3.82	8.30	4.46	4.20	8.11	7.98	7.94	48.71	82.15	0.69	4.56	0.90
CV		0.95	1.68	6.19	0.44	2.09	9.48	11.79	10.53	10.65	15.27	2.60	10.74	8.95	4.45	2.55	3.40	1.10	2.29
Shebedino	AW1777	96.67	12.00	12.00	10.00	34.00	3.00	3.33	8.00	4.33	4.00	8.15	8.00	8.00	46.48	80.48	0.62	4.59	0.97
Shebedino	AW105	97.67	12.11	11.33	10.00	33.44	3.67	3.89	8.00	5.00	4.22	8.00	8.00	8.00	48.89	82.33	0.60	4.54	0.87
Shebedino	AW12305	95.56	12.33	14.00	10.00	36.33	3.67	3.78	8.67	4.00	4.00	8.22	6.67	7.33	46.56	82.89	0.68	3.38	0.58
Shebedino	AW1995	97.00	11.78	11.33	10.00	33.11	3.33	4.00	8.00	4.33	4.44	8.22	8.00	8.00	48.34	81.45	0.44	3.03	0.58
Shebedino	AW3106	96.00	12.00	12.00	10.00	34.00	4.00	3.78	8.00	4.67	4.11	8.07	8.00	8.00	48.78	82.78	0.51	4.54	0.82
Shebedino	AW4083	96.33	12.11	12.00	10.00	34.11	4.00	4.33	8.00	4.00	4.56	8.00	8.00	8.00	49.56	83.67	0.88	4.49	0.94
Shebedino	AW4305	97.33	11.00	7.33	8.00	26.33	3.00	3.22	6.00	4.00	3.67	8.00	6.00	6.00	39.67	66.00	0.67	5.48	0.64
Shebedino	AW4994	97.44	12.33	11.33	8.67	32.33	3.67	4.11	8.00	4.67	4.33	8.00	8.00	8.00	48.67	81.00	0.66	3.38	0.60
Shebedino	AW5994	97.33	13.37	11.33	8.00	32.70	4.00	3.67	8.00	4.67	3.78	8.00	8.00	8.00	48.44	81.15	0.57	3.32	0.52
Shebedino	AW695	96.33	11.33	11.33	8.67	31.33	4.00	4.00	8.00	4.33	4.11	8.00	7.33	8.00	47.78	79.11	0.57	3.47	0.90
Shebedino	AW7494	97.33	12.33	13.00	9.33	34.67	3.67	4.22	8.00	4.00	4.56	7.78	7.33	7.33	46.67	81.33	0.69	4.30	0.91
Shebedino	AW7705	97.67	12.00	10.67	10.00	32.67	3.67	4.00	8.00	4.00	4.22	8.00	8.00	8.00	47.89	80.55	0.81	3.95	0.95
Shebedino	AW8105	96.89	12.66	14.00	10.00	36.66	3.67	3.78	8.00	4.00	4.00	8.07	8.00	8.00	46.74	83.41	0.65	4.54	0.81
Shebedino	AW8806	94.00	12.33	13.00	10.00	35.33	4.00	4.00	8.00	4.00	4.22	8.22	8.00	8.00	48.44	83.78	0.88	3.39	0.96
Shebedino	AW9610	97.89	12.22	10.00	8.00	30.22	4.00	4.11	8.00	4.33	4.33	8.00	8.00	8.00	48.67	78.89	0.60	4.48	0.76
Shebedino	AW9611	97.67	12.44	10.67	10.00	33.11	4.00	4.11	10.00	4.33	4.11	8.00	8.00	8.00	50.44	83.55	0.67	4.10	0.87
Shebedino	AW9617	97.67	12.67	11.33	9.33	33.33	4.00	3.89	9.33	4.33	4.22	7.78	8.00	8.00	49.66	83.00	0.71	3.98	1.01
Shebedino	AW9622	97.67	13.34	10.67	8.67	32.67	4.00	3.56	8.00	5.00	4.00	8.00	8.00	8.00	49.00	81.67	0.81	3.98	0.79
Shebedino	AW9623	97.00	12.00	12.00	10.00	34.00	4.00	4.11	8.00	4.33	4.44	8.15	8.00	8.00	48.93	82.93	0.68	4.46	1.06
Shebedino	AW9628	95.89	12.33	12.00	10.00	34.33	3.33	3.22	10.00	5.00	3.78	7.78	7.33	8.00	48.22	82.55	0.79	3.45	0.80
Shebedino	AW9640	95.67	11.45	10.00	10.00	31.45	4.33	4.00	8.00	4.33	4.22	8.07	8.00	8.00	48.96	80.41	0.90	4.50	0.87
Shebedino	AW9641	96.33	13.22	10.67	9.33	33.22	4.33	3.78	8.00	4.67	4.22	8.15	10.00	8.00	51.37	84.59	0.51	3.26	0.56
Shebedino	AW9644	97.00	13.33	12.00	9.33	34.66	3.67	3.78	8.00	4.67	4.44	8.00	7.33	7.33	47.44	82.11	0.66	3.99	0.84
Shebedino	AW9648	95.56	13.33	14.00	10.00	37.33	4.00	4.33	10.00	4.33	4.56	8.89	8.00	8.00	51.78	89.11	0.57	4.67	1.03
Shebedino	AW9658	97.00	12.00	10.00	8.67	30.67	4.00	3.78	8.67	4.00	3.89	8.15	8.00	8.00	48.70	79.37	0.67	3.45	0.60
Shebedino	AW9660	96.33	12.00	11.33	10.00	33.33	4.00	4.00	8.00	4.67	4.11	8.15	8.00	8.00	48.93	82.26	0.69	4.08	0.85
Shebedino	AW 9662	96.00	13.33	12.00	8.67	34.00	3.67	3.56	8.00	4.33	4.00	8.00	8.00	8.00	48.00	82.00	0.46	3.72	0.76
Shebedino	74112	95.89	12.33	10.67	10.00	33.00	3.67	4.22	8.67	4.67	4.11	8.00	8.00	8.00	49.11	82.11	0.60	2.78	1.00
Shebedino	Angafa	98.22	13.33	13.00	10.00	36.33	4.00	4.33	8.00	4.67	4.56	8.00	8.00	8.00	49.22	85.56	0.52	3.98	0.81
Shebedino	Feyate	97.33	13.00	12.33	10.00	35.33	4.33	4.11	10.00	4.00	4.44	8.07	8.00	8.00	50.85	86.19	0.71	4.01	1.03
Shebedino Mean		96.76	12.40	11.58	9.49	33.47	3.82	3.90	8.31	4.39	4.19	8.06	7.87	7.87	48.41	81.87	0.66	3.98	0.82

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Table 4 (*continued*)

Location	Treatment	SS	SM	Col	Od	RawT	AQ	AI	Acid	AST	Bit	Bod	Flav	OQL	TotalR	RCup	Trigo	Chlor	Caff
StD		0.92	0.64	1.38	0.71	2.16	0.33	0.30	0.83	0.34	0.24	0.20	0.62	0.41	2.09	3.68	0.12	0.6	0.16
CV		0.61	3.50	11.59	6.69	4.28	10.10	5.78	5.01	9.26	7.59	2.62	6.03	4.64	2.30	2.02	8.73	1.49	1.17
Combined	AW1777	96.22	12.00	10.82	9.11	31.93	3.56	3.44	8.22	4.44	4.00	8.12	8.00	8.00	47.67	79.60	0.87	4.34	0.93
Combined	AW105	97.56	11.81	11.63	9.33	32.78	3.78	3.85	8.00	4.44	4.07	8.00	8.00	7.78	47.96	80.74	0.71	4.46	0.91
Combined	AW12305	94.74	12.11	12.15	10.00	34.26	3.67	3.70	8.22	4.33	4.00	8.69	7.33	7.78	47.80	82.06	0.75	3.85	0.74
Combined	AW1995	97.00	11.93	11.41	9.33	32.67	3.89	4.00	8.22	4.56	4.48	8.17	8.22	8.22	49.77	82.43	0.82	3.78	0.69
Combined	AW3106	95.67	12.00	11.56	10.00	33.56	3.67	3.70	8.00	4.44	4.15	8.02	7.78	8.00	47.81	81.37	0.73	4.49	0.81
Combined	AW4083	96.11	12.15	11.04	10.00	33.18	4.11	4.11	8.89	4.33	4.52	8.00	7.78	8.00	49.96	83.15	0.82	4.53	1.04
Combined	AW4305	97.11	10.67	8.89	8.67	28.22	3.33	3.30	7.11	4.00	3.56	8.00	6.67	6.33	42.22	70.45	0.76	4.25	0.76
Combined	AW4994	97.26	12.11	10.74	9.56	32.41	4.11	4.15	8.00	4.44	4.22	8.00	8.44	7.78	49.11	81.52	0.78	4.13	0.78
Combined	AW5994	97.11	12.83	11.04	9.11	32.97	3.78	3.56	8.00	4.33	3.59	8.00	7.56	7.78	46.70	79.68	0.74	3.59	0.64
Combined	AW695	95.78	11.55	11.56	9.56	32.67	4.00	4.00	8.22	4.44	4.04	8.00	8.00	8.22	48.93	81.59	0.68	3.95	0.89
Combined	AW7494	97.11	12.11	11.55	9.78	33.44	4.22	4.30	8.22	4.56	4.85	7.90	8.00	8.00	49.98	83.42	0.76	4.32	0.94
Combined	AW7705	97.56	12.00	11.52	10.00	33.52	3.78	4.00	8.22	4.33	4.30	8.00	8.00	8.00	48.63	82.15	0.84	4.45	1.03
Combined	AW8105	96.52	12.55	11.78	10.00	34.33	4.00	4.04	8.00	4.22	4.00	8.06	8.00	8.22	48.28	82.61	0.87	4.22	0.90
Combined	AW8806	94.67	12.11	12.44	9.78	34.33	4.22	4.00	8.00	4.33	4.19	8.10	8.22	8.44	49.51	83.84	0.89	4.30	0.93
Combined	AW9610	97.96	12.30	10.59	9.33	32.22	4.11	4.15	8.00	4.44	4.44	8.00	8.00	8.00	49.11	81.33	0.90	4.14	0.80
Combined	AW9611	97.56	12.59	10.81	10.00	33.41	4.22	4.15	8.89	4.22	4.04	8.00	8.22	8.00	49.70	83.11	1.01	4.04	0.83
Combined	AW9617	97.56	12.89	10.67	9.78	33.33	3.89	3.85	8.44	4.33	4.18	7.90	7.78	8.22	48.64	81.97	0.80	4.21	0.91
Combined	AW9622	97.56	13.11	10.67	8.89	32.67	3.67	3.41	8.22	4.33	3.67	8.00	8.00	7.78	47.22	79.89	1.01	3.99	0.87
Combined	AW9623	96.67	12.00	11.41	10.00	33.41	4.11	4.15	8.44	4.44	4.59	8.12	8.00	8.00	49.82	83.23	0.77	3.85	0.82
Combined	AW9628	95.63	12.11	11.63	9.33	33.07	3.33	3.30	8.44	4.67	3.48	7.90	6.89	7.78	45.72	78.79	0.71	4.02	0.88
Combined	AW9640	94.89	11.48	10.07	10.00	31.56	4.33	4.00	8.37	4.67	4.19	8.06	8.44	8.22	50.28	81.84	0.85	4.44	0.93
Combined	AW9641	95.78	12.96	11.04	9.11	33.11	3.78	3.70	8.00	4.44	4.07	8.12	8.67	7.56	48.41	81.52	0.69	3.81	0.78
Combined	AW9644	96.67	12.78	11.04	9.78	33.59	3.89	3.70	8.22	4.44	4.37	8.00	8.00	7.78	48.48	82.07	0.90	4.34	0.86
Combined	AW9648	94.74	13.78	14.07	10.00	37.85	4.33	4.44	10.00	4.33	4.52	9.36	8.67	8.89	54.43	92.28	0.77	4.27	0.90
Combined	AW9658	96.67	12.00	10.15	8.89	31.04	3.89	3.70	8.22	4.11	3.96	8.12	7.78	8.22	48.08	79.12	0.74	3.87	0.80
Combined	AW9660	95.78	12.00	11.56	10.00	33.56	4.00	4.00	8.00	4.44	4.04	8.12	7.56	8.00	48.15	81.71	0.81	3.93	0.82
Combined	AW 9662	95.67	12.78	10.96	9.56	33.30	3.44	3.41	8.00	4.44	4.00	8.00	8.22	8.00	47.67	80.96	0.71	4.29	0.91
Combined	74112	95.19	12.11	10.67	10.00	32.78	4.22	4.30	8.67	4.56	3.93	8.00	8.22	8.00	49.81	82.59	0.73	3.65	0.92
Combined	Angafa	98.30	13.78	12.30	10.00	36.07	4.22	4.44	8.45	4.67	4.63	8.00	8.22	8.22	50.74	86.82	0.84	4.89	0.89
Combined	Feyate	97.11	13.00	12.22	9.33	34.55	4.33	4.15	8.89	4.56	4.59	8.06	8.44	8.00	50.98	85.54	0.79	4.15	1.17
Combined Mean		96.47	12.32	11.27	9.61	33.19	3.93	3.90	8.29	4.41	4.16	8.09	7.97	7.97	48.72	81.91	0.80	4.15	0.87
StD		1.40	0.65	0.91	0.42	1.58	0.29	0.33	0.47	0.15	0.33	0.28	0.45	0.40	0.020	3.34	0.08	0.29	0.03
CV		0.80	3.50	9.20	4.40	3.40	10.00	11.00	7.30	11.00	12.00	2.40	10.00	7.20	3.80	2.50	4.80	1.20	4.70

using Turkey test at a 5 % level of significance. Principal component analysis (PCA) was done using SAS software to determine the relative importance of the traits responsible for variation among the sensory attributes and chemical composition. Coffee genotypes were grouped by the ward technique of clustering, which groups and arranges genotypes into clusters to generate a dendrogram using SAS software. The number of clusters was decided by following the approach suggested by Milligan and Cupper (1998) by the cubic clustering criteria (ccc), pseudo F statistics combined with values of pseudo t^2 statistics for the next cluster fusion [30].

5. Results and discussion

5.1. Variability of quality characters among coffee genotypes

A separate ANOVA revealed significant differences ($p < 0.05$ & $p < 0.05$) among genotypes in all locations for all the studied characters (Table 3). The significant difference indicates the presence of a considerable amount of variation for the green bean physical, cup quality, and biochemical composition traits among the studied Arabica coffee genotypes, and this variation could be exploited to bring coffee quality improvement through selection and hybridization. Many studies also reported the existence of statistically significant variation among Arabica coffee genotypes for different traits at different times [8,11,14–16,31,32–35]. The existence of significant variation among the traits indicated the presence of a considerable amount of variation among the studied Arabica coffee genotypes, and this variation could be exploited to improve coffee quality through selection and hybridization.

A combined ANOVA revealed significant ($p < 0.01$ & $p < 0.05$) variation among the main effects (genotypes and environment) for all characteristics except bitterness. Likewise, significant genotype by environment interaction (GEI) was also observed for the studied traits except for bitterness (Table 3). The presence of significant GEI indicates the inconsistency in the performance of the genotypes for green bean physical attributes, cup quality traits, and biochemical composition across environments. This suggested that one genotype's phenotypic expression might be superior to another genotype in one environment but inferior in another environment. Therefore, the coffee quality improvement program should give due attention to incorporating genetic and environmental influences into the development of market-competent specialty coffee varieties. In line with this result, different researchers reported differential performance of genotypes when grown in different environments on quality-related traits in Arabica coffee [10–16, 24, 36, 37].

6. Green bean physical characteristics

6.1. Green bean screen size

The main effects as well as the interaction of genotype and location revealed highly significant ($p < 0.01$) variation for green bean screen size (Table 3). Bold and large bean sizes were recorded for Angafa (99 %) grown at Awada; Angafa, Feyate, AW105, AW9622, AW1995, AW7705, AW4994, AW5994, and AW9610 (98 %) all grown at Wonago; and Angafa (98.22 %) grown at Shebedino. In line with this study, a wider variation in screen size for the Arabica coffee genotype was reported: 98.09–90.33 % [14], 99.13–91.10 [32], 98.50–96.03 [38], and 98.75–96 [39].

Bean size is an important trait for roasters since the homogeneity of the coffee beans avoids the burning of smaller grains [40]. It is one of the most important physical characteristics of green beans and plays a significant role in coffee marketing [41]. According to the Ethiopian coffee grading system, more than 85 % of the coffee beans must have a screen size of 14 in order to meet the standard requirements [42]. Accordingly, the beans of the tested genotypes from three environments were over 85 % screen size, accepted for grading, and fulfilled the Ethiopian coffee grading standard in terms of bean screen size.

6.2. Bean shape and make

In this study, the shape and make of green beans ranged from very good (15 %) to fair (10 %). AW9648 and Angafa (15) grown at Awada, AW9622 (14) grown at Wonago, and AW5994 (13.3667) grown at Shebedino revealed significantly highest green bean shape and make (Table 4). Abrar et al. [2014] also reported the presence of significant variation for 16 Ethiopian Arabica coffee hybrids and 1 check variety for bean shape and make tested in three south Ethiopian growing environments [32]. The shape and make indicate the boldness and uniformity of the bean in a sample. It is an important physical characteristic of coffee, which affects the roasting process and cup quality. Uniform coffee beans are the most preferred and are usually priced highly [32]. In this study, most of the genotypes rated very good to good and preferred by trained panelists.

Green Bean Color The location, genotype, and their interaction significantly ($P < 0.01$) influenced the color of green beans (Table 3). The color rate varies from bluish (15 %) to faded to coated (7.33 %) (Table 4). The maximum rate for green bean color was recorded for AW9648 (15 %) grown at Awada, AW9648 (13.22 %) at Wonago; and AW9648, AW12305, and AW8105 (14 %) all grown at Shebedino. In line with these results, variation in color of coffee beans among the Arabica coffee genotype and the differential response of genotype in the different growing environments were also reported by different studies [32,39,43].

6.3. Bean odder

According to this study result, odder rated from clean odder (10 %) to fair clean (8 %), and most of the genotypes rated clean odder (10 %) at all three locations (Table 4). When we consider the growing environment, the highest mean score (9.91 %) was recorded at Wonago, whereas the lowest (9.42 %) was recorded at Awda growing environment. Accordingly, the Wonago growing environment is more suitable to produce clean odder beans. Many studies also reported differential responses of genotypes across different growing environments for bean odders [14,32,39,43].

6.4. Total row quality

Growing environment and genotype interaction influenced significantly total row quality (Table 3). In this study, genotype AW9648 was best performed with highest row total score mean values of (40), (36.22), and (37.33) at Awada, Wonago, and shebedino respectively over other genotypes including check varieties (Table 4) and could be used as a best parent for selection and hybridization to improve physical quality.

Where; SS = screen size, SM = shape & make, Col = color, od = odor, RawT = raw total, AQ = aromatic quality, AI = aromatic intensity, Acid = acidity, AST = astringency, Bit = Bitterness, Bod = body, Fla = flavor, OQL = overall quality, TotalR = Total Cup Quality, RCup = Total Raw and Cup quality, Trigo = Trigonelline, Chloro = Chlorogenic acid, Caff = Caffeine, StD = Standard deviation, and CV = coefficient of variation.

6.5. Cup quality

6.5.1. Aromatic quality

The interaction of genotype and growing environment significantly influenced ($p < 0.01$) aromatic quality of coffee taste (Table 3). An excellent aromatic quality score (5) was recorded for genotypes AW7494 and AW4994 at Awada growing environment. When we consider growing environments, the highest aromatic score (4.06) was scored at Awada, followed by (3.91) at Wonago, and (3.82) at Shebedino (Table 4). Aromatic quality is an important cup quality parameter that determines the magnitude of the aroma of the coffee beverage and influences the sense organs of the cuppers [44]. In this study, all the genotypes studied scored good to excellent at all three locations. Accordingly, the studied genotype and growing environments are suitable to produce a good-quality aroma beverage. However, genotypes AW7494 and AW4994, as well as the Awada growing environment are more likely to produce excellent aromatic-quality coffee.

6.5.2. Aromatic intensity

A very strong aromatic intensity score (5) was recorded for AW7494 grown at Awada and Angafa grown at Wonago (Table 4). Aromatic intensity is one of the most important cup quality parameters, which determines the magnitude of the aroma of the coffee beverage and influences the sense organs of the cuppers [14,32]. In line with this study, the influence of environmental conditions and coffee varieties was reported in a previous study [45–48]. Except genotype AW4305 grown at Wonago, all the studied genotypes at all three locations scored medium to very strong aromatic intensity.

6.5.3. Acidity

According to this study result, the acidity of coffee genotypes brew at three locations was rated from pointed to medium level. The pointed coffee brew acidity (10 %) was recorded for AW9648 grown at Awada; AW9648 and AW4083 both grown at Wonago; and AW9648, Feyate, AW9628, and AW9648 all grown at Shebedino (Table 4). Acidity is a sensation of dryness that the coffee brew produces under the edges of the tongue and on the back of the palate [32]. Acidic intensity is a desirable feature, appreciated in coffee, as there is a positive relationship between the intensity of the acid impression and coffee quality. High acidity coffee has a pointed sharp pleasing flavor [45].

6.5.4. Astringency

The nil astringency (5 %) was recorded for AW7494, AW9628, and Feyate at Awada; AW7705, AW695, AW1995, and AW9640 at Wonago; and AW105, AW9622, and AW9628 at Shebedino (Table 4). Astringency is a complex sensation accompanied by a shrinking, drawing, or puckering mucosal surface in the mouth, produced by tannins. Coffee beans with a low content of astringency have generally high quality [14]. The astringency of the studied coffee genotypes from three locations is scaled between very light and nil, which indicates a relatively low quantity of astringency and thus good quality.

6.5.5. Bitterness

In this investigation, there was a highly significant difference ($p < 0.01$) in bitterness score among genotypes, but the effects of the growing environment and the genotype × environment interaction were not significant (Table 3). Genotypic performance for the bitterness score ranges from 3.48 to 4.85 with a mean of 4.16 (Table 4). Bitterness is the perception of coffee brew on the tongue of panelists during cup tasting, and it is the opposite of sweetness [32]. In general, good coffee should have low bitterness and a medium to full body [14,32], which is what almost all Arabica coffee genotypes tested in this study fulfilled. However, AW7494 and Angafa are the most preferred genotypes to produce very low bitterness.

6.5.6. Total cup quality

The total cup quality of coffee brews was computed by the summation of aromatic intensity, aromatic quality, acidity, astringency, bitterness, body, flavor, and overall standard, which is evaluated from 60 %. Growing environment, genotype, and their interaction significantly influenced the total cup quality of the coffee brew (Table 3). The highest total cup quality score values were recorded for AW9648 (54.19) followed by AW7494 (53.26) both grown at Awada; AW9648 (57.3), followed by Angafa (53) at Wonago; and

AW9648 (51.78) followed by AW9641 (51.37) at Shebedino, whereas the lowest rate was recorded for AW4305 (38.67) at Wonago and AW4305 (39.67) at Shebedino (Table 4). In this study, the total cup quality of all studied genotypes' brew is very good except for genotype AW4305.

6.5.7. Total row and cup quality

The overall cup quality evaluation was used for the final coffee cup quality judgment from good to excellent. It was calculated from 100 % as a sum of raw (40 %), and cup quality (60 %) [25]. In this study, the highest overall cup quality score values were recorded for genotype AW9648 (94.19 %), followed by Angafa (87.00 %) and Feyate (86.43 %) at Awada; genotype AW9648 (93.55 %), followed by Angafa (87.89 %) and Feyate (86.77 %) at Wonago; and genotype AW9648 (89.11 %) followed by Feyate (86.19 %) and Angafa (85.56 %) at Shebedino. On the other side, the lowest total raw and cup quality values were recorded for genotypes AW9628 (76.26 %) and AW4305 (76.33 %) at Awada; genotype AW4305 (69.00 %) followed by AW9628 (77.55) at Wonago; and genotype AW4305 (66.00 %) followed by AW9610 (78.89 %) grown at Shebedino (Table 4).

Combined analysis results revealed that the highest mean total raw and cup quality over locations was recorded for genotype AW9648 (92.28 %), followed by Angafa (86.82 %), whereas the lowest was recorded for AW4305 (70.45 %), followed by AW9628 (78.79 %) (Table 4). According to this study result, most of the genotypes received more than 80 % scores, except AW4305, AW9658, AW9610, and AW695. Accordingly, most of the genotypes in the present study could be used as sources of a desirable parent for South Ethiopian Arabica coffee cup quality improvement through selection and hybridization. Out of all tested genotypes, AW9648 achieved the highest score in all three growing environments, whereas AW4305 was very poor in quality. Angafa is a South Ethiopian released variety that is known for its superior quality and yield performance. Accordingly, it was used as a parent for south Ethiopian coffee quality improvement, and two hybrid varieties were registered from the cross of it. According to this study result, genotype AW9648 is superior even from Angafa. Therefore, AW9648 could be used as the best selection and best parent for hybridization for south Ethiopian coffee quality improvement if its yielding ability and disease resistance are reasonably good in the respective study area and similar coffee growing agroecology.

6.6. Biochemical composition

6.6.1. Green bean trigonelline

Trigonelline content ranges from 0.73 to 1.49 % dwb, 0.44–0.9 % dwb, and 0.55–0.87 % dwb, with a mean of 1.06 % dwb, 0.67 % dwb, and 0.69 % dwb at Awada, Shebedino, and Wonago, respectively (Table 4). Considering the genotypic effect, the highest value was recorded for AW9611 (1.49 % dwb), followed by Angafa (1.416 % dwb) grown at Awada, whereas the lowest was recorded for AW1995 (0.442 % dwb) grown at Shebedino (Table 4). The highest mean trigonelline content over location was recorded for AW9622 (1.01 % dwb), whereas the lowest was recorded for AW695 (0.68 % dwb) and AW9641 (0.69 % dwb) (Table 4). Different authors [36,49,50] reported significant variations among genotype and location in Arabica coffee trigonelline content.

Trigonelline, which is a pyridine alkaloid, is an important component of the coffee bean, which acts as a reservoir of nicotinic acid in plants [51]. It is known to contribute to the formation of the appreciated coffee flavor, and the higher trigonelline contents could partially explain the better flavor observed [36].

6.6.2. Green bean chlorogenic acid

Chlorogenic acid ranges from 2.908 to 5.897 % dwb, 2.778 % dwb to 5.475 % dwb, and 3.444–5.643 % dwb, with a mean of 3.914 % dwb, 3.976 % dwb, and 4.563 % dwb at Awada, Shebedino, and Wonago, respectively (Table 4). The highest green bean chlorogenic acid content was observed for Angafa (5.90 % dwb) grown at Awada, followed by AW105 (5.61) grown at Wonago, whereas the lowest was recorded for 74112 (2.78 % dwb) at Shebedino (Table 4). According to the combined analysis result, the highest mean green bean chlorogenic acid content was recorded for Angafa (4.887 % dwb), followed by AW4083 (4.53 % dwb), whereas the lowest was recorded for AW5994 (3.58 % dwb) (Table 4). Many authors reported a significant variation among genotypes and genotypes by environment interaction for chlorogenic acid in Arabica coffee [36,49].

Chlorogenic acids are phenolic compounds commonly found in green coffee beans [51]. Chlorogenic acid is of great interest because of its possible positive impact on human health [52]. They also play a significant role in the defensive mechanism of plants, particularly when bacterial and fungal disease invasions are verified [51]. Chlorogenic acids are responsible for the astringency and bitterness of coffee brews [36].

6.6.3. Green bean caffeine

Caffeine content ranges from 0.60 to 1.53, 0.52 to 1.06, and 0.62 to 1.12 with means of 0.89, 0.82, and 0.898 at Awada, Shebedino, and Wonago, respectively (Table 4). Among all genotypes, AW5994 (0.52 % dwb) and AW9641 (0.56 % dwb) grown at Awada, AW1995 (0.60 % dwb) grown at Shebedino, and AW9623 (0.62 % dwb) grown at Wonago had the lowest green bean caffeine content. On the other side, Feyate (1.53 % dwb) at Awda, AW9623 (1.06 % dwb) at Shebedino, and AW9622 (1.12 % dwb) at Wonago had the highest green bean caffeine content (Table 4). The highest mean green bean caffeine content over location was recorded for Feyate (1.17), whereas the lowest was recorded for AW5994 (0.64 % dwb), followed by AW1995 (0.69 % dwb) (Table 4). In line with the present study, several studies reported coffee genetic variability and environmental influence on caffeine content variation [35,36,49,50,53,54]. The existence of wider variation in caffeine content among South Ethiopian Arabica coffee genotypes provides a great privilege for the development of low-caffeine-contenting varieties that have superior cup quality and aroma.

Moderate caffeine consumption is considered to be a safe habit and beneficial [3]. However, there are negative aspects linked to excess caffeine intake that must be considered [3,55]. Caffeine in excess use can cause a state of excitement and anxiety, as well as negative side effects such as tachycardia, headache, palpitations, insomnia, restlessness, nervousness, gastrointestinal disturbance, palpitation, and increasing blood pressure and tremor [55,56,57]. Due to this adverse effect of excess caffeine, the demand for decaffeinated coffee increased around the world. As a result, instant coffee manufacturers have developed methods for artificially removing caffeine from coffee. However, decaffeination is an expensive process that modulates the amount of flavor components and precursors [53,55]. By developing coffee varietals that are naturally high in quality and low in caffeine, it is possible to avoid the expensive decaffeination process while retaining the coffee's original flavor and precursors [53].

Many studies reported different caffeine levels in Arabica coffee; 14.1–142 g kg-1 [23] 1.05–1.52 g kg-1 [22]; 6.2–12 g kg-1 [24]; 9.1–13.2 g kg-1 [53]; 7.7–16.8 g kg-1 [56,57]; and 9.3–14.4 g kg-1 [58]. In the current investigation, a very low caffeine content range was registered for genotypes AW5994, AW1995, AW12305, AW4305, AW 9641, and AW9610. Therefore, these low caffeine-containing genotypes could be used as a parent for the development of low caffeine varieties and it is a great privilege for the nation and the coffee industry to fulfill the customer need and boost the specialty coffee market without decaffeination.

6.6.4. Principal component analysis

The PCA of 30 Arabica coffee genotypes based on a correlation matrix of combined data for 15 characters was performed to estimate the relative contribution of each attribute to the observed variability, and the results are presented in Table 5. The first and second principal components explained 54.42 % and 12.78 % of variation, respectively, and 67 % of total variation (Table 5). The relative weight given to the variables in each component and important variables are those that possess high positive and high negative weights [44]. Based on this suggestion, the most important traits contributing more to the variation in first PCA were observed for caffeine content (0.35), chlorogenic acid (0.34), aromatic quality (0.31), trigonelline (0.29), acidity (0.28), astringency (0.28), and color (0.27), in decreasing order. In the second PCA, high variation was contributed by flavor (−0.48) and screen size (0.46), whereas in the third and fourth PCAs, high variation was accredited by bitterness (0.79) and screen size (0.57), respectively (Table 5).

From the PCA result of the present study, it may be concluded that important variables in Arabica coffee genotype with respect to bean physical, cup quality, and biochemical traits were caffeine, chlorogenic acid, aromatic quality, trigonelline, acidity, astringency, flavor, and screen size. These variables might be taken into consideration for the effective selection of parents.

6.7. Cluster analysis

To investigate the genetic relationship among 30 Arabica coffee genotypes, cluster analysis was conducted, and a dendrogram was generated using the ward method for cup quality, green bean physical characteristics, caffeine, trigonelline, and chlorogenic acid content traits (Figs. 1–3). In the Awada growing environment, genotypes were grouped into two main clusters (Fig. 1). The first main clusters contained two genotypes, namely, Angafa, which is a released variety that maintains a spicy and floral flavor, and AW9648, the top-rated, promising selection. These two genotypes were characterized by excellent cup quality and desirable green bean physical characteristics. The second main cluster comprised 28 genotypes and was bifurcated into two different sub-clusters. The first sub-cluster of the second main cluster consists of eleven genotypes (7412, Feyate, AW9640, AW8806, AW7494, AW4994, AW9644, AW8105, AW9662, AW3106, AW1777) that were characterized by good cup quality and desirable green bean physical characteristics. The second sub-cluster of the second main cluster consisted of seventeen coffee genotypes that were further subdivided into two sub-sub-clusters. The first sub-sub-cluster of the second sub-cluster consisted of seven genotypes, namely, AW9641, AW9628, AW4305, Aw9622, AW5994, AW1995, and AW105, which were characterized by average cup quality. The second sub-sub-cluster consisted of

Table 5
Principal component analysis of 30 Arabica coffee genotypes for 15 green bean row, cup quality and biochemical content parameters.

Character	Eigenvectors			Prin4
	Prin1	Prin2	Prin3	
Screen Size	−0.06	0.46	0.57	−0.13
Shape & Make	0.22	−0.12	0.61	0.11
Color	0.27	−0.29	0.08	0.15
Oder	0.23	0.03	−0.40	0.10
Aromatic Quality	0.31	−0.21	0.19	0.16
Aromatic Intensity	0.27	0.31	−0.17	−0.25
Acidity	0.28	0.31	−0.16	−0.22
Astringency	0.28	−0.16	0.07	−0.12
Bitterness	0.14	0.18	−0.11	0.79
Body	0.25	0.34	−0.04	−0.08
Flavour	0.18	−0.48	−0.04	−0.37
Overall cup Quality	0.25	0.20	0.11	−0.03
Trigonelline	0.29	−0.06	−0.05	0.08
Chlorogenic acid	0.34	0.09	−0.04	−0.09
Caffeine	0.35	−0.05	0.07	0.02
Eigenvalue	8.16	1.92	1.27	1.03
Present variation explained	54.42	12.78	8.47	6.84
Cumulative present variation explained	54.42	67.2	75.68	82.52

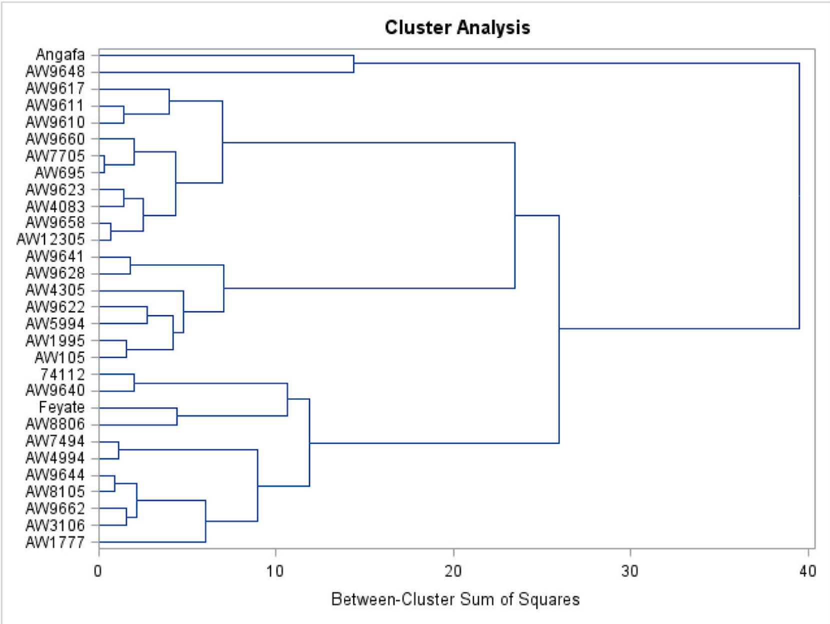

Fig. 1. Cluster dendrogram describing variation among 30 genotypes of Arabica coffee for quality traits at Awada.

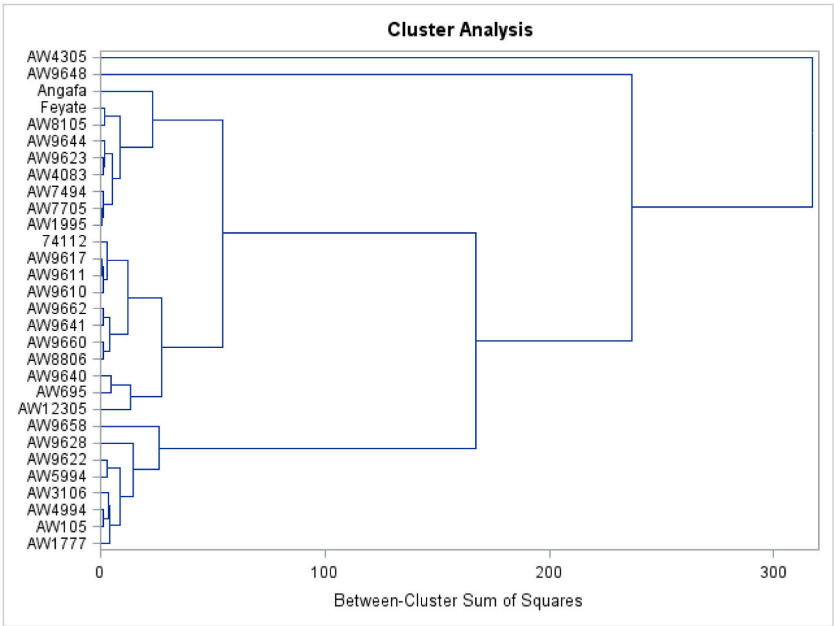

Fig. 2. Cluster dendrogram describing variation among 30 genotypes of Arabica coffee for quality traits at Wonago.

10 coffee genotypes, namely, AW9617, AW9611, AW9610, AW9660, AW7705, AW695, AW9623, AW4083, AW9658, and AW12305, which were characterized by poor cup quality (Fig. 1).

In the Wonago growing condition, the genotypes were grouped into two clusters. The first main cluster consisted of only one genotype, namely AW4305, which was characterized by its poor quality. The second cluster was grouped into two sub-cluster. The first sub-cluster of the second main cluster consisted of only one genotype (AW9648), which was characterized by its top quality. The second sub-cluster of the second main cluster was further grouped into two sub-sub-clusters. The first sub-sub-cluster of the second main cluster consisted of twenty genotypes (Angafa, Feyate, AW8105, AW9644, AW9623, AW4083, AW7494, AW7705, AW1995, 74112, AW9617, AW9611, AW9610, AW9662, AW9641, AW9660, AW8806, AW9640, AW695, and AW2305), which had good quality. The second sub-sub-cluster of the first main cluster consisted of eight genotypes (AW9658, AW9628, AW9622, AW5994,

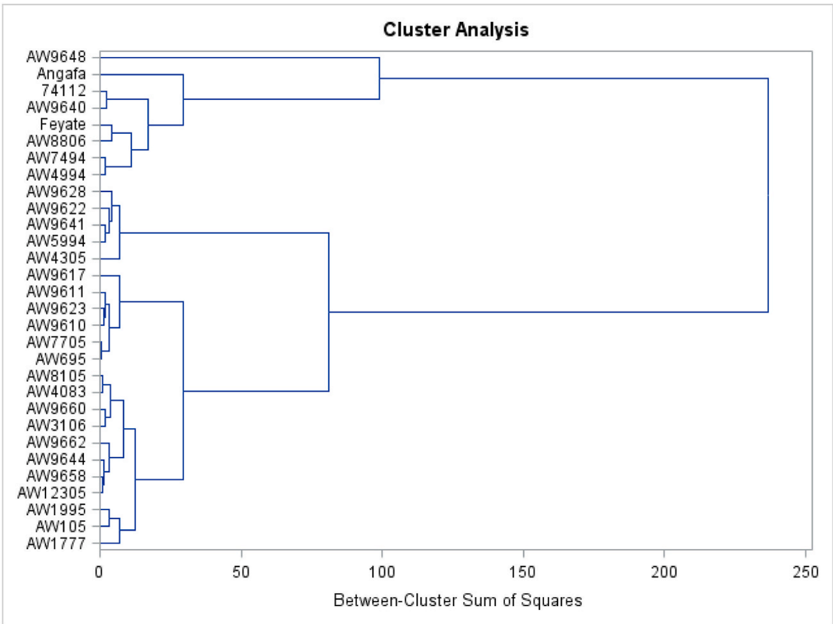

Fig. 3. Cluster dendrogram describing variation among 30 genotypes of Arabica coffee for quality traits at Shebedino.

AW3106, AW4994, AW105, and AW1777) that had poor to moderately good quality (Fig. 2).

The genotypes were clustered into two main clusters in the Shebedino growing environment. The first main cluster was grouped into two sub-clusters. The first sub-cluster of the first main cluster consisted of only one genotype, AW9648, which is characterized by its top quality and is recommended as a superior genotype for quality improvement. The second sub-cluster of the first main cluster consisted of seven genotypes, viz., Angafa, 74112, AW9640, Feyate, AW8806, AW7494, and AW4994, which are categorized by their best quality. The second main cluster was grouped into two sub-clusters. The first sub-cluster of the second main cluster consisted of five genotypes (AW9628, AW9622, AW9641, AW5994, and AW4305), whereas the second sub-cluster of the second main cluster consisted of sixteen genotypes (AW9617, AW9611, AW9623, AW9610, AW7705, AW695, AW8105, AW4083, AW9660, AW3106, AW9662, AW9644, AW9658, AW2305, AW1995, AW105, and AW1777) (Fig. 3). Genetic variation among coffee genotypes and inconsistency in the performance of genotypes when grown in different environments might contribute to the occurrence of different clusters within each environment. Therefore, the breeding program should give due attention to those top quality genotypes in their respective locations for quality improvement through crossing and selection in south Ethiopia.

7. Conclusion

The present study confirmed the existence of significant variation among south Ethiopian Arabica coffee genotypes, growing environments, and genotype by environment interaction for physical character, cup quality, and biochemical composition traits. Therefore, the studied genetic resources should be properly utilized in the quality improvement program through selection and hybridization for the emerging specialty coffee markets, and the coffee quality improvement program should give due attention to incorporating genetic and environmental influences by using a multi-locational selection strategy.

The overall coffee quality score for tested genotypes in three locations were above 80 % for most of the studied genotypes. Therefore, in terms of quality, most of the tested genotypes can be used to produce specialty coffee in the study areas. Out of all tested genotypes in this study, AW9648 achieved the highest score in green bean physical attributes and cup quality parameters at all three-tested locations. Therefore, AW9648 could be used as the best selection and best parent for hybridization for South Ethiopian coffee quality improvement.

From the PCA, it may be concluded that important variables in the Arabica coffee genotype with respect to bean physical, cup quality, and biochemical traits were caffeine, chlorogenic acid, aromatic quality, trigonelline, acidity, astringency, flavor, and screen size. These variables might be taken into consideration for the effective selection of parents.

Data availability statement

All the relevant data are included in the manuscript. No separate repository is attached.

Funding statement

This research work was financed by the Ethiopian Institute of Agricultural Research and partly bay an institutional collaboration program between Hawassa University (Ethiopia) and the Norwegian university of life science.This research work was financed by the Ethiopian Institute of Agricultural Research and partly bay an institutional collaboration program between Hawassa University (Ethiopia) and the Norwegian university of life science.

Additional information

No additional information is available for this paper.

Ethical statement

The experiment was conducted according to established ethical guidelines and written informed consent obtained from the participants.

CRediT authorship contribution statement

Habtamu Gebreselassie: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Bizuayehu Tesfaye:** Conceptualization, Writing – review & editing. **Andargachew Gedebo:** Conceptualization, Writing – review & editing. **Kassaye Tolessa:** Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We wishes to express gratitude to the Awada Agricultural Research Sub Center staff members for their valuable material support, technical assistance, and cooperation in the field experiment. We also wish to extend our thanks to Ethiopian commodity exchange laboratory Hawassa branch staffs trained cuppers and Ethiopian institute of agricultural research chemistry laboratory staffs for their assistance in the laboratory experiment conduction of this study.

References

[1] FAO (Food and Agricultural Organization of United Nations), FAO office of communications. https://doi.org/10.4060/cb4402en, publications catalogue 2021.
[2] A. Samoggia, B. Riedel, Consumers' perceptions of coffee health benefits and motives for coffee consumption and purchasing, Nutrients 11 (3) (2019), https://doi.org/10.3390/nu11030653.
[3] J. Depaula, A. Farah, Caffeine consumption through coffee: content in the beverage, metabolism, health benefits and risks, Beverages 5 (2) (2019), https://doi.org/10.3390/beverages5020037.
[4] M. Zarebska, N. Stanek, K. Barabosz, et al., Comparison of chemical compounds and their influence on the taste of coffee depending on green beans storage conditions, Sci. Rep. 12 (2022), https://doi.org/10.1038/s41598-022-06676-9.
[5] USDA (The United States Department of Agriculture), Ethiopia Coffee Annual Coffee Annual Report, GAIN Report Number: ET1904 (2019) 1–6. https://apps.fas.usda.gov.
[6] M. Yirga, W. Gebreselassie, A. Tesfaye, Genetic diversity of coffee (coffea arabica L.) collections for morpho-agronomic traits in Southwestern Ethiopia, East African Journal of Sciences 15 (2) (2021) 141–154, https://doi.org/10.20372/eajs.v15i2.1685.
[7] USDA (The United States Department of Agriculture), Ethiopia Coffee Annual Report, GAIN Report Number: ET2021-0013 (2021), 1-6, https://apps.fas.usda.gov.
[8] G. Dawit, Genetic Diversity Analysis Among Promising Wollega Coffee (Coffea Arabica l.) Selections in Western Ethiopia. MSc, Thesis of Hawassa University. Thesis Submitted to Graduate Studies of in partial fulfillment of Hawassa University, Hawassa Ethiopia, 2018 P38.
[9] F.M. Borém, M.P. S Luz, T. Sáfadi, M.M.L. Volpato, H.M.R. Alves, R.A.T. Borém, D.A. Maciel, Meteorological variables and sensorial quality of coffee in the mantiqueira region of Minas Gerais, Coffee, Science 14 (1) (2019) 38–47, https://doi.org/10.25186/cs.v14i1.1522.
[10] A.S. Fonseca, J.S. Lima, S. Silva, M.C. Dardengo, A.C. Xavier, Fuzzy logic in the spatial and temporal distribution in the qualitya of the beverage in conilon coffee, Coffee Science 14 (2) (2019) 163–172, https://doi.org/10.25186/cs.v14i2.1563.
[11] A. Adem, H. Mohammed, A. Ayana, Phenotypic Diversity in Arabica Coffee Genotypes from Eastern Ethiopia 5 (4) (2020) 42–47, https://doi.org/10.11648/j.ijee.20200504.11.
[12] J. Dalazen, R.B. Rodrigues, L.L. Rocha, E.A. Pereira, M.C. Alves, C.A. Espindula, de Souza, Beverage Quality of Most Cultivated Coffea Canephora Clones in the Western Amazon, Coffee Science 15 (1) (2020) 1–10, https://doi.org/10.25186/.v15i.1711.
[13] L. Marie, C. Abdallah, C. Campa, P. Courtel, M. Bordeaux, L. Navarini, V. Lonzarich, A.S. Bosselmann, N. Turreira-García, E. Alpizar, F. Georget, J.C. Breitler, H. Etienne, B. Bertrand, G × E interactions on yield and quality in Coffea arabica: new F1 hybrids outperform American cultivars, Euphytica 216 (5) (2020), https://doi.org/10.1007/s10681-020-02608-8.
[14] M.W. Mengistu, M.A. Workie, A.S. Mohammed, Physical and cup quality attributes of arabica coffee (coffea arabica L.) varieties grown in highlands of amhara region, northwestern Ethiopia, International Journal of Agronomy 6 (1) (2020), https://doi.org/10.1155/2020/6420363.
[15] D. Merga, H. Mohammed, A. Ayano, Estimation of genetic variability , heritability and genetic advance of some wollega coffee (coffea arabica L, Landrace in Western Ethiopia Using Quantitative Traits 9 (4) (2021) 182–191, https://doi.org/10.11648/j.jps.20210904.18.
[16] J. Ndikumana, Agro-morphological Characterization of Arabica Coffee Cultivars in burundi, Studies of Jomo kenyatta university, Nirobi, Keniya, 2022. Thesis Submitted to Graduate.

[17] CSA (Central Statistical Authority), Federal republic of Ethiopia, central statistical agency, Agricultural Sample Survey Report on Area and Production of Major Crops, 2014/2015 1 (2015). Statistical Bulletin 578, May 2015, Addis Ababa, 121P.
[18] T. Tadesse, B. Tesfaye, G. Abera, Coffee production constraints and opportunities at major growing districts of southern Ethiopia Coffee production constraints and opportunities at major growing districts of southern Ethiopia, Cogent Food Agric. 6 (1) (2020), https://doi.org/10.1080/23311932.2020.1741982.
[19] EIAR (Ethiopian Institute of Agricultural Research), National Coffee Commodity Research Strategy of Fifteen Years (2016 -2030), Addis Ababa, Ethiopia (2017).
[20] T. Benti, Progress in arabica coffee breeding in Ethiopia: achievements, challenges and prospects, Int. J. Sci. Basic Appl. Res. 33 (No 2) (2017) 15–25. https://api.semanticscholar.org/CorpusID:102724118.
[21] K. Tolessa, M. Rademaker, B. De Baets, P. Boeckx, Prediction of specialty coffee cup quality based on near infrared spectra of green coffee beans Talanta (2016) 367–374, https://doi.org/10.1016/j.talanta.2015.12.039, 2017.
[22] A. Sualeh, K. Tolessa, A. Mohammed, Biochemical composition of green and roasted coffee beans and their association with coffee quality from different districts of southwest Ethiopia, Heliyon 6 (12) (2020) e05812, https://doi.org/10.1016/j.heliyon.2020.e05812.
[23] A. Assa, J.E. Loppies, A.N. Amalia, D. Indriana, U.R.R. Mamang, M. Ariyanti, A. Winaldi, Chemical compounds and sensory characteristics of arabica coffee (Coffea arabica) as a novel specialty coffee from sinjai regency, Indonesia, Food Res. 5 (2021) 107–112, https://doi.org/10.26656/fr.2017.5(S2).001.
[24] M. Redi, B.S. Chandravanshi, A. Mustefa, H. Mamo, Correlation between caffeine contents of green coffee beans and altitudes of the coffee plants grown in southwest Ethiopia. https://doi.org/10.4314/bcse.v32i1.2, 2018.
[25] A. Sualeh, N. Mekonnen, Manual for Coffee. Quality Laboratory (2015) 1–24, https://doi.org/10.13140/RG.2.2.18203.49441.
[26] CSA (Central Statistical Agency), Agricultural Sample Survey: Report on Area and Production of Major Crops of Private Peasant Holdings for Meher Season of 2018/19, Addis Ababa, Ethiopia: Central Statistical Agency, 2019.
[27] W.M. Woelore, Optimum fermentation protocols for arabica coffee under Ethiopian conditions, in: Proceedings of the 15th International Scientific Colloquium on Coffee (ASIC), Montpellier, France, 1993, pp. 727–733. June 6-11.
[28] J.A. Vignoli, M.C. Viegas, D.G. Bassoli, M.D.T. Benassi, The roasting process affects differently the bioactive compounds and the antioxidant activity of arabica and robusta coffees, Food Res. Int. 61 (2014) 279–285.
[29] B.M. Gichimu, E.K. Gichuru, G.E. Mamati, A.B. Nyende, Biochemical composition with in Coffea arabica cv. Ruiru 11 and its relationship with cup quality, J. Food Res. 3 (3) (2014) 31–44, https://doi.org/10.5539/jfr.v3n3p31.
[30] G.W. Milligan, M.C. Cooper, A study of standardization of variables in cluster analysis, J. Classif. 5 (1988) 181–204, https://doi.org/10.1007/BF01897163.
[31] J.J. Cheserek, K. Ngugi, J.W. Muthomi, C.O. Omondi, Genetic Variability and Correlation of Biochemical and Sensory Characteristics of Coffee 14 (2) (2022) 95–103, https://doi.org/10.5539/jas.v14n2p95.
[32] A. Sualeh, N. Mekonnen, M. Degefa, Hybrid coffee (*Coffea arabica* L) genotypes quality evaluation under different environment, Greener Journal of Agricultural Sciences 4 (6) (2014) 245–251, https://doi.org/10.15580/GJAS.2014.6.0523014244.
[33] T.K. Abdulfeta, Characterization and yield performance evaluation of coffee (coffea arabica L.) germplasm accessions from tepi, southwestern Ethiopia MSc, Thesis summated to Hawassa University College of Agriculture (2018) 1–71.
[34] A. Desalegn, Genetic Variability and Character Association of Amaro Coffee (Coffea Arabica l.) Accessions at Awada, Southern Ethiopia, Thesis Submitted to Graduate Studies of Jimma University, Jimma, Ethiopia, 2018.
[35] K. Tolessa, D. Alemayehu, D. Belew, P. Boeckx, in: Biochemical Composition of Ethiopian Coffees (Coffea Arabica L.) as Influenced by Variety and Postharvest Processing Methods, 2019, pp. 48–56, https://doi.org/10.5897/AJFS2018.1770.
[36] B.M. Gichimu, E.K. Gichuru, G.E. Mamati, A.B. Nyende, Biochemical composition within coffea arabica cv. Ruiru 11 and its relationship with cup quality, Canadian Center of Science and Education (2015), https://doi.org/10.5539/jfr.v3n3p31.
[37] B. Cheng, A. Furtado, H.E. Smyth, R.J. Henry, Influence of genotype and environment on coffee quality, Trends Food Sci. Technol. 57 (2016) 20–30, https://doi.org/10.1016/j.tifs.2016.09.003.
[38] M. Tesfa, Effect of Drying Methods on Raw Quality of Selected Cultivars of Arabica Coffee (Coffea arabica L.) Grown in South West, Ethiopia 8 (11) (2019) 1412–1420, 10.21275/ART20202323.
[39] M. Tesfa, S. Abera, A. Sualeh, Effect of drying methods on cup quality of selected cultivars of arabica coffee grown in south west, Ethiopia, agriculture, Forestry and Fisheries 10 (2) (2021) 52, https://doi.org/10.11648/j.aff.20211002.13.
[40] N.C. Bicho, A.E. Leitão, J.C. Ramalho, N.B. Alvarenga, F.C. Lidon, Application of colour parameters for roasting coffee assessment, Ciência e Tecnologia dos Alimentos 32 (2) (2012) 1–7. https://doi:10.9755/ejfa.v26i1.17190.
[41] D. Yigzaw, Assessment of Cup Quality, Morphological, Biochemical and Molecular Diversity of *C. Arabica* L. Genotypes of Ethiopia, A PhD Dissertation, University Free State, 2005.
[42] ECX (Ethiopian Commodity Exchange), Daily market bulletin, in: 125 Quarter I, Ethiopian Commodity Exchange, Addis Ababa, Ethiopia, 2010.
[43] L. Severa, J. Buchar, S. Nedomov, Shape and size variability of roasted arabica coffee beans, Int. J. Food Prop. 15 (2) (2012) 426–437.
[44] F. Abbas, M. Alkarkhi, A. Wasin, A. Alqaraghuli, Principal Components Analysis, Academic Press, Easy Statistics for Food Science with R, 2019, pp. 125–141, https://doi.org/10.1016/B978-0-12-814262-2.00008-X, 9780128142622.
[45] N. Bhumiratana, K. Adhikari, E. Chambers, Evolution of sensory aroma attributes from coffee beans to brewed coffee, Food Sci. Technol. 44 (10) (2011) 2185–2192.
[46] J.N. Wintgens, Coffee: Growing, Processing, Sustainable Production, Wiley, Hoboken, NJ, USA, 2004.
[47] A.S. Bosselmann, K. Dons, T. Oberthur, C.S. Olsen, A. Ræbild, H. Usma, The influence of shade trees on coffee quality in small holder coffee agroforestry systems in Southern Colombia, Agric. Ecosyst. Environ. 129 (1–3) (2009) 253–260.
[48] W.B. Sunarharum, D.J. Williams, H.E. Smyth, Complexity of coffee flavor: a compositional and sensory perspective, Food Res. Int. 62 (2014) 315–325.
[49] J.J. Cheserek, K. Ngugi, J.W. Muthomi, C.O. Omondi, K.N. Ezekiel, Green bean biochemical attributes of Arabusta coffee hybrids from Kenya using HPLC and soxhlet extraction methods, Aust. J. Crop. Sci. 15 (2) (2021) 201–208, https://doi.org/10.21475/ajcs.21.15.02.p2581.
[50] C. Ogutu, S. Cherono, C. Ntini, L. Wang, Y. Han, Comprehensive analysis of quality characteristics in main commercial coffee varieties and wild Arabica in Kenya, Food Chem. 14 (2022) 100294, https://doi.org/10.1016/j.fochx.2022.100294.
[51] A. Belay, Some biochemical compounds in coffee beans and methods developed for their analysis, Int. J. Phys. Sci. 6 (28) (2011) 6373–6378, https://doi.org/10.5897/IJPS11.486.
[52] N. Tajik, M. Tajik, I. Mack, P. Enck, The potential effects of chlorogenic acid, the main phenolic components in coffee, on health: a comprehensive review of the literature, Eur. J. Nutr. 56 (7) (2017) 2215–2244, https://doi.org/10.1007/s00394-017-1379-1.
[53] D. Yigzaw, M.T. Labuschagne, G. Osthoff, L. Herselman, Genetic diversity and correlation of bean caffeine content with cup quality and green bean physical characteristics in coffee (Coffea arabica L.). https://doi.org/10.1002/jsfa.3271, 2008.
[54] B.T. Gebeyehu, S.L. Bikila, Determination of caffeine content and antioxidant activity of coffee, Am. J. Appl. Chem. 3 (2015) 69–76.
[55] Y. Zou, M. Gaida, F.A. Franchina, P.H. Stefanuto, J.F. Focant, Distinguishing between decaffeinated and regular coffee by HS-SPME-GC×GC-TOFMS, chemometrics, and machine learning, Molecules 27 (6) (2022), https://doi.org/10.3390/molecules27061806.
[56] C.W. Kathurima, Characterization of the Diversity of Coffee Genotypes in Kenya by Genetic, Biochemical and Beverage Quality Profiles, A Thesis Submitted in Partial Fulfilment for the Degree of Doctor of Philosophy in Food Science and Technolog, 2013. PhD Thesis.
[57] I.A. Ludwig, M.N. Clifford, M.E. Lean, H. Ashihara, A. Crozier, Coffee: biochemistry and potential impact on health, Food Funct. 5 (8) (2014) 1695–1717, https://doi.org/10.1039/c4fo00042k.
[58] A. Getachew, T. Sentayehu, B. Leta, Gezahegn, genetic variability of Ethiopian coffee (coffea arabica L.) accessions collected from east wollega zone for bean biochemical constituents, Ethiopian Journal of Agricultural Science 30 (3) (2020) 77–97.