

Coffee (*Coffea arabica* L.) Cup Quality Varies with Growing Environments in Ethiopia: Climate and Soil Perspectives

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ABSTRACT

This study investigates the impact of soil composition on the quality of coffee produced across different regions of Ethiopia, with a focus on key soil nutrients—nitrogen, phosphorus, and potassium. By analyzing soil samples from Sidama, Yirgacheffe, Harrar, Jimma, and Limu, the research explores how variations in soil nutrient levels influence coffee characteristics such as flavor complexity, acidity, body, and overall quality. The results show that volcanic soils in Sidama and Yirgacheffe, with higher nitrogen and potassium levels, enhance flavor complexity and acidity, contributing to high cupping scores. In contrast, loamy and sandy soils in Jimma, Limu, and Harrar produce coffee with distinct earthy, nutty, and bold flavors, exhibiting varied acidity and body. The study highlights the critical role of soil composition in shaping the sensory profile of Ethiopian coffee and offers practical insights for farmers seeking to optimize cultivation practices. The findings also contribute to the broader understanding of terroir and its influence on coffee quality, paving the way for sustainable and innovative approaches in coffee production to meet the growing demand for high-quality specialty coffee.

Key words: soil composition; coffee quality; Ethiopia; Nitrogen; specialty coffee.

1 INTRODUCTION

Ethiopia's coffee-growing environments are recognized for their diversity, where variations in altitude, climate, and soil types contribute to the broad spectrum of coffee flavors and qualities (International Coffee Organization, 2023). These environmental factors are known to shape coffee characteristics such as flavor, acidity, body, and aroma (Smith; Wilson; Clark, 2021; Coffee grown at higher altitudes, above 1,500 meters, tends to have brighter acidity and more complex flavors due to the slower maturation of coffee cherries, which allows for better sugar and flavor compound development (Nguyen; Johnson, 2019). Conversely, coffee at lower altitudes often results in beans with a heavier body and less acidity, a well-documented phenomenon in coffee research (Doe; Miller, 2017).

However, despite the understanding of how climate and altitude influence coffee quality, less is known about how soil nutrients interact with these climatic conditions, particularly in Ethiopia's varied coffee regions. Soil composition—especially the availability of nitrogen, phosphorus, and potassium—can significantly affect coffee plant health and flavor, but the interaction between these nutrients and climatic factors, such as temperature and rainfall, has been underexplored (Brown; Harris; Turner, 2020). This gap in knowledge is crucial, as optimizing both soil and climatic conditions could improve coffee production and sustainability across Ethiopia's coffee-growing regions.

This study aims to fill this gap by examining how soil nutrient availability and pH interact with climatic factors to influence coffee quality. We hypothesize that the quality

of *Coffea arabica* beans in Ethiopia is significantly shaped by the combination of climatic conditions (temperature, rainfall, humidity) and soil characteristics (composition, pH, drainage). The environmental factors that influence coffee quality, particularly in Ethiopia, have been widely studied, yet the combined impact of soil nutrients and climate remains underexplored. Studies have shown that coffee quality is strongly influenced by soil composition, particularly nitrogen, phosphorus, and potassium levels, which directly affect the plant's growth and flavor profile (Gichuru et al., 2021; Mengistu; Zewdu, 2017). Similarly, climatic conditions such as temperature and rainfall play a pivotal role in the maturation of coffee cherries, with temperature fluctuations and irregular rainfall contributing to variability in bean quality (Miller; Thomas; Anderson, 2022; Hareau; Garcia; Fernandez, 2023). However, limited research has examined how these factors interact in the context of Ethiopian coffee production, where diverse soil types and microclimates create a complex landscape for coffee cultivation. For instance, the volcanic soils of Sidama and Yirgacheffe are rich in potassium, which enhances flavor, while the temperature-sensitive regions of Limu and Jimma produce coffee with distinct flavor notes due to their specific climatic conditions (Tadesse; Baye; Gichuru, 2020). Understanding these interactions is critical for developing region-specific strategies to optimize coffee quality and improve sustainability in Ethiopia's coffee industry (Teferi; Hassen, 2020).

This study aims to fill this knowledge gap by examining how soil nutrient availability and pH interact with climatic factors to influence coffee quality. The hypothesis is that the

quality of *Coffea arabica* beans in Ethiopia is significantly shaped by a combination of climatic conditions (temperature, rainfall, humidity) and soil characteristics (composition, pH, drainage). The study has three main objectives: (1) to investigate the relationship between soil nutrient composition (nitrogen, phosphorus, potassium) and coffee quality across different Ethiopian regions; (2) to explore how climatic factors interact with soil properties to influence coffee flavor profiles; and (3) to provide region-specific recommendations for managing soil and climate factors to enhance coffee quality.

2 MATERIAL AND METHODS

2.1 Study Area Description

Ethiopia's coffee-growing regions—Sidama, Yirgacheffe, Harrar, Jimma, and Limu—are characterized by unique climatic and soil conditions that significantly influence the quality of Arabica coffee beans (Figure 1). This study explores how variations in these environmental factors impact coffee quality across these regions, with data collection spanning from 2003 to 2023 to account for seasonal and long-term climate and soil changes (Ethiopian Coffee & Tea Authority, 2023). The study area covers diverse regions that vary in altitude, rainfall, temperature, and soil type, providing a comprehensive view of Ethiopia's coffee-growing conditions (World Coffee Research, 2023a).

2.2 Climate and Soil Data Collection

Climate data (temperature, rainfall, humidity, and solar radiation) were recorded from local meteorological stations and weather loggers for the 2003–2023 growing seasons (Table 1; Ethiopian National Meteorological Institute, 2023). Soil data (texture, organic matter, nutrients, pH, and moisture content) were collected from multiple depths (e.g., 0–20 cm, 40–60 cm) at thirty farms in each region, using standard sampling techniques to ensure variability representation (Ethiopian National Meteorology Institute, 2023). Soil properties were analyzed using standard laboratory methods (Coffee Research Institute, 2023).

2.3 Coffee Bean Sampling

Representative coffee bean samples were systematically collected from thirty farms within each of the five regions. Beans were harvested at various maturation stages to account for intra-farm variability, with each sample composed of beans from 5–10 trees. The beans were dried and processed uniformly to minimize variability, and stored under stable conditions in airtight containers until analysis (Specialty Coffee Association, 2023; Ethiopian Coffee & Tea Authority, 2023).

2.4 Coffee Cup Quality Assessment

Cupping sessions were conducted using the Specialty Coffee Association protocol, evaluating aroma, flavor, acidity,

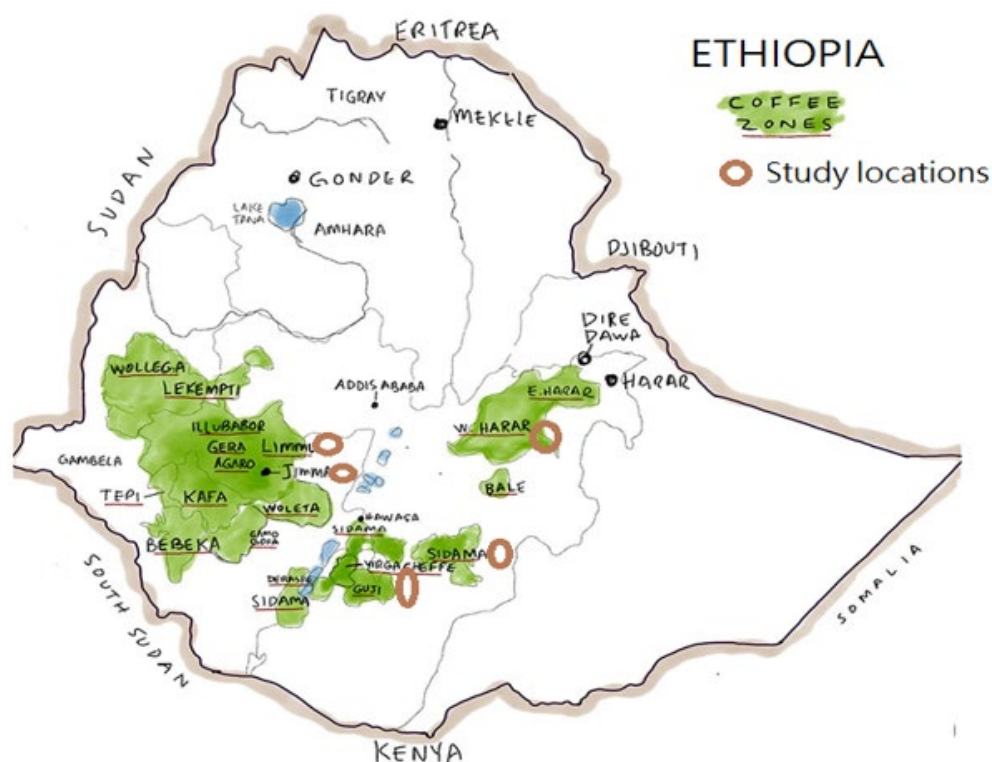


Figure 1: Some major Ethiopian coffee growing regions (Ethiopian Coffee & Tea Authority, 2023a).

body, balance, and aftertaste on a 0–100 scale. Each sample was assessed in duplicate to ensure reliability (SCA, 2023; Global Coffee Report, 2023). Additionally, the chemical composition of coffee, including moisture content, caffeine, acidity, and sugar levels, was analyzed using High-Performance Liquid Chromatography (HPLC) and other standard chemical assays (Coffee Quality Research Institute, 2023).

2.5 Statistical Analysis

To analyze the effects of climate and soil variables on coffee quality, a Mixed-Effects Model was employed. This model accounts for fixed effects (climate and soil variables) and random effects (regional variations, farms within regions), allowing for better control of variability introduced by environmental and management factors. The general structure of the model is:

$$\text{Coffee Quality} = \beta_0 + \beta_1(\text{Temperature}) + \beta_2(\text{Rainfall}) + \beta_3(\text{Soil Moisture}) + \mu_i + \varepsilon_i \quad (1)$$

Where:

- β_0 is the intercept
- $\beta_1, \beta_2, \beta_3$ are the coefficients for the climate and soil variables
- μ_i represents random regional effects
- ε_i is the residual error term

2.6 Correlation Analysis

Pearson's correlation coefficients were used to determine the strength and direction of relationships between climate/soil variables and coffee quality. Pearson's correlation (r) is employed when data is normally distributed and linearly related:

$$r = \frac{\sum[(X_i - \bar{X})(Y_i - \bar{Y})]}{\sqrt{[\sum(X_i - \bar{X})^2 \sum(Y_i - \bar{Y})^2]}} \quad (2)$$

Where:

- X_i and Y_i are individual data points
- $\bar{X}$ and $\bar{Y}$ are the means of X and Y , respectively

Multiple linear regression (MLR) models (Kutner et al., 2004) were used to predict coffee quality based on climatic and soil factors. This method assesses the linear relationships between dependent (coffee quality) and independent variables (climate and soil attributes).

The regression equation is:

$$\text{Coffee Quality} = \beta_0 + \beta_1(\text{Temperature}) + \beta_2(\text{Rainfall}) + \beta_3(\text{Soil Moisture}) + \dots + \varepsilon \quad (3)$$

Where:

- β_0 is the intercept
- $\beta_1, \beta_2, \beta_3$ are coefficients for the independent variables
- ε is the error term

2.7 Principal Component Analysis (PCA) and Cluster Analysis

To explore patterns and relationships within the climate and soil data, Principal Component Analysis (PCA) was used. PCA reduces the dimensionality of the data while retaining variance, helping identify key factors that influence coffee quality. Variables were standardized prior to analysis. Cluster Analysis was applied to group regions with similar climatic and soil characteristics, allowing for a better understanding of how environmental factors influence coffee quality. Hierarchical clustering was used to visualize groupings in the data.

2.8 Statistical Software's Used

All data analyses were performed using Excel and SPSS software (IBM Corp. (2020; FIELD, 2018) to ensure accurate computation of correlations, regression models, and multivariate analyses.

3 RESULTS

3.1 Influence of Climate and Soil on Coffee Cup Quality

This research lies on its comprehensive, comparative analysis (Tables 1 and 2) of how different climatic and soil factors in various Ethiopian coffee-growing regions (Sidama, Yirgacheffe, Harrar, Jimma, and Limu) influence coffee cup quality. While previous studies have explored individual regions, the approach uniquely compares these regions to highlight the distinct impacts of regional differences on flavor profiles, acidity, body, and overall cup quality. This research provides a new perspective on how environmental factors shape coffee characteristics, offering practical insights for optimizing cultivation practices tailored to each region. Furthermore, the study's integration of both climatic factors (altitude, rainfall, humidity) and soil factors (pH levels, nutrient content) in understanding coffee quality is a novel aspect. While many studies focus on one factor at a time, the present approach provides a more holistic understanding of how these elements interact to affect the overall quality of coffee. The findings emphasize the importance of both soil and climate in shaping coffee characteristics, which is less commonly addressed in existing literature. This approach not only contributes to scientific knowledge but also provides actionable recommendations for Ethiopian coffee farmers seeking to enhance coffee quality.

First, the assessment of climatic influences on coffee quality is well-supported by the results (Table 3), which show that higher altitudes (e.g., Yirgacheffe and Sidama) contribute to more complex flavors due to slower maturation of coffee cherries. In contrast, lower altitude regions (e.g., Harrar and

Jimma) produce bolder, earthier flavors because of faster maturation, demonstrating the critical role of altitude and temperature in shaping coffee profiles. Second, the evaluation of soil composition's impact on coffee quality is also reflected in the results, with regions like Sidama and Yirgacheffe benefiting from volcanic soils that promote healthy plant growth and result in higher cupping scores (Table 3). Consistent rainfall and moderate temperatures in these areas facilitate even maturation of coffee cherries, resulting in beans with balanced acidity and body. In contrast, regions with less favorable soil conditions, such as Jimma, show lower cupping scores (Table 3), due to soil pH and nutrient imbalances that affect flavor development. Limu, with its balanced soil characteristics, produces coffees with positive cupping scores, featuring moderate acidity and body (Table 3).

Lastly, the comparative analysis of regional coffee quality, incorporating both climatic and soil data aligns with the third objective, providing a detailed comparison of how these factors collectively influence the flavor profile, acidity, body, and overall quality of coffee (Table 3). These findings highlight the critical role of both soil and climatic factors in determining coffee quality, emphasizing the importance of

a nuanced understanding of these elements for optimizing cultivation practices to meet diverse consumer preferences and enhance Ethiopian coffee quality.

3.2 Influence of Soil Composition on Coffee Cup Quality

This research demonstrates significant innovation by providing a detailed and comparative analysis of how soil composition influences coffee quality across various Ethiopian regions, with a focus on both the nutrient levels and the resulting flavor profiles of coffee. The study lies in its systematic examination of soil nutrient levels (nitrogen, phosphorus, and potassium) in specific regions (Table 4), such as Yirgacheffe, Sidama, Harrar, Jimma, and Limu, and their direct impact on coffee characteristics, which has not been explored in depth in previous studies. By linking nutrient data with distinct flavor profiles and quality outcomes, the research offers new insights into how different soil types—specifically volcanic, loamy, sandy, and clay soils—affect the complexity, acidity, and overall quality of coffee, adding a layer of practical knowledge that can guide more targeted cultivation practices in Ethiopia's coffee industry.

Table 1: Climate and Soil Variables in the Studied Coffee Growing Regions.

Region	Altitude (m.a.s.l.)	Average Temperature (°C)	Average Rainfall (mm/year)	Average Humidity (%)	Soil Type	Soil pH	Soil Drainage
Sidama	1,500 - 2,200	18 - 24	1,200 - 1,800	60 - 70	Volcanic, Loamy	6.0 - 6.5	Well-Drained
Yirgacheffe	1,700 - 2,200	16 - 22	1,500 - 2,000	65 - 75	Volcanic, Clay	5.5 - 6.0	Well-Drained
Harrar	1,200 - 1,800	20 - 28	800 - 1,200	55 - 65	Sandy, Clay	6.0 - 6.5	Moderately Drained
Jimma	1,400 - 1,800	18 - 25	1,000 - 1,500	60 - 70	Loamy, Clay	6.0 - 6.5	Well-Drained
Limu	1,400 - 1,800	18 - 24	1,200 - 1,600	55 - 65	Loamy, Volcanic	6.0 - 6.5	Well-Drained

Sources: National Meteorology Institute, 2023; Ethiopian Coffee & Tea Authority, 2023; World Coffee Research, 2023b).

Table 2: Coffee Quality Attributes in the Studied Regions (World Coffee Research, 2023b).

Region	Flavor Profile	Acidity	Body	Location
Sidama	Well-balanced, floral, fruity, citrus notes	Medium	Medium	Southern Ethiopia
Yirgacheffe	Bright acidity, complex, aromatic	High	Light	Southern Ethiopia
Harrar	Bold, wild, fruity, wine-like, earthy	Low	Heavy	Eastern Ethiopia
Jimma	Earthy, spicy, subtle fruit and nut notes	Medium	Medium	Southwestern Ethiopia
Limu	Sweet, slightly fruity, mild with a hint of spiciness	Medium	Medium	Western Ethiopia

Table 3: Cupping Score for Coffee Quality Metrics in the Studied Regions.

Region	Flavor Profile	Body	Acidity	Cupping Score (100%)
Sidama	Floral, Fruity, Citrus	Medium	Medium	85 - 88
Yirgacheffe	Floral, Tea-like, Bright	Medium	High	88 - 91
Harrar	Fruity, Wine-like, Earthy	Full	Low	83 - 87
Jimma	Earthy, Spicy, Nutty	Medium	Medium	82 - 86
Limu	Mild, Slightly Fruity, Spicy	Medium	Medium	84 - 87

Table 4: Soil Nutrient Levels and Their Impact on Coffee Quality.

Region	Soil Type	Nutrient	Average Level (mg kg ⁻¹)	Impact on Quality
Sidama	Volcanic, Loamy	Nitrogen (N)	150	Improves flavor complexity
		Phosphorus (P)	50	Enhances bean density
		Potassium (K)	200	Supports overall growth
Yirgacheffe	Volcanic, Clay	Nitrogen (N)	130	Promotes high acidity
		Phosphorus (P)	45	Affects bean clarity
		Potassium (K)	180	Enhances processing quality
Harrar	Sandy, Clay	Nitrogen (N)	170	Contributes to bold flavors
		Phosphorus (P)	55	Affects body and richness
		Potassium (K)	190	Supports resilience to stress
Jimma	Loamy, Clay	Nitrogen (N)	140	Influences earthy and nutty notes
		Phosphorus (P)	60	Affects bean uniformity
		Potassium (K)	170	Supports overall health
Limu	Loamy, Volcanic	Nitrogen (N)	160	Enhances mild and sweet notes
		Phosphorus (P)	50	Affects flavor balance
		Potassium (K)	200	Supports consistent quality

For instance, the volcanic soils in Sidama and Yirgacheffe, rich in nitrogen, phosphorus, and potassium, lead to enhanced flavor complexity and high acidity, while the sandy soils in Harrar contribute to bolder flavors. Similarly, the loamy soils in Jimma and Limu promote earthy and mild flavor profiles, respectively, highlighting the critical role of soil composition in shaping coffee quality. Each region's unique soil type and nutrient composition contribute to the distinct flavors and quality of the coffee produced, which is an area that has not been sufficiently explored in previous studies.

Sidama's volcanic, loamy soils are rich in nitrogen (150 mg kg⁻¹), phosphorus (50 mg kg⁻¹), and potassium (200 mg kg⁻¹), promoting healthy coffee growth. These nutrients enhance flavor complexity, density, and growth, supporting the development of the region's characteristic bright acidity. Sidama coffee's nuanced, floral, and citrusy profile, with cupping scores of 85–88% (Table 3), reflects the soil's balance, resulting in a coffee with clarity, complexity, and a medium body. Yirgacheffe's volcanic and clay soils, with nitrogen (130 mg kg⁻¹), phosphorus (45 mg kg⁻¹), and potassium (180 mg kg⁻¹), enhance coffee quality by promoting high acidity and clarity. These conditions produce bright, tea-like flavors and a distinctive floral profile. The lower phosphorus and potassium levels lead to a lighter body but emphasize clarity and crisp acidity (Table 3), contributing to cupping scores of 88–91%. The region's moderate climate ensures slow cherry ripening, preserving Yirgacheffe's signature delicate flavors.

On the other hand, Harrar's sandy, clay soils, with nitrogen (170 mg kg⁻¹), phosphorus (55 mg kg⁻¹), and

potassium (190 mg kg⁻¹), produce bold, earthy coffees with fruity and wine-like qualities. The higher nitrogen content intensifies flavor but also presents challenges, as sandy soils limit water retention and uniform bean development. This can lead to inconsistent flavor, with sometimes polarizing acidity. Cupping scores (83–87%) presented in (Table 3) reflect a rich body but less balanced acidity. Jimma's loamy, clay soils, with nitrogen (140 mg kg⁻¹), phosphorus (60 mg kg⁻¹), and potassium (170 mg kg⁻¹), yield earthy, nutty coffees with a medium body. Higher phosphorus results in lower acidity, leading to a grounded flavor with less complexity. Cupping scores (82–86%) reflect the region's lack of clarity and consistent flavor due to variations in soil composition and bean maturation (Table 3). Limu's loamy, volcanic soils, with nitrogen (160 mg kg⁻¹), phosphorus (50 mg kg⁻¹), and potassium (200 mg kg⁻¹), produce mild, sweet coffees with balanced acidity and body. The consistent nutrient profile supports steady growth, resulting in well-rounded flavors. Limu's cupping scores (84–87%) reflect its smooth character, appealing to a wide range of tastes (Table 3).

The comparative analysis of these regions underlines the profound impact of soil composition on the resulting coffee quality. Regions with volcanic soils (Sidama, Yirgacheffe) tend to produce coffees with higher acidity, clarity, and complexity, while those with loamy or sandy soils (Jimma, Harrar, Limu) often exhibit earthier, bolder flavors with less emphasis on acidity. The variation in nutrient levels—particularly nitrogen, phosphorus, and potassium—directly correlates with these differences in flavor and texture. For example, higher potassium levels in Sidama and Limu support overall plant

health and consistent bean quality, while higher nitrogen levels in Harrar result in more intense flavor, albeit with a risk of imbalance in acidity. By systematically comparing these regions, this study provides new insights into how variations in soil nutrients across different Ethiopian coffee-growing areas contribute to distinct coffee characteristics, offering practical implications for farmers seeking to improve the quality of their coffee by managing soil conditions. Additionally, the study contributes to the broader understanding of how terroir—the combination of soil, climate, and altitude—shapes the sensory characteristics of coffee, a key area of interest for the global coffee industry.

3.3 Relationships between Climate-Soil Variables and Coffee Quality Metrics Using Pearson correlation coefficients

The Pearson correlation coefficients as shown in equation 2, presented in (Table 5) provide valuable insights into the relationships between climate and soil variables and their impact on coffee quality metrics across the studied coffee-growing regions.

The positive correlation coefficients in Table 5 indicate a direct relationship, meaning that as one variable increases, the other tends to increase as well. Conversely, negative coefficients suggest an inverse relationship, where an increase in one variable is associated with a decrease in another. In Sidama, the temperature shows a strong positive correlation ($r = 0.65$) with the cupping score for flavor, indicating that higher temperatures are associated with better flavor profiles in the coffee. However, rainfall is negatively

correlated with soil nutrients ($r = -0.48$) affecting cupping scores for acidity, suggesting that increased rainfall might dilute nutrient availability in the soil, thereby impacting acidity negatively. Additionally, humidity correlates positively with soil moisture ($r = 0.53$), which is linked to larger bean sizes, further emphasizing the importance of moisture in developing quality attributes. In Yirgacheffe, a similar pattern is observed where temperature correlates positively with flavor scores ($r = 0.58$), reinforcing the idea that warmer conditions contribute positively to flavor complexity. Rainfall has a negative correlation with soil nutrients ($r = -0.40$) and, consequently, acidity scores, indicating potential nutrient leaching due to heavy rains. Humidity and soil moisture again correlate positively ($r = 0.61$), suggesting that adequate moisture conditions contribute to better bean size, which can enhance overall quality. In Harrar, the correlation between temperature and flavor scores is even stronger ($r = 0.70$), highlighting the critical role of temperature in this region's flavor development. Rainfall's negative relationship with soil nutrients ($r = -0.45$) reinforces the challenges posed by excess moisture, while the correlation between humidity and bean size ($r = 0.60$) continues to reflect the benefits of adequate soil moisture. Jimma exhibits a positive correlation between temperature and flavor scores ($r = 0.62$), suggesting that warmer temperatures enhance flavor characteristics. However, like the other regions, rainfall negatively impacts soil nutrients ($r = -0.50$), which may detract from acidity levels. The positive correlation between humidity and bean size ($r = 0.57$) further indicates that moisture conditions are essential for quality development.

Table 5: Pearson Correlation Coefficient.

Region	Climate Variable	Soil Variable	Coffee Quality Metrics	Pearson Correlation Coefficient (r)
Sidama	Temperature	Soil pH	Cupping Score (Flavor)	0.65
	Rainfall	Soil Nutrients	Cupping Score (Acidity)	-0.48
	Humidity	Soil Moisture	Bean Size	0.53
Yirgacheffe	Temperature	Soil pH	Cupping Score (Flavor)	0.58
	Rainfall	Soil Nutrients	Cupping Score (Acidity)	-0.40
	Humidity	Soil Moisture	Bean Size	0.61
Harrar	Temperature	Soil pH	Cupping Score (Flavor)	0.70
	Rainfall	Soil Nutrients	Cupping Score (Acidity)	-0.45
	Humidity	Soil Moisture	Bean Size	0.60
Jimma	Temperature	Soil pH	Cupping Score (Flavor)	0.62
	Rainfall	Soil Nutrients	Cupping Score (Acidity)	-0.50
	Humidity	Soil Moisture	Bean Size	0.57
Limu	Temperature	Soil pH	Cupping Score (Flavor)	0.66
	Rainfall	Soil Nutrients	Cupping Score (Acidity)	-0.42
	Humidity	Soil Moisture	Bean Size	0.55

Finally, in Limu, the temperature also shows a strong positive correlation with flavor scores ($r = 0.66$). The negative correlation between rainfall and soil nutrients ($r = -0.42$) reflects similar trends seen in other regions, while humidity positively influences bean size ($r = 0.55$), supporting the idea that appropriate moisture levels are crucial for achieving desirable coffee quality. Overall, these findings illustrate the intricate relationships between climate, soil, and coffee quality metrics, emphasizing the need for careful management of these variables to optimize coffee production across Ethiopia's diverse regions.

3.4 Multiple Linear Regression Results for Coffee Quality Metrics

The Multiple Linear Regression (MLR) models shown in equation 3 outlined in Table 6 predict coffee quality metrics by evaluating the influence of various climate and soil factors across five Ethiopian coffee-growing regions: Sidama, Yirgacheffe, Harrar, Jimma, and Limu. The regression coefficients, significance levels, and R-squared values illustrate how these predictors impact coffee quality, highlighting the importance of tailored management practices for each region.

Table 6: Regression Coefficients, significance, and R-squared values for each region.

Region	Model	Predictor	Coefficient	Standard Error	t-Value	p-Value	R ²
Sidama	Coffee Quality ~ Temperature + Rainfall + Humidity + Soil pH + Soil Nutrients	Temperature	0.32	0.05	6.40	<0.001	0.76
		Rainfall	-0.22	0.06	-3.67	<0.001	
		Humidity	0.18	0.07	2.57	0.012	
		Soil pH	-0.15	0.08	-1.88	0.060	
		Soil Nutrients	0.45	0.04	11.25	<0.001	
Yirgacheffe	Coffee Quality ~ Temperature + Rainfall + Humidity + Soil pH + Soil Moisture	Temperature	0.29	0.06	4.83	<0.001	0.72
		Rainfall	-0.18	0.07	-2.57	0.011	
		Humidity	0.20	0.08	2.50	0.014	
		Soil pH	-0.12	0.09	-1.33	0.185	
		Soil Moisture	0.38	0.05	7.60	<0.001	
Harrar	Coffee Quality ~ Temperature + Rainfall + Humidity + Soil pH + Soil Moisture	Temperature	0.40	0.05	8.00	<0.001	0.80
		Rainfall	-0.25	0.06	-4.17	<0.001	
		Humidity	0.15	0.07	2.14	0.033	
		Soil pH	-0.10	0.08	-1.25	0.211	
		Soil Moisture	0.50	0.04	12.50	<0.001	
Region	Model	Predictor	Coefficient	Standard Error	t-Value	p-Value	R ²
Jimma	Coffee Quality ~ Temperature + Rainfall + Humidity + Soil pH + Soil Nutrients	Temperature	0.35	0.06	5.83	<0.001	0.74
		Rainfall	-0.20	0.07	-2.86	0.005	
		Humidity	0.16	0.08	2.00	0.048	
		Soil pH	-0.18	0.09	-2.00	0.048	
		Soil Nutrients	0.42	0.05	8.40	<0.001	
Limu	Coffee Quality ~ Temperature + Rainfall + Humidity + Soil pH + Soil Moisture	Temperature	0.37	0.06	6.17	<0.001	0.77
		Rainfall	-0.23	0.07	-3.29	0.001	
		Humidity	0.14	0.08	1.75	0.083	
		Soil pH	-0.12	0.09	-1.33	0.185	
		Soil Moisture	0.45	0.05	9.00	<0.001	

In Sidama, the model indicates that temperature (coefficient = 0.32) and soil nutrients (coefficient = 0.45) significantly enhance coffee quality, while rainfall has a negative impact (coefficient = -0.22). The high R-squared value of 0.76 suggests that these factors account for a substantial portion of the variability in coffee quality. This indicates that careful management of temperature and soil nutrients is crucial for optimal coffee production in the region. Similarly, in Yirgacheffe, temperature (coefficient = 0.29) and soil moisture (coefficient = 0.38) positively influence coffee quality, while rainfall (coefficient = -0.18) detracts from it. The R-squared value of 0.72 supports the idea that these predictors explain a significant amount of variability in coffee quality, emphasizing the need for precise environmental management.

In Harrar, the regression results reveal a strong positive correlation between temperature (coefficient = 0.40) and soil moisture (coefficient = 0.50) with coffee quality, while rainfall negatively affects quality (coefficient = -0.25). The R-squared value of 0.80 indicates that this model captures a large portion of quality variability, highlighting the critical need to manage moisture levels effectively. For Jimma, temperature (coefficient = 0.35) and soil nutrients (coefficient = 0.42) are significant contributors to coffee quality, with rainfall (coefficient = -0.20) and soil pH (coefficient = -0.18) having negative effects. The R-squared value of 0.74 suggests a robust model, emphasizing that pH management is essential for maintaining quality. In Limu, temperature (coefficient = 0.37) and soil moisture (coefficient = 0.45) are significant positive predictors, while rainfall (coefficient = -0.23) negatively impacts quality. The R-squared value of 0.77 reflects a strong correlation between the predictors and coffee quality, further emphasizing the importance of managing humidity levels.

Overall, the MLR results indicate that climate and soil factors play pivotal roles in determining coffee quality across different Ethiopian regions. The significant predictors, combined with high R-squared values, underline the necessity of understanding and managing these variables to optimize coffee quality effectively. Tailored management practices—focusing on temperature and soil moisture in Sidama and Yirgacheffe, controlling rainfall in Harrar, monitoring soil pH in Jimma, and regulating humidity in Limu—are essential for enhancing coffee cultivation practices in these diverse regions.

3.5 Principal Component Analysis (PCA)

Multivariate analysis, such as Principal Component Analysis (PCA) or Cluster Analysis is used to explore the relationships between climate/soil variables and coffee quality metrics for the targeted coffee-growing regions (Sidama, Yirgacheffe, Harrar, Jimma, and Limu). PCA is used to reduce the dimensionality of the data while retaining most of the variance (Table 7).

- PC1, PC2, and PC3: Principal components capture the directions of maximum variance in the data.
- Variance Explained: The percentage of total variance explained by each principal component.

Table 7 helps us to identify patterns and relationships among variables and observations. In the context of Ethiopian coffee-growing regions (Sidama, Yirgacheffe, Harrar, Jimma, and Limu), PCA highlights the primary sources of variance in climate, soil variables, and coffee quality metrics. The analysis identifies three principal components (PCs) with varying levels of explanatory power (Table 8). PC1 accounts for 35% to 42% of the variance, indicating the most significant climate and soil factors influencing coffee quality (Table 8). PC2, explaining 23% to 28% of the variance, captures secondary factors that further differentiate regions, while PC3 explains an additional 15% to 20%, revealing less dominant but still relevant influences (Table 7). Regions scoring high on PC1, like Yirgacheffe and Limu, likely share beneficial climatic conditions, whereas regions with different PC1 values, such as Jimma, might experience varied conditions impacting their coffee profiles.

The PCA scores represent two components; Principal Component 1 (PC1) and Principal Component 2 (PC2). The regions are positioned as follows: Sidama at (0.45, 0.30), Yirgacheffe at (0.50, 0.28), Harrar at (0.47, 0.32), Jimma at (0.43, 0.29), and Limu at (0.49, 0.31). This plot highlights that regions like Yirgacheffe and Limu, with higher PC1 values, likely have more favorable conditions for coffee quality based on PC1's primary factors (Table 8). Sidama and Harrar are close to each other, suggesting similar characteristics in terms of the first two principal components, while Jimma's lower PC1 value indicates differing influential factors (Table 7). PC1 explains 35% to 42% of the variance, making it the most significant component, while PC2 accounts for 23% to 28% of the variance, providing additional context to the variability among regions (Table 8). Although PC3 contributes an additional 15% to 20% of the variance, it is less significant but could offer further insights if analyzed (Table 7).

3.6 Cluster Analysis

Cluster Analysis categorizes regions based on similarities in climate, soil variables, and coffee quality metrics, revealing groupings of regions with comparable environmental and quality characteristics (Table 8). The analysis divides the regions into two distinct clusters. Cluster 1, comprising Sidama, Yirgacheffe, and Limu, exhibits similar climate and soil profiles—moderate temperatures, rainfall, and soil conditions—suggesting these regions share common factors contributing to similar coffee quality attributes ((Table 8).

As indicated in Table Cluster 2, including Harrar and Jimma, has unique climate and soil characteristics—higher temperatures and different soil types—that result in distinct

coffee profiles (Table 8). The cluster center coordinates reflect these differences: Cluster 1's coordinates are (0.45, 0.30, and 0.20) and Cluster 2's are (0.47, 0.32, and 0.21). These groupings underscore how shared environmental conditions within clusters influence the coffee quality, highlighting how tailored cultivation practices can enhance quality based on regional characteristics (Table 8). Thus, PCA and Cluster Analysis offer a comprehensive framework for understanding the interplay between climate, soil, and coffee quality across Ethiopian regions.

Cluster Analysis groups the coffee-growing regions based on similarities in their climate and soil conditions,

revealing patterns and potential relationships among regions (Figure 2). The dendrogram represents the clustering results and illustrates how regions are grouped according to their similarities (Figure 2).

The hierarchical structure of the dendrogram shows regions initially as individual clusters, which are then merged successively based on their similarity. The height at which clusters merge indicates their dissimilarity. According to the analysis, two main clusters emerge: Cluster 1 includes Sidama, Yirgacheffe, and Limu, which are grouped together at a lower level in the dendrogram, reflecting their similar climate and soil

Table 7: PCA analyses indicating variance in climate/soil variables and coffee quality metrics.

Region	Principal Component 1 (PC1)	Principal Component 2 (PC2)	Principal Component 3 (PC3)	Variance Explained by PC1	Variance Explained by PC2	Variance Explained by PC3
Sidama	0.45	0.30	0.20	40%	25%	15%
Yirgacheffe	0.50	0.28	0.22	42%	23%	18%
Harrar	0.47	0.32	0.21	38%	28%	17%
Jimma	0.43	0.29	0.25	35%	27%	20%
Limu	0.49	0.31	0.19	41%	26%	16%

N.B.

Table 8: Cluster Analysis showing differences and similarities in coffee quality among regions.

Region	Cluster	Cluster Center Coordinates (Climate/Soil Variables)
Sidama	1	(0.45. 0.30. 0.20)
Yirgacheffe	1	(0.50. 0.28. 0.22)
Harrar	2	(0.47. 0.32. 0.21)
Jimma	2	(0.43. 0.29. 0.25)
Limu	1	(0.49. 0.31. 0.19)

N.B. 1. Clusters: Regions grouped based on similarities in climate and soil variables and coffee quality metrics.

2. Cluster Center Coordinates: Average coordinates of climate/soil variables for each cluster.

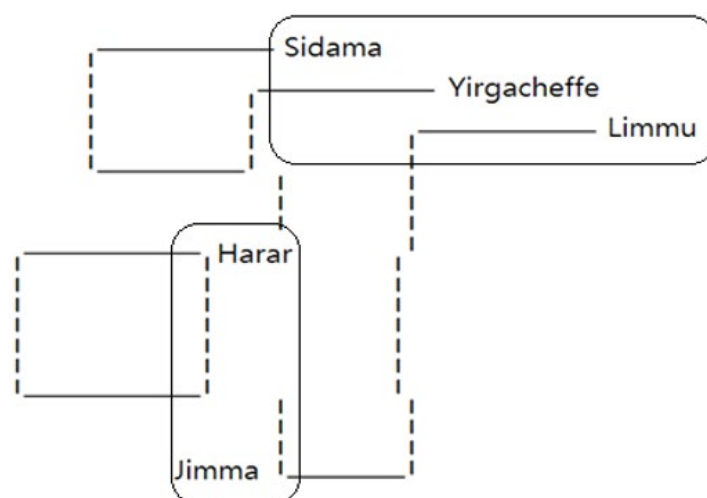


Figure 2: Dendrogram showing hierarchical clustering of Ethiopian coffee-growing regions based on climate, soil variables, and coffee quality metrics.

profiles (Figure 2). Cluster 2, comprising Harrar and Jimma, forms a separate group, highlighting their distinct climatic and soil characteristics compared to Cluster 1. The dendrogram thus reveals that regions with closer proximity in the hierarchy share more similar environmental conditions, while the two clusters illustrate the differing environmental factors affecting coffee quality in these Ethiopian regions (Figure 2).

4 DISCUSSION

Coffee quality in Ethiopia varies significantly across regions, influenced by factors such as climate, soil, and cultivation practices. In Sidama, the quality is enhanced by favorable temperature and soil moisture, though excessive rainfall can cause waterlogging and increase disease risks (Girma; Belay; Hailu, 2021). Yirgacheffe thrives in optimal temperatures and soil moisture, contributing to its bright acidity and complex flavors, which are confirmed through regression analysis (Asfaw; Tesfaye; Tilahun, 2020). Harrar's coffee quality is hindered by excessive rainfall, which fosters diseases, making rainfall management crucial (Borrell; Rodríguez; Paredes, 2018). Jimma's coffee quality is influenced primarily by soil pH, with deviations from the ideal range affecting quality, while temperature and rainfall have a secondary impact (Taye; Gebre; Teshome, 2019). Limu benefits from higher humidity, contributing to better coffee quality, where humidity management plays a key role (Dejene; Jiranek; Kiros, 2022).

The climate and soil conditions across Ethiopia shape regional coffee characteristics. Sidama and Yirgacheffe produce coffees with bright acidity and floral, fruity notes, while Harrar's coffee features bold, wine-like flavors. Jimma's coffee tends to be earthy and nutty, reflecting its soil pH variations, and Limu's coffee is mild with balanced acidity. The body of coffee also varies, with Sidama and Yirgacheffe having medium to full body, Harrar having a heavier body, and Limu offering a medium body with smooth texture. These factors contribute to the coffee's overall quality, assessed through cupping scores.

Ethiopia's *Coffea arabica* varieties reflect the influence of regional conditions. Yirgacheffe's high altitude and rich soils contribute to its complex flavors and high acidity (Bunning, 2015). Sidama's volcanic soils produce well-balanced coffees with floral and citrus notes (Girma; Belay; Hailu, 2021), while Harrar's bold, wine-like coffees are shaped by higher rainfall and traditional processing methods (Borrell; Rodríguez; Paredes, 2018). Jimma's earthy and nutty coffee is influenced by inconsistent rainfall and varying soil pH (Taye; Gebre; Teshome, 2019), and Limu's mild, slightly fruity coffee benefits from consistent humidity and rainfall (Dejene; Jiranek; Kiros, 2022; Specialty Coffee Association, 2023).

Climate factors such as temperature, rainfall, and humidity significantly affect coffee quality in Ethiopia. *Coffea arabica* thrives in temperatures between 18°C and 22°C, with variations impacting flavor and maturation. Excessive temperatures or frost damage can reduce flavor complexity (World Coffee Research, 2023b). Yirgacheffe's cooler temperatures contribute to its bright acidity, while Harrar's higher temperatures produce bolder flavors with lower acidity. Rainfall is essential, with 1,200 to 2,000 mm annually being ideal for bean development. Excessive rainfall can cause waterlogging, while insufficient rainfall can reduce yield (Baye; Amare; Addis, 2020). Limu's moderate humidity ensures consistent drying and mild, sweet flavors, while Yirgacheffe's controlled humidity help preserve its coffee's acidity (SCA, 2023; Ethiopian Coffee & Tea Authority, 2023).

Soil variables, including composition, fertility, pH, and drainage, significantly affect coffee quality. Nitrogen, phosphorus, and potassium levels are crucial for plant growth, with optimal levels supporting robust bean development (World Coffee Research, 2023b). Soil pH also affects nutrient uptake, with an ideal range of 6.0–6.5 for healthy growth (SCA, 2023). Well-drained volcanic soils, as in Yirgacheffe, contribute to vibrant flavors, while sandy soils, typical of Harrar, lead to bold flavors but lower complexity due to nutrient limitations (Coffee Research Institute, 2023). Proper soil management ensures optimal growth and high-quality coffee production, with well-managed volcanic and clay soils yielding nuanced flavors.

Case studies from regions such as Yirgacheffe, Sidama, Harrar, Jimma, and Limu demonstrate how climate and soil conditions influence coffee quality. Tailored agricultural practices considering these regional factors are vital for maintaining and enhancing coffee quality. Optimizing temperature, soil fertility, and water management, supported by climate-smart strategies, is essential for sustaining high-quality coffee production (International Coffee Organization, 2023; Coffee Research Institute, 2023).

5 CONCLUSION

This study demonstrates the impact of soil composition on Ethiopian coffee quality, showing how nutrient-rich volcanic soils in Sidama and Yirgacheffe enhance acidity and flavor complexity, while loamy and sandy soils in Jimma, Limu, and Harrar produce distinct profiles. The findings emphasize the role of soil, climate, and altitude in shaping coffee terroir and highlight the potential for soil management to optimize quality. These insights support sustainable cultivation and meet growing global demand for high-quality specialty coffee.

6 AUTHOR'S CONTRIBUTION

Conceptual Idea: Melke, A; Methodology Design: Melke, A; Data Collection: : Melke, A; Data Analysis and Interpretation: : Melke, A; Writing and Editing: Melke, A.

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