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Beyond genetics × environment interaction on quality drivers of *Arabica* coffee: a review of implication for Gedeo indigenous agroforestry systems under changing climates

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Abstract

Quality coffee offers a wonderful taste and flavor for its consumers. However, the drivers of quality coffee were not documented fully for scaling up and further use of the practices in the study area. Hence, the present study was developed for reviewing the main factors responsible for the quality and productivity of coffee and identifying the research gaps. Preferred reporting items for systematic reviews and meta-analyses called PRISMA technique was used by critically reviewing six articles on genetics, 50 articles on environmental factors, 35 articles on management conditions, and 23 articles on socioeconomics. Results showed that people believed in a particular climate and environment as important markers of the quality of coffee; nevertheless, this research showed that established coffee management also had a crucial impact. It was also found that native agroforestry systems were necessary for high-quality coffee due to well-established relationships between shade trees, coffee plants, and farmer management as these practices alter the microclimate including the soil carbon, moisture, and nutrition regimes, allowing it to adapt to changes in evapotranspiration patterns. More significantly, coffee quality is determined by the socioeconomic factors affecting livelihoods, such as the adoption of new technologies, credit availability, farm size, additional inputs, market knowledge, physical infrastructure, extension services, literacy rate, frequency of extension visits, proximity to research centers, and producer incentives. To maintain the high standards of quality coffee production, there is a need to maintain a particular edaphic and climatic interaction, and established management systems for a particular cultivar. More importantly, infrastructural, social, and economic environments of coffee producers should be enhanced to ensure quality production.

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Introduction

Coffee is the second most traded commodity in the world market after oil, accounting for an estimated export worth in 2021 of 36.3 billion USD[1,2]. It is the main source of foreign currency earnings for over 80 tropical countries, including Ethiopia[3]. The coffee industry provides job opportunities and livelihoods for over 100 million people and 25 million farmers worldwide[3]. Triolo et al.[4] also argued that coffee is more than just a beverage, indicating its extraordinarily rich history and shift in cultural identity over time. The majority of Ethiopian coffee (> 90%) is produced by smallholder farmers in semi-forest and garden systems in the major coffee-growing regions in less than 2 ha of land involving over 4.5 million small-scale farmers[3,5,6]. Furthermore, the crops account for 4%−5% of GDP and approximately 15 million people directly or indirectly rely on income from the sector for their livelihood[7,8]. Ethiopia ranked first in Africa and fifth in the world as a producer and exporter of coffee following Brazil, Vietnam, Columbia, and Indonesia[9]. In Ethiopia, only Arabica coffee (*Coffea arabica* L.) is produced, and the country is the third-largest Arabica coffee producer in the world, next to Brazil and Colombia[10]. Ethiopia contributes 40% of Africa and 4% of the global market share[11]. The production and cultivation of coffee in the country has increased over the past 60 years, with some short-term declines over the years due to the lack of sustainability and poor competitiveness of the sub-sector in the national and international markets[12], but the changes in its productivity and quality are minor[13]. Moreover, relying on increasing coffee production and productivity may result in national and international market failures; therefore, it is vital to focus on high-quality coffee production.

In Ethiopia, coffee grows at various altitudes ranging from 550 to 2,750 m above sea level (a.s.l.). However, *Arabica* thrives best between altitudes of 1,300 and 1,800 m a.s.l., optimum minimum and maximum air temperatures of 15 and 25 °C and annual rainfall ranging from 1,500 to 2,500 mm, respectively[14]. Arabica coffee contributes around 70% of the world coffee production and 90% of the traded value globally, has a higher quality with lower caffeine and produces a more aromatic brew when compared to other coffee varieties[15]. Similarly, coffee crop production can be performed on many different soil types, but the ideal soil conditions for cultivating coffee are believed to be fertile and well-draining. These soils are deep and well-rained with a pH of 5–6, and have medium to high contents of most of the essential elements, except nitrogen and phosphorus. In addition, most coffee plantations are often managed with shade trees on a small scale, with minimal fertilization. Litter fall and decomposition play an important role in nitrogen cycling and the maintenance of soil fertility[16].

In Ethiopia, Oromiya, Sidama, Southern and South Western regions are the major coffee-growing areas. The southwest highlands of Ethiopia are considered to be the centers of origin and diversity of coffee[17]. All listed regions are well known for their respective coffee quality brands, such as Harar/Mocca, Sidamo, and Yirgachefe[18,19] respectively. These coffees are recognized in the trade circuits of the world coffee market as having unique qualities[20]. Thus, Ethiopia is a key player in the global coffee industry and the country's coffee market is distinct based on biophysical and socioeconomic factors[21]. The importance of coffee in Ethiopia is clear because it is one of the most valuable primary products in country trade[9]. In addition, quality is critically important in coffee production in the coffee industry, where it includes aroma, flavor, acidity, and physical characteristics, such as length, width, weight, shape, and color of coffee beans[22,23].

Past studies on Ethiopian coffee productivity and quality have confirmed that the changes in productivity and quality have been negligible in the past 60 years and vary with growing locality[24]. Moreover, about 95% of the country's coffee production is carried out using diverse coffee varieties following organic farming practices as cultivations were done traditionally without the use of pesticides and fertilizers[25]. Coffees from the eastern (Harar) and southern regions are better in overall quality, and coffee from the northwestern region is higher in chlorogenic acid and sucrose content, whereas those from the Harar and Southwestern regions are lower in caffeine and chlorogenic acid content, respectively. Moreover, Harar coffee has higher fatty acid content than coffees from the other regions[25]. However, coffee production and quality have been challenged in many parts of Ethiopia due to changes in biophysical (climatic, topographic, and edaphic) and socioeconomic factors[26,27]. Thus, despite the variety of local coffee types and long history of its production, maintaining high standards of quality coffee requires a great deal of work and commitment from all the actors. To this end, each step starting from selecting the coffee variety for coffee planting until the final coffee drink preparation determines the cupping quality. Moreover, the environmental factors, including altitude, daily temperature fluctuations, the amount and distribution of rainfall and the physical and chemical properties of the soil affect quality directly because it affects the growing plant, the bean size and quality[28,29].

In the Gedeo zone, coffee is produced in all districts but considerably high in the districts of Dilla Zuria, Wonago, Yirgachefe, Kochere, and Gedeb, where it serves as a major means of income for the livelihood of coffee farming families. For instance, Yirgachefe brand coffee obtains premium prices in Ethiopia as well as in the world market and contributes about 19% of the country's export revenue and direct or indirect income sources for over 500,000 smallholders'[9,30–34]. However, only a few farmers from Yirgachefe, Gedeb, and Kochore were recognized as specialty coffee producers among the 142 farmers who participated in the cup of excellence competition[35]. Although most farmers of Gedeo produce coffee of inherent quality, limited access to wet processing plants, lack of roads, extension and financial support are known to affect coffee quality. To understand the underlying cause–effect relationships and enhance the coffee quality, producers, and other actors along the value chain require management information necessary to address the poor quality, which this paper attempts to explore. This would help in the understanding of why quality coffee producers suffer from fluctuating international markets, and need support from the government to sustain their livelihoods. Moreover, the physiographic, climatic, edaphic, and socioeconomic bases of selection for quality have not been determined for use at the grass root level during decisions associated with microclimate management, variety selection, agronomy, plant nutrition; post-harvest handling or that directly determines the content of sucrose, caffeine, fatty acid, or storage practices protein in coffee beans. Hence, the objective of this review is to highlight the main factors responsible for the quality and productivity of coffee and identify the research gaps in coffee quality- and productivity-related traits for potential future research in the Gedeo zone of southern Ethiopia.

Materials and methods

This review was conducted based on PRISMA[36] techniques using secondary data sources. It was summarized and concluded by using sources such as the Web of Science, Scopus index, PubMed, Embase, Publons, the Science Direct database, and published articles using search engines of tandfonline.com, Crossref, MagPortal.com, library genesis, google scholar, JSTOR, and Research Gate. In total, 114 articles were identified that addressed the research questions including six articles on genetics, 50 articles on environmental factors, 35 articles on management conditions, and 23 articles on socioeconomics based on selection criteria of smallholder coffee quality, organic coffee, agroforestry, soil acidity and organic matter, evapotranspiration and humidity, socioeconomic factors of quality. The de-selection criteria were commercial coffee production, chemical fertilizers, insecticides, and pesticides that were not typical in the Gedeo coffee-based farming system, and practices that were disallowed in Gedeo organic coffee production. The manuscript was organized by starting with what quality means, elaborating on the factors determining quality, and identifying research and management gaps to maintain quality coffee under the Gedeo coffee-based agroforestry system.

Definition for coffee quality

According to the International Trade Center[20], the quality of a coffee parcel is determined by a mix of botanical variety, topographical circumstances, meteorological conditions, and the care provided during growing, harvesting, storage, export preparation, and transit. Coffee quality refers to price, taste, aroma, flavor, effect on health and alertness, geographical origin, and environmental and sociological aspects (organic coffee, fair trade, etc.) at the consumer level[37]. In Ethiopia, certification, geographical origin, traceability, processing methods, and quality grades are considered quality indicators[38]. The Ethiopian Commodity Exchange (ECX) evaluates and grades the quality of coffee in Ethiopia, assuming top grades (grades 1 and 2) as the best quality but includes four physical quality attributes of green beans (i.e., primary defects, secondary defects, odor, and color), four cup quality attributes (i.e., acidity, body, cup cleanness, and flavor), and total preliminary quality (the sum of physical and cup qualities)[39]. As summarized in Table 1, those that gate Grades 1 and 2 enter into specialty quality assessment that includes 10 cup quality attributes (i.e., aroma, body, acidity, flavor, cup cleanness, balance, sweetness, uniformity, aftertaste, and overall cup preference) to deliver the sum of the 10 cup quality attributes. In this way, all coffee that enters the ECX is given a grade and a geographical designation denoting the belief that coffee quality and biochemical composition vary with geographical origin. The ECX serves as a public-private partnership nexus that aims to reduce the information imbalance that puts coffee producers at a disadvantage. Coffee quality can be determined by cupping, physicochemical, and chromatographic methods. It is difficult to study coffee quality in terms of cup quality with the exclusion of conventional or advanced analytical techniques. This is mainly because cup quality characteristics are closely related to the sensory evaluation of cuppers (Table 1).

At the farmer level, coffee quality is a combination of the production level, while at the exporter or importer level, price and ease of culture are important. Coffee quality is linked to bean size, lack of defects and regularity of provision, tonnage available, physical characteristics, and price, whereas coffee quality depends on moisture content, stability of the characteristics, origin, price, biochemical compounds, and organoleptic quality[44]. Recently, the cup of excellence as a measure of drinking or liquor quality has been used as a quality indicator, with a reward for premium quality. Under the latter condition, cup quality (how good or bad the coffee smells and tastes are) is assessed by rigorous standard protocols. This approach is preferred if buyers want to track every aspect of coffee production, growth, processing, and distribution. However, cup quality assumes a suitable composition of biochemical constituents (caffeine, trigonelline, chlorogenic acids (CGAs), sucrose, and lipids) that influence commercially important sensory traits[15]. Coffee quality is a highly complex trait because of its variation with pedo-climatic conditions, post-harvest treatments, and genetics.

The complexity of finding green coffee of an appropriate and stable quality, as well as the complexity of the causes that persuade quality, means that, nowadays, knowledge of these factors need to be far greater than in the past. Moat et al.[41] also projected an overall negative influence on coffee due to climate change across Ethiopia for the present coffee growing landscape, but also anticipated a potential fourfold increase in the production area if climate-informed decisions were made for relocation and expansion to new sites and already adapted areas, respectively, to ensure sustainability and resilience for the Ethiopian coffee.

Factors affecting coffee quality

Genetics

There are genetic sources of variation in coffee quality, which calls for the predominant use of unimproved local coffee landraces in Ethiopia. The presence of extensive heterogeneity and sizeable potential for Arabica coffee landraces indicates that the country is a center of origin and diversification[45]. The cultivar or variety of coffee establishes the dimensions (size and shape) of the beans and the color, element concentration, and aroma of the product[46]. Coffee's genetic makeup was compared to four qualities (acidity, body, taste, and fragrance), all of which are suitable selection criteria for genetic enhancement of total liquor quality[47]. Moreover, acidity, body, and flavor have relatively high sensitivity and have been used to discriminate between different coffee genotypes[48]. One hundred normal Arabica beans weigh between 18−22 g, which shows that the size and shape of green beans are heritable traits peculiar to coffee varieties. Ethiopia is the primary center of origin and genetic diversity of *Coffea Arabica* L., and the existence of such genetic diversity provides an immense opportunity for coffee improvement[49].

Thus, genomic analysis of wild relatives of coffee (*Coffea* spp.) may be required to determine the phenotypic diversity required for effective association of genetic analysis[50]. There has been growing interest in the potential of wild coffee species in areas as an attempt to address the limitations

Table 1. Grading of coffee as evaluated by experienced cupper experts.

I. Physical (raw) quality attributes for washed coffee (40%)	
Shape (15%)	Very good = 15, good = 12, fairly good = 10, average = 8, mixed = 6, and small = 4.
Color (15%)	Bluish = 5, grayish = 4, greenish = 3, coated = 2, faded = 1, and white = 0.
Odor (10%)	Clean = 10, fair clean = 8, trace = 6, light = 4, moderate = 2, and strong = 0.
II. Physical (raw) quality attributes for unwashed coffee (40%)	
Shape (15%)	Very good = 15, good = 12, fairly good = 10, average = 8, mixed = 6, and small = 4.
Defect count (15%)	Very good = ≤ 5, good = 6−15, fairly good = 16−30, average = 31−45, fair = 46−60.
Odor (10%)	Clean = 10, fair clean = 8, trace = 6, light = 4, moderate = 2, and strong = 0.
III. Organoleptic cup quality attributes (60%)	
Aromatic intensity (5%)	0 = nil (unacceptable), 1 = very light, 2 = light, 3 = medium, 4 = strong, and 5 = very strong.
Aromatic quality (5%)	0 = nil (>>), 1 = bad, 2 = regular, 3 = good, 4 = very good, and 5 = excellent.
Acidity (10%)	0 = nil (>>), 2 = very light, 4 = light, 6 = medium, 8 = strong, and 10 = very strong.
Astringency (5%)	5 = nil (>>), 4 = very light, 3 = light, 2 = medium, 1 = strong, and 0 = very strong.
Body (1%)	0 = nil (>>), 2 = very light, 4 = light, 6 = medium, 8 = strong, and 10 = very strong.
Bitterness (5%)	5 = nil (>>), 4 = very light, 3 = light, 2 = medium, 1 = strong, and 0 = very strong.
Flavor (10%)	0 = nil (>>), 2 = bad, 4 = fire, 6 = average, 8 = good, and 10 = very good.
Overall standard (10%)	0 = nil (>>), 2 = bad, 4 = regular, 6 = good, 8 = very good, and 10 = excellent.

Adapted from literatures[40−43].

imposed by its genetics and breeding. Leroy et al.[44] also recommended the integration of coffee quality attributes as the main target in breeding programs to combat the challenges of overproduction and price fluctuations observed in some years. Genetic gains for quality can be achieved either by interspecific hybridization strategies or within-species strategies for breeding the main targets of improvement in quality, resistance to pathogens, and yield[44]. Coffee breeding endeavors should minimize adaptation problems and avoid blending effects of known location-specific quality with coffee from other area(s) by designing breeding work using local landraces or crossing from the respective location with the objective of developing yield-competitive improved varieties[51]. This site-specific breeding endeavor shall recognize that each locality is home to unique flavors of coffee within the country, which requires keeping coffees from different growing origins apart. The large amount of heterosis observed for desirable characteristics could be exploited by crossing distantly related varieties, as high genetic recombination is expected in progenies of genetically distant parents[49]. Vigorous development and selection of new coffee cultivars of superior quality are always required before public or private propagation and distribution of improved and disease- resistant varieties at the nearest gate[12], and their use in new areas, but should be given due consideration to the agroforestry system in which coffee *Arabica* thrives best and repeatedly shows a higher degree of pest control, climatic resistance, and pollination services[52]. Combating climate change impacts on coffee quality would be possible by generating adaptation options, such as the conservation of coffee genetic resources, developing drought and disease-resistant varieties, and using coffee varieties with better adaptation to a range of adverse growth conditions[12].

Environment or ecological factors

As a non-genetic source of variation, the environment has a strong effect on coffee quality[28]. Next, climatic variables are discussed which are considered to be associated with quality.

Sunshine

Floral initiation is sunlight-dependent in *Coffea arabica*. Fewer flowers develop under lower solar radiance, resulting in lower fruit productivity. Enhanced irradiance enables more bean fillings owing to longer assimilation into fewer beans[53]. However, there is a prediction for decreased sensory attributes of coffee under increased light exposure owing to the changing climate[54]. Coffee grown in full sun did not take full advantage of high solar radiation, as coffee grown in a dense shade as overdose or suboptimal radiation has a negative effect on both acidity and the body[55].

Temperature

The optimal mean annual temperature range for *Arabica* coffee is 18 to 22 °C, which permits cultivation at lower altitudes[56]. Temperatures above or below this optimum level predispose coffee beans to incomplete maturation and poor quality. Temperatures beyond these may prevent blossoming and accelerated ripening, affecting flavor profiles, whereas heat waves and frosts can cause significant declines in yield and quality declines[57]. Accelerated maturation in hot and humid environments has a negative effect on the flavor and structure of fruits. Daily temperature variations are important factors that affect coffee quality[14]. It affects coffee ripening and flowering by affecting bean growth. The ripening process of coffee berries takes longer at higher elevations or under shade due to low air temperatures, allowing for more time for complete bean filling. As a result, the delayed maturation process plays an important role in defining good cup quality as it ensures the complete expression of all biochemicals. As a result, the delayed maturation process plays an important role in defining good cup quality, as it ensures the complete expression of all biochemical stages necessary for beverage development. Coffee does not tolerate a wide range of mean temperatures[28]. If the average annual temperature is below 18 °C, coffee growth is depressed[58−60], exposure above 23 °C can cause the coffee plants to ripen, which negatively affects the taste and quality[56] and its exposure above 30 °C leads to stress, which depresses growth and causes abnormalities, such as the yellowing of leaves and growth of tumors on the stem[61]. Yield and quality may be negatively influenced by years of high temperatures.

Rainfall

Rainfall is the second most limiting factor, followed by temperature, during the cherry development period[62,63]. *Arabica* coffee requires an optimum total rainfall range of 1,500−1,800 mm over a growing period of 8 to 9 months[62]. Lack of rainfall during the cherry development period resulted in smaller bean sizes, i.e. lower quantity and quality of produce[14]. Coffees cannot tolerate water logging or extended drought conditions. Rainfall requirements of coffee plants depend on factors such as the retention properties of the soil, atmospheric humidity, cloud cover, and cultivation practices[59,60]. A short dry spell, lasting 2−4 months, corresponding to the quiescent growth phase, is important for stimulating flowering in Arabica coffee[60]. In these 2−4 drier months, when growth slows, young wood hardens, and flower buds develop[64]. Intense rainfall throughout the year (without dry seasons) is often responsible for scattered harvests and low yields[63].

Relative humidity

The relative humidity of the air influences the growth of coffee trees and the development of pests.

Relative humidity is an extrinsic factor that affects coffee quality in the harvesting method[65,66]. To maintain the inherent quality of coffee beans, they should be stored in bags made of natural fiber, for example, sisal and hydrocarbon-free jute material, and optimum relative humidity[67]. If the relative humidity exceeds the optimum level, it can provoke the growth of mold, which drastically affects the taste and quality of the coffee cup. In high relative humidity and warm atmospheres, coffee beans absorb moisture and develop molds. Storage temperatures of approximately 20 °C, and relative humidity of 50%−60% are recommended. Optimum drying is an important step in high-quality coffee production, as moisture levels higher than 12% can promote microbial growth and mycotoxin formation[68,69].

Hail and frost

Climate change is associated with temperamental weather changes, which put production at risk.

Among such factors, unseasonable frost affects coffee-producing countries worldwide. Although its occurrence is sporadic, it may strongly compromise the economic viability of coffee crops. Its impact includes the destruction of leaves and fruits in *Arabica* coffee in the year of occurrence[70], the effect in the following year[70] and finally, it can completely kill the coffee tree[59]. Brazil is the first coffee-producing country in the world and has been challenged by the occurrence of frost. For example, according to the reports of Reuters on 6th August 2021, the South American country had faced the 'most devastating frost' since 1994[71]. This has led to the cost of beans rising to a multi-year high (that includes specialty coffee), and in the 2021/22 crop year, 70% of Brazil's coffee has already been harvested for the 2021/22 crop year, and frost damage is deemed to be so severe that farmers have had to replant trees. This means that production will be unable to resume for up to three years.

Hail and frost can damage plants and cherries and affect the final quality of green coffee. In Ethiopia, unseasonable frost caused by climate change affects the physiological growth and fruit quality of coffee. In 2016, the occurrence of frost in different parts of Ethiopia affected the coffee quality and productivity[72,32]. This coincides with the study by Wolde[32] in the Gedeo zone, which reported that 75% of coffee producers lost coffee yield due to frost and rainfall variability in 2016. Similarly, Tadesse et al.[6] showed that normal frost, hail, temperature, rainfall, and humidity caused a reduction in coffee yield and quality in major coffee growing districts in Southern Ethiopia.

Topography

Coffee can be grown from 500 to 2,400 m a.s.l. across different regions as long as appropriate sunshine and temperature prevail. Higher altitudes reduce heat-induced stress in plants, increase the leaf-to-fruit ratio and net photosynthetic rate, and prolong the berry maturation period[73]. Higher altitudes also increased the acidity of *Arabica* coffee, mainly because of lower temperatures and intense UV radiation (Table 2). As there is less oxygen, coffee plants grown at higher altitudes take longer to mature than those grown at lower altitudes, with comparatively higher altitudes favoring the production of beans of large size and heavy weight[74]. With increasing altitude, there was an increase in caffeine, trigonelline, chlorogenic acids, lipids, and seed weight but a decrease in sucrose content (Table 2). Under conditions of increased altitude, improved sensory attributes of coffee were reported[54]. Thus, elevation considerably affects coffee quality through changes in temperature, availability of light, and water during flowering, bean expansion, and the ripping period[14,28,29]. With warmer climatic conditions at lower altitudes, more rapid maturation of coffee beans occurs, resulting in more immature beans. The effects of shifts in carbon dioxide, water stress, and temperature on the response of coffee quality and how this varies with location, elevation, and management conditions in response to changing climate have been identified as key areas of research[54].

Orchard management

This section describes the influence of management (M) on environment (E) and genetics (G). Many scholars agree that there is a close link between coffee quality and the environment, as coffee grown in places other than its preferred environment does not always have a good flavor[15,46]. According to Cheng et al.[15], coffee quality is the result of the genes governing coffee flavor during bean development and the resulting metabolites (caffeine, trigonelline, chlorogenic acids (CGAs), sucrose, and lipids) developed in the fruit, which are explained by both G and E interactions. Gebreselassie et al.[51] recommended the incorporation of genetic and environmental factors based on findings on genotype and environmental interactions in *Arabica* coffee. Thus, there is a third factor specific to the social and economic setting of each locality, referring to management. Furthermore, a variety known for premium quality in one location might not deliver similar quality in another location, which calls for an understanding of the location-specific day-to-day operations of farmers. Thus, a specialty of coffee boils down to the growing region, season, management, and coffee variety. The association of a genotype with special environmental conditions can produce outstanding coffee, but varieties planted under other environmental conditions do not produce the same quality of coffee. The shape and structure of the beans were the result of genotype, environmental, and management factors. The main factors that influence the quality of green coffee are the genotype, environment, field management, preparation, and storage, which the farmer must understand and assess the quality of prior sales through sensory and organoleptic assessment from representative samples[46,75]. Very small changes in the coffee growing climate within each year's growing season (e.g., low rainfall) can influence yield and cup quality. Unfortunately, the relationship between management, genotype, and environment has not been thoroughly investigated to date. Jabbour[76] argued that shade and more diverse coffee systems provide a higher degree of pest control, climatic resistance, and pollination services. This implies that farmers' indigenous knowledge is at the heart of the optimization of management decisions, services, and goods produced and delivered from agro-ecosystems.

Soil nutrient availability

The chemical and physical characteristics of soil are important factors that enhance soil fertility and coffee quality[14]. Coffee requires macro- and micronutrients for healthy production and better quality because coffee beans are considered to have a certain nutritional and dietary value for consumers[77]. Fertile soils usually produce larger beans with better flavors. Thus, the presence and availability of organic fertilizers used by smallholder farmers is important. In Ethiopia, the application of chemical fertilizers for coffee production is almost nonexistent.

Table 2. Shade and altitude affect biochemical compounds related to bean quality.

No.	Compounds	Flavor attributes	Content	Shade	Altitude
1	Caffeine (%)	Strength, body and bitterness	0.6 to 1.8	Increases	Increases
2	Trigonelline (%)	Aromatic perception, bitterness	0.80 to1.82	Decreases	Increases
3	Chlorogenic acids (%)	Acidity, astringency and bitterness	4.0 to 8.4	Decreases	Increases
4	Sucrose content (%)	Flavour precursor	7.4 to11.1	Decreases	Decreases
5	Lipids (%)	Flavour carriers, texture and mouth feel	15	Increases	Increases

Source: Adapted from Cheng et al.[15].

Alternatively, organic fertilizers, such as manure, cover crops, and coffee husks, are used. Taye et al.[62] stated that the use of decomposed coffee husk at a rate of 10 ton ha^{-1} (4 kg $tree^{-1}$ on a dry weight basis) was found to be superior in terms of yield performance of coffee trees. A significant improvement in the growth and yield of mature coffees have been reported in response to coffee pulp and husk compost application. The survey result by Wolde[32] in the Gedeo zone indicated that compost application for the production of coffee is a necessary condition for preparing premium coffee quality. However, excessive use of nitrogenous residues or manure can increase production but reduce bean density and quality, thereby increasing the caffeine content and resulting in a bitter taste of the brew. If the calcium and potassium contents of the beans exceed 0.11% and 1.75%, respectively, cup quality is affected negatively. The bitter and hard taste of coffee might arise from the high concentrations of calcium and potassium in beans. A deficiency of iron and magnesium adversely affects coffee quality, providing amber or soft beans with reduced quality[46]. The same author reported that a lack of zinc would lead to the production of small light gray beans, which would produce poor liquor[46]. Conversely, the application of high doses of elephant grass residue or livestock manure results in an increased percentage of undesirable brown-colored beans, and thus, poor roasting characteristics, as it is associated with a deficiency of basic cations[46].

Soil moisture availability

Periods of moisture stress can limit flowering but can be advantageous for the drying and harvesting of fruits in Arabica coffee[78,79]. During the dry periods, the physiological activity of coffee decreases as water shortage during the critical period (weeks 6 to 16 after fecundation) may cause huge losses because of the formation of empty beans Furthermore; the remaining beans were smaller because of die-backs. This phenomenon reduces the market value of beans[79,80].

Shade trees

In the past *Cordia africana*, *Mimosa scabrella, Leucaena leucocephala*, and *Hevea brasiliensis* have been used as shade trees in coffee fields[81]. About 40%–50% shade has been reported to have positive effects on coffee productivity and quality by optimizing temperature, light, and water availability during flowering, bean expansion, and ripping period of coffee plants[14,28,29,81,82] through its effect on soil moisture[83]. The resulting morphological modifications and physiological adaptations and their leaves are capable of absorbing more than 90% of the energy is contained in wavelengths between 400 and 700 nm[84]. Shade trees also reduce erosion, increase plant nutrition, and improve food security and fuel wood use. Shade trees protect crops from strong winds, high temperatures and extended dry periods[85]. However, higher or lower than 40%-50% shade affects productivity and quality adversely. According to Jaramillo et al.[86], denier shades cause a reduction in temperature by up to 4 °C which ultimately delays coffee maturation and prolongs the duration of grain filling. The same author reported a 34% decrease in coffee bacterial blight than expected owing to the use of shade trees. Negasso et al.[87] stated that adverse environmental stresses, such as high irradiance, high soil temperatures, and low relative humidity, can be improved by the implementation of shade trees under coffee plants. Cheng et al.[15] reported increasing positive quality attributes (appearance and preference) together with decreasing negative attributes (bitterness and astringency) in shade-grown coffee owing to the extended duration of maturation (Table 2). Shades also play an essential role in contributing to soil organic matter, which is one of the causes of the sustainable production and supply of the finest quality organic coffee[6]. In addition to the beneficial effect of a longer duration of the bean-filling period, a larger leaf area-to-fruit ratio (better bean-filling capacity) may also be linked to superior cup quality. Hence, there is a need to scale up best shading practices across farming communities.

If shade is higher than 40% or altitude is higher, there will be a decrease in ambient temperature, which reduces heat-induced stress in plants, increases the leaf-to-fruit ratio and net photosynthetic rate, and prolongs the berry maturation period[73]. However, the increased demand for fuel wood and the extraction of timber and non-timber forest products have become contemporary challenges posed by shade trees of coffee[12].

Pruning as pre-harvesting factors

In coffee production, actions taken on coffee plants before harvest plays an essential role in coffee bean quality. During this phase, pruning, rejuvenation, and the prevalence of insects and pests affect the coffee quality. Pruning is an essential management practice and has its role in coffee quality. According to Belay et al.[14], the goal of pruning is to create well-structured, healthy trees that provide good cherry yields over a long period or to rejuvenate old trees by stumping. This practice also avoids unnecessary competition for nutrients by removing unproductive wood, removing weak branches that will not yield, avoiding high humidity and fungus development through better air circulation, creating better access to the core of the trees when spraying pesticides, and decreasing the risk of damage to the coffee tree canopy during periods of heavy rain and/or wind[88]. In addition, a study conducted by Birhan et al.[89] reported that pruning is one of the practices that has a significant effect on the quality of coffee in Gomma Woreda of the Jimma zone. Studies on tree physiology, plant age, and picking period all interact to produce the final characteristics of the product. Indeed, it was found that tree age, location of the fruits within the tree, and the fruit-to-leaf ratio had a strong influence on the chemical content of green beans, showing that medium-aged trees (15 to 20 years old) bear beans with good flavor, acidity, and body. With similar findings, scholars such as Tadesse et al.[6], Teshome et al.[67], and Wolde[32] showed that there was a challenge for the farmer to completely prune aged coffee and obtain quality coffee from their farm in the Gedeo zone. This may be due to the lack of input required for pruning and the time gap required to attain yield.

Intercropping, weeding, and cultivation

Coffee flowers attract honeybees, which stimulate the production of coffee berries through pollination. Moreover, pollination can boost crop yields and harvest quality even in self-fertile *Arabica* coffee by improving the regularity and synchrony of fruit sets, thereby reducing the cost of harvesting and sorting. In addition, coffee-colored light with an attractive flavor has been reported in bees fed coffee sucrose nectar[90,91]. Such crops include Korerima (*Aframomum corrorima*), black pepper (*Piper nigrum*), ginger (*Zingiber officinale*), turmeric (*Curcuma longa*), and cardamom (*Elettaria cardamomum*). In some localities, indigenous coffee-based farming systems cultivate multiple spice crops beneath the canopy of story coffee[92]. Weeds can be suppressed through appropriate planting densities, suitable cover crops, or timely cultivation. Weeding creates good growth conditions and has a positive effect on bean size and flavor[46].

Insect pest and disease management as pre-harvesting factors

Pests and diseases that attack coffee cherries directly and indirectly affect the bean quality. To this end, coffee berry borer [CBD] *Hypothenemus hampii* feeds and reproduces inside coffee beans and deteriorates their quality to deteriorate[46]. Coffee berry borers (CBB) and Coffee Berry Disease (CBD) are the most important pests and diseases that directly affect coffee fruits. The antestia bug and the Mediterranean fruit fly *Ceratitis capitata* are also pests that attack coffee berries. In southern Ethiopia, bacterial blight of coffee (BBC), CBD, CWD, coffee leaf blight (CLB), CLR, coffee stem drying disease (SD) leaf dryness (LD) and leaf spot (LS) are the most common diseases[6]. Similarly, Teferi & Belachew[93], also referred to as CBD, CWD, CSC, DB, and LS, are common diseases in Sidama and Gedeo zones, affect coffee yield and quality. A survey study by Teshome et al.[67] in the Gedeo zone also identified the prevalence of diseases such as coffee wilt disease (CWD), coffee berry diseases (CBD), BBC, damping off, *Gibberella xylarioides*. As a result, the quality and quantity of coffee may have decreased considerably. This finding is in line with a report that mentions CBD, *Colletotrichum kahawae*, CWD, G. *xylarioides*, coffee leaf rust (CLR), and *Hemileia vastatrix* as the major diseases that reduce coffee production and quality in Ethiopia[94].

Harvesting factors

Harvesting the coffee cherries without causing damage to the tree is an important task. As the coffee cherries mature, the coffee fruit contains suitable chemical compositions which lead the fruit to the best quality. This is the reason why immature coffee beans are associated with high caffeine and CGA concentrations and poor cup quality[81]. Therefore, harvesting times and methods are essential factors for improving the cup quality of coffee but vary with locations[28]. Therefore, smallholder farmers should selectively harvest red cherries from the whole tree or branches by hand-picking, preferably using ladders for tall coffee trees; however, a premature harvest can sometimes be carried out by strip picking for the need for cash and fear of thefts[95,96]. This way farmers can reduce differences in flowering and maturation dates. According to Taye & Tesfaye[78], low caffeine content is found in beans harvested at an immature stage (unripe). For matured coffee cherries, it is widely agreed that traditional hand-picking and husbandry labor, as opposed to mechanical harvest, produce the best quality coffee beans by minimizing the percentage of defects in coffee batches[89,97]. Some authors have reported low caffeine content in beans harvested late in over-ripe coffee beans and attributed it to biodegradation of the over-ripe stages of fruit development[62]. However, harvesting red cherries is very labor-intensive, and because in a high inflationary context, farmers prefer drying their coffee as a form of savings and insurance throughout the entire year.

Post-harvesting management

Coffees with good inherent quality can be rejected if they follow poor processing practices. This is because the practice after harvesting also plays a crucial role in coffee quality as an improper processing method and lack of post-harvest handling, such as storage facilities underline poor-quality coffee[12]. To this end, it is important to adopt drying beds, hand pulpers, central coffee washing stations, and drying materials[12]. Processing and storage are essential practices in coffee production and play a significant role in quality determination. Post-harvest management is a method of converting cherries into green coffee and should be undertaken with great care, as quality could be enhanced or compromised during processing. In this regard, Musebe et al.[98] reported that coffee quality is determined by 40% in the field, 40% in post-harvest primary processing, and 20% in secondary processing and handling practices. The Ethiopian average proportion for dry and wet-processing methods was 70% and 30% of the coffee produced in the country, respectively[95] whereas this proportion dropped to 65% and 35% in Gedeo, respectively[67,99]. Wet processing is simply the removal of the pulp and mucilage by washing and fermentation followed by drying of parchment coffee. Most of the countries' washed coffee falls in grades 2 and 3, but the unwashed coffee, which represents 70% of the country's production is commonly sold in the local market[100]. The wet method is believed to provide better quality depending on the availability of water, processing facilities, sunshine, temperature, the concentration of mucilage, and labor. Endris & Weldsenbet[101] identified that parchment coffee dried at the highest drying depth (5 cm) gave the lowest cup quality, while the other drying depths (2, 3, and 4 cm) gave better cup quality values. Then, parchment coffee is dried and ready for transport to where it is sold in auctions (still in parchment form). The same authors noted that coffee fermented under shade takes more time, and shaded fermentation tanks help to achieve a uniform fermentation process and better quality coffee than unshaded ones[101]. To this end, shortages in processing technologies (wet and dry processes) and storage practices should be improved through government support or promotion of investment. Conversely, Alemseged & Yeabsira[102] stated that dry processing is an age-old method of processing coffee and is still used in many countries where water resources are limited, but witnessed that it delivers inferior quality. The low coffee quality from dry processing is partly due to the high risk of secondary fermentation because of the mucilage, which is very hygroscopic remaining with the coffee cherry. In some places, improved quality coffee beans with high raw quality are produced if the dry processing method is coupled with drying on a mesh wire[103]. However, about 90% of farmers who carry dry processing practice drying on wooden and bamboo beds in Gedeo area[67], which might be a contributing factor at times to the lower quality of dry processed coffee. If the beans are too wet (> 12.5% moisture), they will mold easily during storage. If the beans are too dry (< 8% moisture), they will lose flavor. Moisture content influences how coffee roasts and weight loss occurs during roasting. Therefore, the moisture content of the coffee beans should be maintained between 10.5% and 11.5% because moisture is an important attribute and indicator of quality.

Coffee storage and handling is a fundamental process that influences quality, and thus requires due care. It is better to have a cool and dry store (10−18 °C and 50%−70% RH) to better preserve coffee quality. Belay et al.[14] described that storage facilities should be clean, cool, shaded, dry, and well-ventilated.

Under conditions of high relative humidity and temperatures, coffee beans absorb moisture and develop molds that would lead to bleached color and loss of desirable flavor. Long-term storage under high relative humidity and warm conditions increases bean moisture content and consequently reduces quality in terms of raw and roasted appearance, as well as liquor[104]. The survey work by Teshome[67] showed that some farmers used both jute and plastic bags as packing materials in the Gedeo zone, practices that were not in line with the principle of proper packaging. Some authors have also reported that poor storage facilities lead to changes in the inherent qualities and appearance of green coffee as a result of the potential development of molds[89]. Thus, the goal of coffee storage is to achieve and maintain its commercial value for as long as possible by preserving the integrity of the bean with all its characteristics[105,106]. Furthermore, inadequate harvesting, processing, storage, and transportation systems are responsible for the widespread failure to maintain the inherent quality of coffee produced in Ethiopia[67]. This requires proper packaging with jute bags to maintain their inherent quality.

If beans are harvested in proper moisture, they should also be stored properly in cold places that do not expose the beans to sunshine and moisture. This practice enables the retention of freshness of the bean. So there is a need to store in dry places that have sufficient air circulation and practice the use of vacuum bags and jute bags, and avoid storage of coffee beans in the underground pits, on the soil surface, unclean storage structures, places where chemical residues were kept, and sites where livestock urine exists, etc. The survey work by Teshome et al.[67] showed that some farmers used both jute and plastic bags as packing materials in Gedeo zone, practices which were not along with the principles of proper packaging. Some authors also reported that poor storage facilities lead to changes in the inherent qualities and appearance of the green coffee as a result of the potential development of molds[89]. Thus the goal of coffee storage should achieve and maintain its commercial value as long as possible by preserving the integrity of the bean with all its characteristics[106]. Furthermore, inadequate systems of harvesting, processing, storage, and transportation are responsible for the wide spread failure to maintain the inherent quality of coffee produced in Ethiopia[107]. More importantly, farm records of management like dates of picking, processing, storage and transport should be kept to trace back the quality of the coffee. Because the market demand and coffee quality is known to decrease through longer storage, it is necessary to keep operations due according to calendar dates without unnecessary delay giving urgent priority to opened jute bags or containers. This justifies why Haile & Hee Kang[108] attributed 60% of the quality of green coffee beans to the post-harvest operations include pulping, processing, drying, hulling, cleaning, sorting, grading, storage, roasting, grinding, and cupping[108].

Socioeconomic factors

Socioeconomic factors such as access to physical, economic, and educational resources are one of the key difficulties confronting small-scale coffee farmers and affecting the quality of their produce[28]. Among these, access to credit, farm size, access to supplementary inputs, and technical and institutional support such as extension services determine the adoption of technologies. A study by Takele[109] showed that Ethiopian quality coffee is decreasing and market performance is also decreasing in the world, and attributes it to poor adoption of improved technology, oldness of coffee trees, and poor pruning and recycling systems are among the major problems[109]. Efa et al.[110] reported that the adoption of improved varieties, literacy, extension visits, and proximity to research centers positively influenced farmers' perceptions. Many studies have also shown that female households have less access to improved technologies, credit, and extension services[111]. On the other hand, male-headed households have better access to information than do female households, which helps in the adoption of improved agricultural technologies. Kebede[112] also added that deforestation and land degradation, diseases, predominantly traditional production, failure to use appropriate coffee technologies, inadequate services (credit, inputs, and equipment), and lack of sustainability and competitiveness in the coffee sector were challenging coffee quality and production improvement in Ethiopia. According to Wolde[32], smallholder coffee farmers in the Gedeo area have limited access to market information, physical infrastructure (roads, storage facilities, and transport facilities), and frequent and time-bounded training opportunities concerning coffee production and management; as a result, the absence of these were shown to adversely affect quality and production.

Survey results by Toma Dilebo[113] also stated that the household head's education level, credit use, land covered by coffee, and experience in coffee production and marketing were the most significant variables affecting the volume of coffee supply at the household level in the Yirgachefe district of the Gedeo zone. The volume of coffee supplied to the market increased by 91.3% for households that used credit compared to those who did not; an increase in one year of formal education increased the volume of coffee supplied by 8%; a year increase in experience of coffee production and marketing increased the volume of coffee supplied to the market by 2.5%, and a one-hectare increase in the size of land covered by coffee increased the volume of coffee supplied to the market by 70.93%. Similarly, physical, economic, and educational resources are the main resources that challenge smallholder coffee producers to ensure efficient and high-quality coffee production in the Southeast and Southwest parts of Ethiopia[28]. Some non-governmental organizations started considering the presence of firms to set international prices that offer quality-related price premiums for both organic and fair-trade certified coffee as motivation for quality coffee production[114]. In the matter of fair trade coffee, this global social movement has transformed the traditional coffee trade structure of inequality and unfairness into a conglomerate of international institutions that embrace equity and inclusivity[114].

Research gaps identified

Research gaps were found regarding our understanding on the effects of shifts in carbon dioxide, water stress, and temperature on the response to coffee quality, and how this varies with location, elevation, and management conditions. Next, gaps were identified in the relationship between crop husbandry vis-à-vis maturation patterns of beans, physical appearance, organoleptic cup quality, and inherent chemical constituents of the green bean. Thirdly, appropriate management that optimizes the quality and productivity across a specific set of genotype × environment conditions needs to be considered. Moreover, the factors that enhance coffee quality may not have a similar effect across localities Farm records of G × E × M of model farmers requires due exploration. Next, the association between physiological age and the quality of coffee in specific genetic and environmental settings provides a direction for the required management. Similarly, new areas of coffee relocation as an adaptation option for a changing climate should be mapped to design management alternatives. Genetic gains for improvement in quality, resistance to pathogens, and yield can be achieved by selecting resistant lines from wild species, or through inter-specific hybridization strategies. Equally important was to know how climate change affects coffee quality in Gedeo agroforestry systems. Varietal authentication and traceability using molecular markers is also needed to enhance the quality of coffee beans. There is also a need to certify quality coffee seed producers and plant nurseries that enable the production of quality beans from healthy plants.

Discussion and conclusions

The ability of the coffee sector to acquire appropriate pricing from product is a significant aspect in order winning. A thorough analysis of the literature and databases that were accessible were conducted to determine the coffee quality that influences consumer pricing. It was realized that the chemical compositions and physical properties of coffee beans are affected by different factors such as environment, genetics, agronomic activities, harvesting, and post-harvest operations. Improving coffee quality can lead to higher coffee exports and could be a great way to raise coffee prices. Ethiopian coffee's superior row and cup quality may be attributed mainly to the genetic composition of the varieties cultivated in appropriate climates using organic farming methods employed by smallholders. Ethiopian coffee is well-liked in the international market for determining customer preferences based on factors such as bean size, cup quality, or chemical content because of the distinct tastes produced by the specific genotype (G), environment (E), management, and socioeconomic relationships. Coffee farmers were driven to meet the prospective market by the recent trend of paying extra for high-quality coffee. This is only achievable, though, if strategic management choices were taken to uphold and enhance coffee quality all the way through the value chain.

Quality coffee production was traditionally thought to have resulted from medium-shaded circumstances and carefully chosen shade trees, native coffee plants, selective bean picking during middle harvesting seasons, and organic farming. As a response to climate change, it is imperative that the greatest coffee technologies be upheld in each region and production area. This includes adopting heat- and drought-tolerant coffee varieties, improving agricultural techniques, and enhancing post-harvest handling. Thus, scaling up the best shading practices on a commercial scale are vital for farming communities. Coffee farmers' also need to alter using unimproved local landraces of coffee and keeping old trees. Honey bee introduction and intercropping with story spices would stabilize the income and improve quality of life in rural coffee growing areas. In the nation, value addition to coffee is essentially non-existent and coffee quality declines along the value chain, necessitating coordinated actions along the chain for value addition. This assessment also emphasized the need to investigate agronomic, socioeconomic, and environmental aspects in order to pinpoint quality deficiencies, monitor them, and implement remedial actions for particular coffee-growing regions—such as the Gedeo area because most quality coffee producers lack infrastructural, economic, and extension support. The possibilities for improvement in coffee production and enhancement in its quality in the face of climate change would be optimizing microclimates, making the most of irrigation and groundwater resources, applying more shade, and optimizing agricultural inputs as adaptation strategies that can improve the production and quality of coffee. To maintain excellent standards for the coffee they cultivate, Gedeo's coffee growers should also continue to use organic farming methods, concentrate on the best pre- and post-harvest management strategies, and minimize the amount of dry processing to keep pace with the market for high-quality coffee. Infrastructural accessibility, economic, and extension support to coffee growers should be a priority to stabilize quality coffee delivery.

Author contributions

The authors confirm contribution to the paper as follows: conceptualization: Getahun T, Mamo G, Markos D; data collection, resources, and draft manuscript preparation: Getahun T; methodology: Mamo G, Haile G; formal analysis: Markos D; writing - review and editing: Mamo G, Haile G, Tesfaye G. All authors have read and approved the final manuscript.

Data availability

The data used for this study can be obtained from the corresponding author upon reasonable request.

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Conflict of interest

The authors declare that they have no conflict of interest.

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