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Research Article

The Coffee Processing Method Had a More Pronounced Effect than Location and Production Systems on the Overall Quality of Kaffa Biosphere Reserve Coffees

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A comprehensive examination of the physical and cup quality of Kafa Biosphere Reserve coffees was essential to identify the inherent qualities of the coffees in connection with the area's soil physical and chemical characteristics. As a result, preliminary coffee quality data was acquired from bean physical and cup quality examination of coffees derived through a three-stage nested design combining districts (Gimbo, Gawata, and Decha), coffee production systems (forest, semiforest, and garden), and coffee processing methods (wet, semiwet, and dry). Representative soil samples were collected according to the sampling structure and analyzed following the standard procedures. Multiple factor analysis and Pearson's correlation coefficient analysis were applied to the collected data. According to the results of multiple factor analysis, the Gimbo and Decha districts are not significantly different from each other in terms of coffee quality. However, they are substantially different from the Gawata district in terms of coffee quality. Similarly, within each district, there are no clear differences in coffee production systems. However, the production systems of districts varied significantly. The coffee processing method had a pronounced effect on the overall quality and preliminary grade, physical and raw quality variables of coffee. Screen retention (14) was correlated with soil iron, but it was related negatively to boron and sodium contents. A significant and positive relationship was observed between green coffee bean moisture content and soil potassium, calcium, magnesium, boron, sodium, organic carbon, silicon content, and soil pH. A positive and significant relationship between soil molybdenum and the coffee quality variable was observed across the studied districts whereas most soil micronutrients, specifically, zinc, sulfur, and manganese, were significantly and negatively related to the organoleptic qualities of the coffees. Further investigation that includes the effects of elevation is recommended in future studies.

1. Introduction

Coffee is a commercially preferred commodity and one of the few crops utilized for nonalcoholic beverage preparation [1]. To maintain better coffee beverage quality, there should be proper production and supply of coffee beans [2,3]. The development and composition of coffee green beans, which affect beverage quality, are influenced by environmental variables, production systems, physiological plant growth phases, and preparation procedures [4, 5]. The biochemical changes that are created inside the beans that are grown in a certain environment are what cause the overall beverage quality variance [6, 7]. Altitudinal variation, rainfall patterns [8, 9], temperature, relative humidity, light, moisture, and soil nutrients [10–12] are all significant aspects of terroir.

Ethiopia possesses the world's most extensive and appropriate agroecology for Arabica coffee production [13]. Specifically, the southwestern Ethiopian tropical forest agroecologies are rich in coffee genetic diversity [14]; they are also a source of typical quality coffee. The contribution of the coffee forests is significant for the livelihoods of producers [15]. However, the forests have gone through different modifications due to deforestation and expansion of cropping land, and these expose the forest resources to deterioration of genetic resources. Hence, the Kafa Biosphere Reserve was established in 2010 as a UNESCO-registered area to overcome the problem and maintain the genetic resources of the forests through proper utilization across locations in the biosphere [2, 16]. The coffee production systems practiced in the Kafa Biosphere Reserve and generally in Kaffa are believed to have an effect on the quality of coffee produced.

Ethiopian coffee production system is categorized as forest, semiforest, garden, and plantation coffee. The management activities applied vary according to the systems used. The traditional production systems (forest, semiforest, and gardens) are practiced mostly by small-scale farmers and contribute about 85% of Ethiopia's coffee production [17]. Forest and semiforest coffee production systems are conducted under a natural canopy layer. They are differentiated based on the intensity of shade level and weed management practices. In the forest coffee production system, coffee is produced under dense shade level, whereas in semiforest system the shade level is significantly reduced and legume tree species are allowed to grow at lower layers. Minor weed clearance that will be done before harvesting is the only management activity practiced in the forest coffee production system. On the other hand, in the semiforest production system, weed clearance is conducted twice a year, before harvesting and before the onset of the rainy season. In both systems, the presence of a huge amount of litter improves soil fertility and no inorganic fertilizer is applied [18].

In both production systems, selective harvesting of red coffee berries is not practiced where unripe, ripe, and overripe berries are harvested by the striping method (strip picking). The annual green bean coffee yield in forest and semiforest production systems is estimated to be 200–250 kg/ha and 300–400 kg/ha, respectively [19]. In both coffee production systems, the coffee plants are mostly from the wild *Coffea arabica* landrace [20]. Due to the presence of shade and litter that affect the mineralization of coffee forests, there is no addition of inorganic fertilizers at all for both production systems.

The garden coffee production system is mainly practiced around the vicinity of the farmers. In this production system, intensive crop management practices like frequent weeding (two to three times a year), farmyard manure and crop residue applications, and intercropping are practiced, which differentiates the garden coffee production system from the above two production systems [19]. Coffee plant diversity is reduced relative to the previous systems and the green bean yield is estimated to be 400–500 kg/ha. The commercial/plantation coffee production system is mainly practiced by largescale producers, where improved production technologies are applied and a limited number of coffee types are intensively cultivated (KFCCU, 2016 personal communication) [17].

Plants have a specific need for nutrients. If soil nutrients are limited, a plant cannot attain proper growth and development [12]. In coffee, enhancement of the physical and organoleptic quality of the coffee was observed in beans because of fertilization [9]. Soil characteristics and nutrient content were related to bean size, chlorogenic acid, and antioxidant activity [21]. In Ethiopia, major soil nutrients (P and K) and texture characteristics (silt and clay) were positively correlated with better cup quality. In addition to the major elements, Mg, Mn, Zn, and pH levels impacted coffee aroma when they existed at higher levels. Furthermore, soil texture differences have resulted in cup quality variations in coffee [22]. However, little information has been documented about the influence of location differences and production systems on the variation of coffee quality in relation to the physicochemical properties of soil in the Kafa Biosphere Reserve and generally in Kaffa.

Proper harvesting and processing methods help to ensure the maintenance of a naturally existing coffee quality. Therefore, there is a need for selective hand picking of red ripe coffee cherries to have proper coffee preparation procedures and to get the best quality of coffee [5]. Wet and dry coffee preparation methods are used by coffee growers around the world. Ethiopian coffee cultivars respond well to the two preparation methods [23]. A cost-effective method that requires less water for preparation is the semiwet method (ECTDTA, 2016 not published [5]), and with a mucilage removal procedure, it responds well to Ethiopian coffees [24]. However, the coffees in the region have not been tested with the preparation methods and the response of coffees of coffee grown in different production systems to the processing methods was not well documented.

The overall effect of the environment, production systems, pre- and postharvest practices, and the treatment of cherry processing are thought to affect plant growth, development, and the overall quality of the coffee. However, there is no detailed assessment of the relationship between the above-mentioned factors and the Kafa Biosphere Reserve coffee quality variables. Thus, to this, it was vital to add additional information to support the ongoing conservation practices that are applied with the help of coffee-producing farmers. In addition, to improve the livelihood of producers, it was vital to study the important factors that needed to be considered to improve the quality of coffee produced in the biosphere reserve. Based on this, the present study was executed with the objective of identifying, classifying, and correlating contributing factors and finding the essential soil nutrients that have a significant contribution to the improvement of coffee quality in the Kafa Biosphere Reserve.

2. Materials and Methods

2.1. Description of the Study Areas. Three Kffa Zone coffee growing districts that have representation in the Kafa Biosphere Reserve were selected purposefully to execute the study. The biosphere is located in the southwestern part of

Table 1: Environmental description of districts prioritizing sampling locations.

Districts	Representation in the biosphere	Average elevation (m.a.s.l.)	Rainfall (mm)	Temperature (°C)		Relative humidity (%)
				Min	Max	
Gimbo	Bonga forest	1782	1735–2545	11.70	28.20	73.39
Gawata	Boginda forest	1689	1094–1790	15.00	27.10	73.31
Decha	Bonga forest	1737	1490–2195	14.10	24.50	72.75

m.a.s.l. = meter above sea level, mm = millimeters, Max = maximum, Min = minimum, RH = relative humidity, Source: NABU [20] and NMA [76].

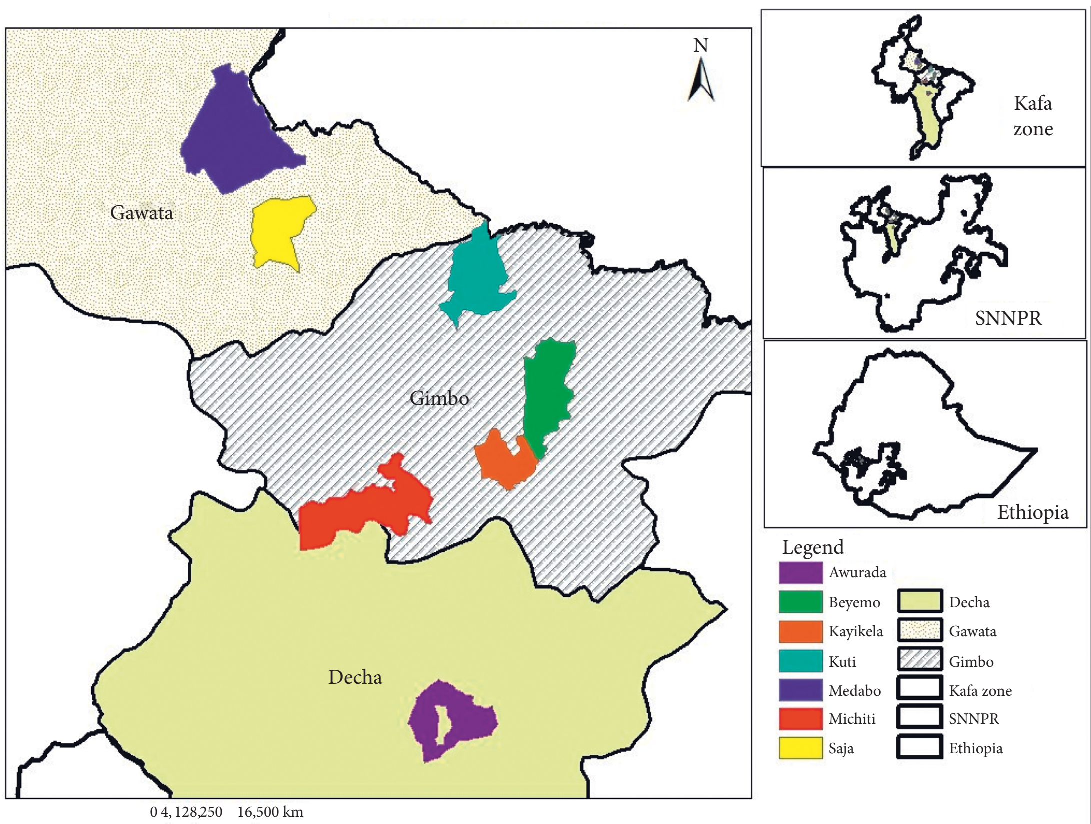

Figure 1: Map of districts and distribution of sampling areas covered in the study.

Ethiopia, and it is characterized by humid agroecology [20]. Because of ecological changes, the topography of the area is uneven and undulated [25]. According to Schmitt [26], up to 50 cm in depth, regosols (dystric) soils are the most common. At the zonal level, more than 281 thousand hectares of land are covered with coffee. In total, 57% of the coffee farms are categorized as garden coffee. The remaining 19.3, 18.3, and 4.8% of the coffee farm types are characterized as forest, semiforest, and plantation coffee, respectively (Kaffa zone agriculture office report, 2019, not published).

2.2. Study Design and Site Selection. Site selection was conducted following a three-stage balanced nested design procedure within Boginda and Bonga forests in an elevation range of 1600–1900 m.a.s.l with the help of GPS Garmin Etrex 30. Accordingly, for coffee and soil sample collection, three administrative districts (Gimbo, Gawata, and Decha) (see Figure 1) and farms that have specific features of the three coffee production systems (forest, semiforest, and garden) were selected purposefully within the districts. Forest and semiforest coffee production systems were selected in buffer zones in which producers could manage and harvest coffee [27].

2.3. Sampling Techniques and Sampling Procedures. During the peak harvesting period (October to December 2017), four replicate samples that represent each of the coffee production systems (forest, semiforest, and garden) were taken from independent coffee farms of the three districts. This makes 36 independent coffee samples from the three districts (12 samples from each). Fully ripe red coffee cherries (15–18 kg) were harvested from each farm by hand picking from randomly assigned 20–30 trees to get 3 kg of green coffee beans depending on the conversion ratio suggested by Sualeh and Dawid [28]. Then, each of the collected samples was divided into three equal amounts to apply the three processing methods (wet, semiwet, and dry). Finally, a total of 108 samples were obtained for final quality analysis.

2.4. Soil Sampling and Analysis. Ten soil samples were gathered in a zigzag pattern from each of the cherry sampling plots at a depth of 0–20 cm using an Auger [29]. The soil was physically blended to generate a 2-kilogram composite soil sample, which was then air-dried to a constant weight and sieved to 2 mm before chemical analysis. Horticoop Ethiopia (Horticultural) Private Limited Company carried out a physical and chemical examination of the soil using standard analysis methodologies. Total nitrogen was obtained using the Kjeldahl procedure. The Walkley and Black procedure was used to obtain organic carbon. Except for the above-mentioned properties, the remaining macronutrients (available phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S)), and micronutrients (iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), boron (B), molybdenum (Mo), sodium (Na), cobalt (Co), and silicon (Si)) were obtained using the Mehlich 3 method. It is a low-acid soil extraction method for determining macro- and micronutrients [30]. In addition, the soil pH was measured using the ES ISO 10390 : 2014 technique (1 : 2.5 soil-to-water ratio) [31]. The Bouyoucos Hydrometer Method was used to identify the soil texture classes [32].

2.5. Coffee Samples Processing and Quality Analysis. The coffee cherries were processed and dried at the Bonga Agricultural Research Center in accordance with national guidelines. The cherries were cleansed of immature berries and extraneous elements before going through the various processing procedures. A manual pulping machine (Mckinnon India) was used to dehull cherries for wet and semiwet-processed coffees. For wet processing, the wet parchment coffees were fermented for 48 hours, cleaned, and soaked for 16 hours to remove any residual mucilage. Finally, the coffees were washed and sundried after 64 hours. Semiwet-processed coffees were prepared in the same way as wet-processed coffees but without the fermentation step. As a result, pulped cherries were washed repeatedly to remove the pulp. The wet parchment coffees with mucilage cover were sundried on a raised wire mesh panel. For dry processing methods, wet cherries were sundried on raised square wire mesh panels for about two to three weeks (ECTDTA, 2016, not published). All coffee samples were sundried until the moisture content of the beans reached 11.5–12% (determined using Mckinnon digital moisture) before being stored at room temperature [33]. The coffees were hulled, washed, and packaged (0.6 kg) in a clean plastic bag and stored at room temperature prior to quality testing [34].

At the Ethiopian Commodity Exchange (ECX) Bonga Branch, physical and liquor tests were performed by Q-grade cuppers in 2018. Tests on on-screen retention (14) and bean moisture content were carried out. To determine primary and secondary defects, defective beans and foreign elements were sorted out. The raw value of unwashed/dry-processed coffee was calculated using 30 percent defects (15 percent each for primary and secondary defects) and 10% odor. Apart from this, the raw value of wet/semiwet-processed beans was measured by 20% defects (10% for primary and secondary defects each), shape and make (5%), color (5%), and odor (10%). For cup quality taste, 100 g of beans was roasted for 8–12 minutes, cooled, ground, and placed in 250 ml cups. Finally, the brew was ready for three cuppers to test cup cleanness (15%), acidity (15%), body (15%), and flavor (15%) for wet, semiwet, and dry-processed commercial coffees. Finally, based on preliminary evaluation grades, the total of both raw total (40%) and cup/liquor total (60%) values was utilized to classify coffee samples [33].

2.6. Data Analysis and Presentation. Multiple Factor Analysis (MFA) was conducted using R statistical software version 4.1.0. used under RStudio version 1.4.1717 and FactoMineR and factoextra packages that are prepared to analyze, visualize the data set, and plot graphs [35]. In the current study, MFA was used to investigate coffee quality variations based on the studied factors (district, production system, and coffee processing methods) as well as soil physical and chemical quality variables. The analysis was utilized to acquire a comprehensive view of the observations as well as the correlations between the different groupings of variables. Based on this, ten quantitative and qualitative groups were purposefully classified according to the data they acquired. The variance in the data set was calculated by using four active groups of quantitative variables that contained continuous variables of raw and cup quality tastes. The groups are physical quality (screen retention and bean moisture), raw quality (odor and raw total), cup quality (acidity, flavor, and cup total), and total and grade (total value and preliminary grade). Due to the variation in the scoring procedure of raw taste among the wet/semiwet and dry process coffees, only the odor score was observed as a variable in the result of the correlation plot under the raw quality group. However, the result of all raw quality variables was included in the analysis, and the result is observed as raw in the correlation plot under the raw quality group. Similarly, in the analysis, cup cleanness was not included individually as a variable due to the evenness of the score, but its score was included in the cup's total score. As for supplementary variables, four categorical groups (district, production system, coffee processing method, and soil textural class) and two continuous variable groups (soil physical and chemical properties) were used. These supplementary components were not part of the calculation of eigenvalues like active groups; rather, they were utilized to enhance and simplify the analysis and interpretation of variables in the data matrix [36].

The MFA's eigenvalues reflect how much variation each dimension retains; hence, dimensions with values greater than one and accounting for more variance were kept [35]. One divided by the number of variables produced the predicted average contribution of group variables (four in

Table 2: Eigenvalues, coordinates, variable contribution, and squared cosine values of active and supplementary group variables.

	Dim 1	Ctr (%)	Cos2	Dim 2	Ctr (%)	Cos2
Variance/Eigenvalue	2.00			1.05		
Percent of variance	37.03			19.36		
Cumulative percent of the variance	37.03			56.39		
Active groups						
Coffee physical quality	0.07	3.27	0.00	0.91	86.79	0.63
Coffee raw quality	0.62	30.83	0.31	0.09	8.45	0.01
Coffee cup quality	0.39	19.39	0.14	0.03	2.70	0.00
Coffee total and grade	0.93	46.51	0.86	0.02	2.05	0.00
Supplementary groups						
District	0.14		0.01	0.28		0.04
Production system	0.24		0.01	0.33		0.01
Processing method	0.46		0.01	0.60		0.01
Soil textural class	0.09		0.00	0.05		0.00
Soil physical quality	0.01		0.00	0.02		0.00
Soil chemical quality	0.07		0.00	0.14		0.01

Dim: dimension, Ctr: contribution, Cos2: squared cosine.

the current experiment). As a result, variable contribution percentages and over 25% are regarded as significant contributors to the component. Closer variable values corroborate the variables' connection, and two closer groupings have a proximal structural influence on data points in the data set [37]. Larger squared cosine (Cos2) values (values approaching one) resulted in a better projection of the element on the axis for groups/variables [38].

The difference between the significant and nonsignificant categories was shown using the confidence ellipse [37]. Furthermore, overlapping ellipses confirm that they are not at all different, but ellipses that are not overlapped are strictly distinct [39].

SAS software version 9.3 was used to carry out the Pearson correlation coefficient analysis [40]. It was conducted to study and quantify the level of linear relationships between coffee and soil quality characteristics variables.

3. Results

3.1. Relationship of Group Variables on Multiple Factor Analysis. The result of multiple factor analysis shows the relationship between different variable groups collected on coffee and soil quality variables (see Table 2). The first two dimensions, which have variances/eigenvalues values above one (2 and 1.05) and account for more variance, were retained. The percent of variance explained by both dimensions was 37.03 and 19.36%, respectively. The cumulative measured variance explained by the retained dimensions was 56.39%.

The result of the first two retained dimension active groups, principally, dimension one, is primarily represented by and retains higher coordinate values from total and grade (0.93) and raw (0.62) values. Those groups individually accounted for 46.51% and 30.83% of the contribution, and in the group, they accounted for 77.34% of the variation. Similarly, in dimension two, the highest (0.91) coordination point was recorded in the coffee physical quality group and it accounted for 86.79 of variation (see Table 2).

Among the supplementary groups, processing methods had the highest (0.46) coordinate value on dimension one, and the result coincided with the active group variables of coffee total and grade (0.93) and raw quality (0.62). Similarly, in the second dimension, the processing method also scored the highest coordinate value (0.60), and the result is in line with the coffee physical quality group, which has the highest (0.91) coordinate value quantified under the active group.

3.1.1. Relationship of Coffee Samples with Location, Production Systems, and Soil Quality Categorical Variables. Supplementary categorical factor groups (district, production systems, and processing method) and a variable group (soil textural class) were used to plot individual factor maps in the dataset (see Figures 2 and 3). The MFA map differentiates districts into different quadrants (see Figure 2). Accordingly, the overlap of ellipses of Gimbo and Decha districts showed that the districts are not significantly different from each other based on their coffee quality values. However, they are significantly different from the Gawata district.

The MFA showed that most of the ellipses of the production system overlapped each other, and that assured the absence of significant differences among the systems (see Figure 2). There is no strict significant difference between the coffee production systems within each district. However, there is a significant difference between the production systems of different districts. Thus, Gimbo garden coffee is strictly different from Decha semiforest and all other coffee production systems in the Gawata district, but it shares similarities and is not significantly different from the other coffee production systems. The Gimbo forest and Decha garden coffee production systems are not significantly different from each other, but they are significantly different from all the other coffee production systems in the Gawata district. Except for the Gawata forest production system, the remaining Gawata coffee production systems share some

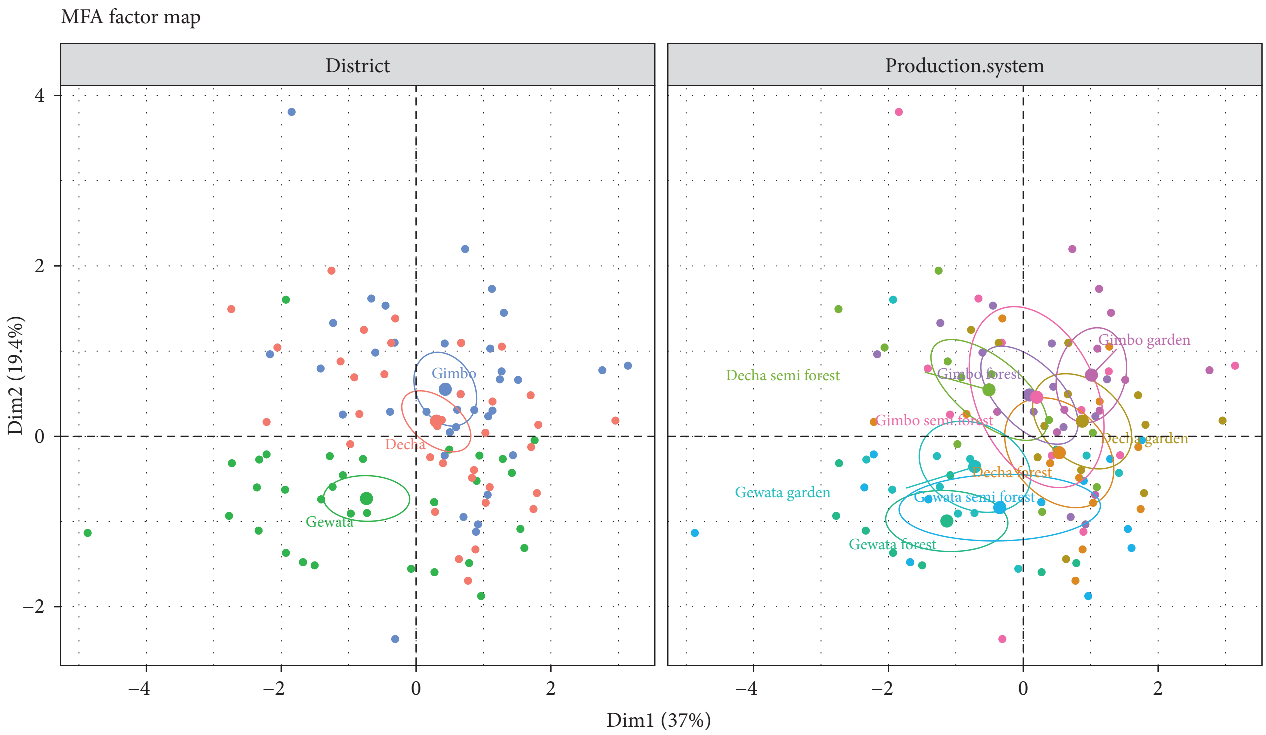

Figure 2: Individual coffee samples and their relationship with districts and production systems.

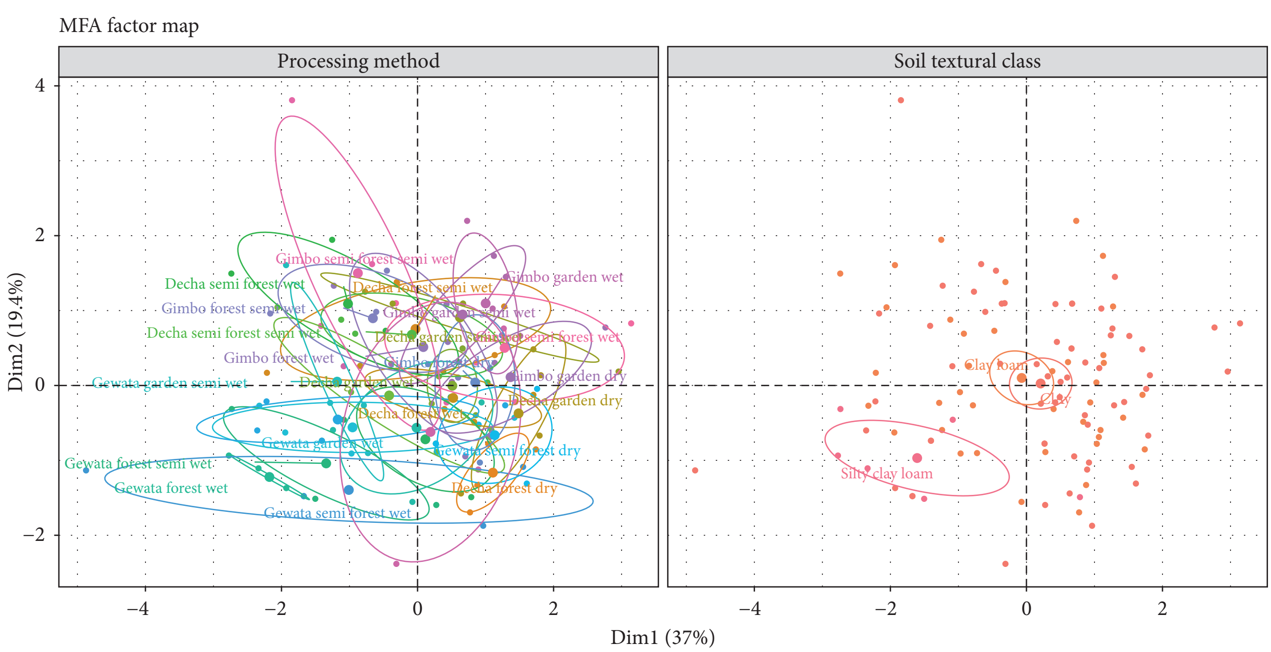

Figure 3: Individual coffee samples and their relationship with the coffee processing systems and soil textural class.

similarities with parts of Gimbo semiforest and Decha forest coffee production systems.

The coffee processing methods used on the coffees were aligned on different quadrants along dimensions one and two, according to the districts and coffee production systems from which the coffees were sourced (see Figure 3). Except for some coffee processing methods that share similar coffee quality status with Decha and Gawata district coffees, semiwet and dry-processed semiforest Gimbo district coffees share similar quality status with most of the coffee processing methods of the remaining two districts. Wet-processed Gimbo district garden coffee, which is mapped in the first quadrant, was not significantly different from all Gawata district coffees, but not strictly different from Decha district coffees. Wet-processed Gawata district forest coffee is significantly different from all Gimbo and Decha district coffees

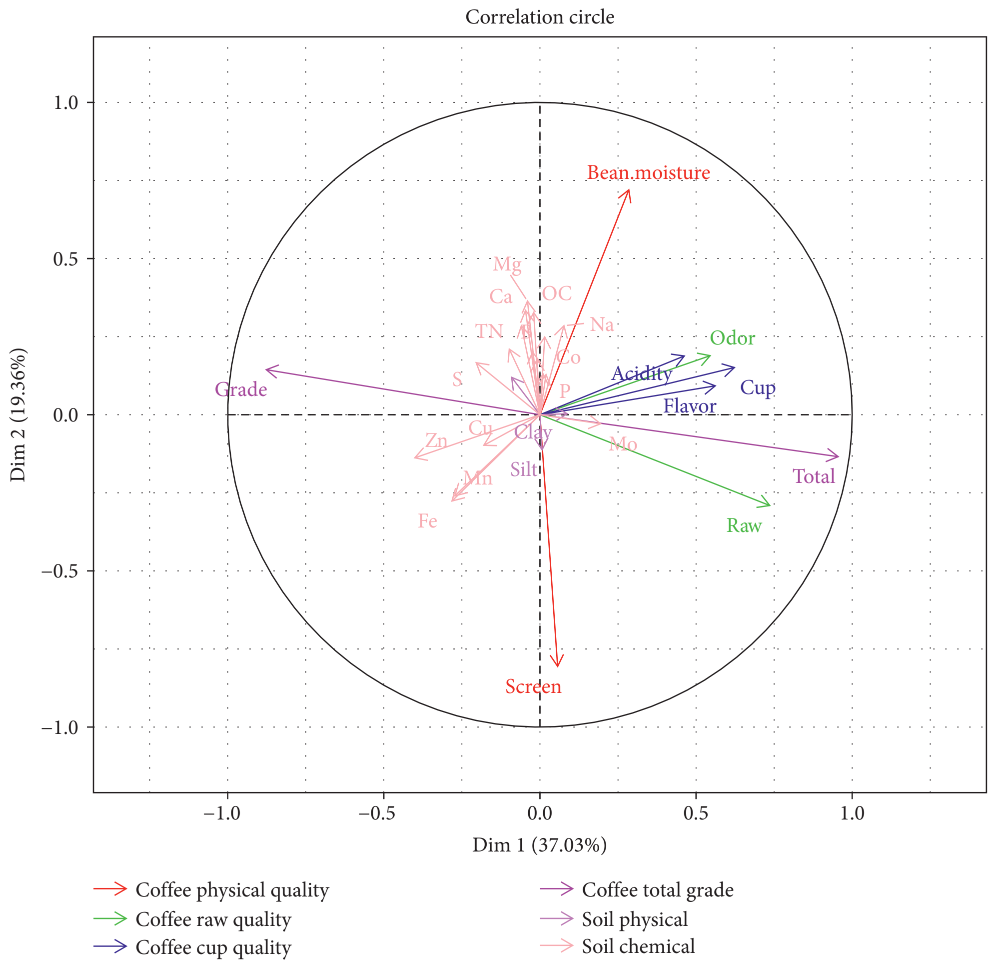

Figure 4: Correlation plot of measured quantitative variables.

produced with all production systems and processed with all preparation methods.

The MFA factor map (see Figure 3) showed that soil textural classes were put into different groups. Clay and clay loam soil are close to the origin of the map, and they are not strictly different from each other. Silty clay loam soils are far from the origin of the map and are strictly different from the other two soil textural classes. They could be used to differentiate districts and production systems according to the values they have in the MFA.

3.1.2. Relationship between Coffee and Soil Quality Variables. On the correlation circle, all coffee raw and cup quality variables mapped in quadrants one and four were aligned at the positive end of dimension one whereas bean moisture percentage and screen retention (14) were aligned on the positive and negative end of dimension two, respectively. Positively correlated variables are close together, whereas opposing variables are reflected on the opposite side of the origin of the correlation circle observed on the map (see Figure 4). Based on this, the raw score had a direct and positive relationship with soil molybdenum but related negatively to variables reflected on the opposite side, like total nitrogen, sulfur content, sand percentage, and others. Bean moisture, organic carbon, magnesium, and sodium are positively correlated variables. However, they are negatively related to above 14 screen retention, soil iron, manganese, and zinc content. A strong relationship was observed between raw and cup quality variables with soil molybdenum and clay percentages. However, they correlated negatively with coffee grade (which does not mean lower quality), soil sand percentage, soil zinc, copper content, and other oppositely reflected variables.

3.2. Overall Pearson's Correlation Analysis of Coffee and Soil Quality Variables. The overall Pearson's correlation analysis revealed that moisture content was significantly and positively linked with soil potassium ($r = 0.33^{***}$), calcium ($r = 0.26^{**}$), magnesium ($r = 0.26^{**}$), boron ($r = 0.24^{*}$), sodium ($r = 0.25^{**}$), silicon ($r = 0.20^{*}$), organic carbon ($r = 0.25^{**}$), and soil pH ($r = 0.20^{*}$). On the other hand, it was negatively associated with soil manganese ($r = -0.24^{*}$) and iron ($r = -0.23^{*}$). A significant relationship was observed between coffee screen retention and soil micronutrients like iron ($r = 0.21^{*}$), boron ($r = -0.20^{*}$), and sodium ($r = -0.19^{*}$) (see Table 3). Odor had a significant and positive relationship with soil pH ($r = 0.23^{*}$). The overall raw quality score is significantly related to the sand percentage

Table 3: Pearson's correlation coefficients (r) of preliminary coffee quality and soil physical and chemical variables.

Soil quality variables	Coffee physical quality variables		Preliminary coffee quality variables						
	Bean moisture	Screen retention	Raw quality		Cup quality			Overall quality	
			Odor	Raw	Acidity	Flavor	Cup	Total	Grade
TN (mg/Kg)	0.13	−0.01	0.07	−0.37***	0.12	0.17	0.18	−0.18	0.14
P (mg/Kg)	0.16	−0.07	0.12	0.02	−0.12	−0.04	−0.08	−0.03	−0.04
K (mg/Kg)	0.33***	−0.02	0.19	−0.02	−0.18	−0.10	−0.15	−0.11	0.06
Ca (mg/Kg)	0.26**	−0.15	0.17	−0.27**	−0.02	0.14	0.10	−0.15	0.09
Mg (mg/Kg)	0.26**	−0.17	0.12	−0.32***	0.10	0.18	0.18	−0.13	0.11
S (mg/Kg)	0.14	−0.02	0.01	−0.32***	−0.13	−0.01	−0.07	−0.28**	0.16
Mn (mg/Kg)	−0.24*	0.18	−0.13	−0.06	−0.33***	−0.20*	−0.29**	−0.23**	0.22*
Zn (mg/Kg)	−0.18	0.16	−0.09	−0.30**	−0.28**	−0.23*	−0.29**	−0.42***	0.34***
Fe (mg/Kg)	−0.23*	0.21*	−0.13	−0.06	−0.35***	−0.21*	−0.31**	−0.25*	0.22*
Mo (mg/Kg)	0.07	−0.07	−0.05	0.33***	0.10	−0.10	−0.04	0.24*	−0.22*
B (mg/Kg)	0.24*	−0.20*	0.17	−0.11	−0.18	−0.02	−0.09	−0.14	0.08
Cu (mg/Kg)	−0.14	−0.01	−0.003	0.02	−0.26**	−0.23*	−0.28**	−0.15	0.17
Na (mg/Kg)	0.25**	−0.19*	0.02	−0.08	0.13	0.12	0.15	0.03	−0.08
Co (mg/Kg)	0.10	−0.17	−0.03	0.07	0.02	−0.08	−0.05	0.03	0.02
Si (mg/Kg)	0.20*	−0.09	0.16	−0.01	−0.19*	−0.03	−0.11	−0.07	0.03
OC (mg/Kg)	0.25**	−0.13	0.15	−0.27**	0.09	0.16	0.15	−0.11	0.08
pH	0.20*	−0.14	0.23*	−0.10	−0.12	0.11	0.03	−0.06	0.04
Sand (%)	0.07	0.00	−0.08	−0.28*	0.08	0.15	0.15	−0.13	0.07
Clay (%)	−0.01	−0.09	−0.07	0.15	0.15	−0.05	0.03	0.14	−0.07
Silt (%)	−0.05	0.08	0.14	0.13	−0.20*	−0.10	−0.16	−0.01	−0.01

*Significant at $P < 0.05$; **Significant at $P < 0.01$; ***Significant at $P < 0.001$; values without asterisk = nonsignificant.

($r = -0.28^*$), total nitrogen ($r = -0.37^{***}$), calcium ($r = -0.27^{**}$), magnesium ($r = -0.32^{**}$), sulfur ($r = -0.32^{***}$), zinc ($r = -0.30^{**}$), molybdenum ($r = 0.33^{***}$), and organic carbon ($r = -0.27^{**}$). A significant and negative relationship was obtained between preliminary coffee acidity and soil silt percentage ($r = -0.20^*$), manganese ($r = -0.33^{***}$), zinc ($r = -0.28^{**}$), iron ($r = -0.35^{***}$), copper ($r = -0.26^{**}$), and silicon ($r = -0.19^*$) contents. Likewise, manganese ($r = -0.20^*$), zinc ($r = -0.23^*$), iron ($r = -0.21^*$), and copper ($r = -0.23^*$) were linked significantly with coffee flavor. A negative and significant relationship was obtained between the overall cup score and manganese ($r = -0.29^{**}$), zinc ($r = -0.29^{**}$), iron ($r = -0.31^{**}$), and copper ($r = -0.28^{**}$). The total quality score was related significantly to sulfur ($r = -0.28^{**}$), manganese ($r = -0.23^{**}$), zinc ($r = -0.42^{***}$), iron ($r = -0.25^*$), and molybdenum ($r = 0.24^*$). On the other hand, the preliminary coffee grade becomes significantly poor in the presence of high amounts of micronutrients like manganese, zinc, iron, and boron. However, it becomes significantly better in the presence of high amounts of soil molybdenum (see Table 3).

4. Discussion

The present study demonstrated the relationship of coffee physical and cup quality variables with location, production system, processing methods, and soil physical and chemical attributes inside the Kafa Biosphere Reserve. According to [35], based on the contribution percentage of active group variables in the first two dimensions, coffee total and grade, raw quality variables were the important variables to define variations resulting from the factors used in the study. The presence of higher coordinate values of active and supplementary group variables of the dimensions demonstrated a closer relationship between the variables. Hence, two closer groups have a proximate structural effect on individuals in the data set [37]. Primarily, the coffee processing method and, secondly, the coffee production and location effects were pronounced on the above-mentioned quality variables of Kafa Biosphere Reserve coffees. Sualeh et al. [23] reported the significant effect of the processing method on the variation of Ethiopian coffee quality in relation to roast duration. According to Le et al. [38], the result of squared cosine values (Cos2) of groups/variables which have larger Cos2 values or values approaching one showed a better projection of the element on the axis. Based on this, the above-mentioned variables/groups had a significant contribution to the variation of the data set. Hence, relative to the location, production system, and processing, the contribution of soil chemical quality was more important than soil physical quality in the variability of physical and raw quality attributes of Kafa Biosphere Reserve coffees. Abebe et al. [41] reported the important contribution of soil factors to quality variables of Ethiopian rainforest wild Arabica coffees.

According to Kassambara [35], it is possible to define the relationship between individual variables, the quality of the representation of variables, and the correlation of variables with dimensions. Hence, based on the quality of coffee, the Gimbo and Decha district coffees are more related to raw and cup quality variables except above 14 screen retention. The coffees are grown on clayey soils and soils that have a high molybdenum content. As reported by Tassew et al. [42] and Abebe et al. [41], the positive influence of fine-textured soils was observed on the cup quality of Ethiopian coffee. Furthermore, the coffees have a relatively high bean moisture content that is directly related to increased soil potassium, calcium, magnesium, sodium, organic carbon content, and high soil pH. Gawata coffees were more related to better screen retention and soil silt percentage. In addition, primary micronutrients (iron, manganese, zinc, and copper) were important for differentiating Gawata coffees from others.

The Decha (garden and forest) and Gimbo (garden) production systems coincide with better raw and cup quality scores of coffee, and clayey soil is a feature of these production systems. The Decha garden and forest coffees are distinguished from the rest due to their high amount of soil molybdenum and clayey soils. The betterment of garden coffee quality could be attributed to better crop management practices like frequent weeding, intercropping, and application of farmyard manure and crop residues [19]. Although the Decha semiforest production system coffees have some similarities with the garden and forest production system coffees of the same district, the coffees are grown on soils that have a high sand percentage and they are relatively poor in raw coffee quality. The Gawata semiforest production system coffees have better screen retention than the two production systems in the same district. Most Gawata coffees and exceptionally forest and garden production system coffees are identified by their silty clay loam soils which have high amounts of iron, manganese, copper, and zinc.

To reduce the loss of physical and sensory quality of coffee, green beans' moisture content needs to be between 8 and 12 percent [43,44]. It was observed that Gawata's forest-based coffees correlated with a reduced amount of bean moisture, which coincided with poor acidity and overall cup quality scores. On the other hand, all Gimbo and Decha garden coffees are related to better bean moisture content, which coincides with better cup quality scores. It was observed that soil nutrients, specifically potassium, calcium, magnesium, sodium, and organic carbon, are positively correlated with bean moisture content. The contribution of nutrients is important in the osmotic adjustment status of plants. In this regard, in a study conducted on Ethiopian Arabica coffee cultivars, an increment in the accumulation of potassium, calcium, and magnesium content was observed in the leaves of water-stressed seedlings [45].

The potassium nutrient is required by plants for photosynthetic CO_2 fixation [46], stomatal conductance [47], and fruit load [48]. In the study area, the presence of a high amount of rainfall [49] could enhance the uptake of potassium due to the presence of enough moisture in the soil [50]. This leads the coffee plants to luxuriously use the available nutrients from the soil, and this improves the water status of the plant as well as the green beans, thereby improving the overall cup quality of the coffee beans. This was observed in Tanzania, where a direct and positive relationship between potassium and coffee organoleptic qualities was obtained in compact hybrid coffees [51].

The direct relationship between calcium and better bean moisture content would be due to its direct influence on the growth and development of the plant through better root growth, vigorous plant growth, improvement in uptake of potassium nutrients [52], and relative yield increment on coffee plants [53]. According to Ramalho et al. [54], the contribution of calcium in stabilizing chlorophyll and maintaining better photochemical efficiency of leaves makes the nutrient important in coffee production. In addition, it could physiologically adjust the osmotic status of under-stressed plants through increasing soluble sugar and proline content in the plant system [55,56].

Magnesium plays a significant role in plant growth and development and its positive influence is observed in the production and translocation of dry matter to sink organs. The presence of enough magnesium enhances the translocation of metabolites to sinks, thereby improving the root system, and this leads to better utilization of available soil moisture [57]. The quantity of soil sodium in the soils of all districts and production systems is within the range of optimal to high (9.38 to 25.39 mg/kg) [58]. In the absence of potassium, sodium plays an important role in plants in improving the water use efficiency of plants at a certain level [59]. The presence of a positive relationship between the nutrient and green bean moisture content could be due to this effect.

According to ECX [33], coffee samples' above 14 screen retention should be at least 85% by weight to get a better quality of beans. There is a direct relationship between screen retention and Gawata coffees, which are grown on iron, manganese, copper, and zinc-rich soils. These metal nutrients (iron, zinc, and copper) are vital for plant cell metabolism [60], whereas manganese plays a significant role in oxygenic photosynthesis [61]. Their positive influence on bean size could be attributed to these effects. According to Martinez et al. [21], zinc-supplemented plants have shown better exportable large-size beans in screen sizes 17 and 18. Though all Gawata coffees exhibited large screen retention, the presence of shade and light intensity, which contributed to the better development of fewer flowers and cherries [62], and the enlargement of seeds [63], were assumed to affect screen retention. However, they were not the only reasons for exhibiting the condition. Rather, factors like higher temperature can be taken out as a significant contributor to the difference in coffee screen size [64].

Coffee beans need to have better moisture content (>8%) to have better cup quality scores [5]. Since Gawata district coffees were projected toward low bean moisture content, this could be the reason behind the poor quality (acidity, odor, and overall cup) status of the coffees. On the other hand, the relatively poor quality status of the district could be related to soil chemical quality and related factors. This significant reduction in the quality of coffee coincided with the increased amounts of iron, manganese, zinc, and copper in the soils of the district and its production systems. According to Melke and Ittana [58] and Jones [65], the amount of these nutrients, specifically iron, was within the range of optimum level (267.67–413.33 mg/kg), but a relatively higher amount (345.49 413.33 mg/kg) was recorded for the Gawata district coffees. Similarly, the manganese content (>300 mg/kg) exceeds the expected optimal range (50 mg/kg) for coffee. On the other hand, the amount of copper found in the sols of all districts is within the optimum range (0.3–10 mg/kg). However, relatively higher contents

(2.37) and 3.96) mg/kg of copper were recorded from the soils of Gawata's district forest and garden coffee production systems, respectively. Similarly, the soil zinc content of most districts' production systems is within the optimum range. However, the above Gawata coffees scored onefold higher (23.96–24.19 mg/kg) than the amount expected (2–10 mg/kg) than other production systems' zinc content.

Higher amounts of TN, Ca, Mg, S, Zn, OC contents, and sand percentage had a significant antagonistic effect on raw coffee quality, which was partly consistent with the findings of Salla [66], who reported a negative relationship between total coffee quality score and soil Ca and OM contents in Ethiopia. According to Farah [34], the contribution of nitrogenous compounds to the flavor of coffee is positive. However, in the current study, its negative relationship with the raw score is diminished due to the presence of an increased amount of soil molybdenum, which reduces the accumulation and antagonistic effect of total nitrogen on the quality of coffee [67]. Furthermore, the significant and positive correlation between soil molybdenum and the raw quality of coffee could be related to its contribution to nitrogen metabolism and proper seed production [68,69].

A poor but positive relationship was observed between acidity, flavor, and cup scores with total soil nitrogen and this could be attributed to the effect of nitrogenous compounds (proteins/peptides and free amino acids), which play a significant role in the Maillard reaction as precursors of volatile compounds (furans, pyridines, pyrazines, pyrroles, aldehydes, and melanoidins) [34]. In line with the present finding ($r = -0.18$), Mintesnot et al. [70] reported the antagonistic effect of nitrogen on the organoleptic quality of coffee.

Sulfur tends to accumulate more in beans [71] and affects the aroma and flavor of coffee through volatile compounds [72]. The presence of high organic matter that results from the decomposition of litter from the vegetation in the studied coffee production systems ensures mineralization and an increase in the amount of nutrients [18]. Since organic matter and plant residues are major sources of plant available sulfur [73], it is expected that the amount of the nutrient will be increased in areas where growing environments meet the conditions. Although the amount of this nutrient in the soils of most studied coffee production systems is low (<24 mg/Kg) [65], its antagonistic effect on the overall coffee quality score may be related to its relative amount with other nutrients.

In parity with the current study findings, Yadessa et al. [22] and Mintesnot et al. [70] reported a negative and significant correlation between soil Mn, Zn, Fe, and Cu amounts with cups and the overall quality of Ethiopian coffees. From the nutrients, zinc contributes to the biosynthesis of IAA (Indole acetic acid), helps in nucleic acid and protein synthesis, and helps proper utilization of P and N [74] to positively influence the chlorogenic acid content of coffee beans [21]. In our study, the amount of zinc (5.74–24.19 mg/kg) in the soil was partly beyond the adequate limit under the Mehlich 3 extraction method [65]. Therefore, it could be one of the reasons behind the poor cup quality scores in Gawata district coffees.

Silty soils are usually well aggregated, but in moist conditions, they are likely to be disintegrated and transported easily [75]. This makes the soil undesirable and specifically not preferable for coffee production [69]. However, a positive relationship between silt percentage and coffee quality was reported by Kilambo et al. [51] and Yadessa et al. [22] in Tanzania and Ethiopia, respectively. In contrast to this, in the current study, an undesirable effect of the soil types that existed was observed in Gawata's coffee production systems, where a high percentage of silty soil particles were coupled with a high amount of lengthy rainfall conditions.

5. Conclusion

The result of the study shows that processing methods used in the study had a significant contribution greater than the effects of location and production system effects on the variation observed in coffee quality variables. The overall MFA result showed that coffee total and preliminary grade and coffee physical quality variable groups were affected more because of processing methods. In addition to this, the processing method effect was also pronounced on raw coffee quality variables (odor and raw total). The study confirms that the variations in soil textural class, chemical, and physical properties were important in describing the differences among coffee quality variables studied. Screen retention has been positively correlated with soil iron, whereas it has been negatively correlated with boron and sodium content. Silty clay loam soils have been correlated with increased bean size that was pronounced in Gawata district coffees. A positive and significant correlation was observed between bean moisture content and soil potassium, calcium, magnesium, boron, sodium, organic carbon, silicon content, and soil pH. The significant and positive relationship between soil molybdenum and the overall quality of coffee variables signifies the importance of the nutrient in quality coffee production whereas the correlation between most of the macro- and micro soil nutrients and the overall raw and cup quality of the coffee was negative. The strong correlation between overall coffee quality and soil zinc and sulfur content signifies the effect of the nutrients on poor quality coffee production across the studied production systems. Since the study focused only on production systems and soil quality status in mid-elevation coffee production systems, the effects at higher and lower elevations were not studied. Hence, it is commendable to include the effect of elevation as an additional factor to identify variability within the quality of Kafa Biosphere coffees.

Data Availability

The data are available from the corresponding author and can be accessible under proper request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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