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Shaded agroforestry systems: A review on enhancing coffee growth, yield and sustainability

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Abstract
Coffee plants, naturally shade-loving, thrive under the canopy of taller trees, making shaded agroforestry systems essential for sustainable coffee cultivation. This review explores the multi-layered impact of shade on coffee ecology, growth, yield and quality. Shade trees provide ecological benefits, including soil fertility enhancement, erosion prevention and carbon sequestration, while mitigating climatic stress and improving soil moisture. Shaded environments foster consistent flowering and yield, minimize biennial bearing and enhance bean size and biochemical quality, leading to superior beverage attributes and higher market value. Moreover, shade moderates' extreme temperatures, supports pest and disease management and reduces reliance on agrochemicals, ensuring environmental and economic sustainability. Despite these advantages, deforestation and climate variability challenge shaded coffee systems, highlighting the need for adaptive practices. This review highlights the role of shade management in sustaining coffee production amidst changing global climates and underscores its importance for ecological preservation, biodiversity and enhanced livelihoods in coffee-growing regions.

Keywords: Coffee cultivation, shade management, agroforestry systems, ecological benefits, soil fertility

Introduction

Coffee plants grow naturally in the forest understory, where they are shaded by taller trees and do not require full sun. When humans domesticate coffee, the plant is planted under other huge trees that offer shade, simulating the coffee plant's natural growing conditions in its native forest undergrowth. According to coffee is a shade-loving plant and shade trees relieve stress in coffee (*Coffea* spp.) by alleviating harsh climatic circumstances and nutritional imbalances. Coffee agroforestry technology provides numerous economic benefits and meets the demands of homes for medicine and timber. Agroforestry approaches, particularly the addition of nitrogen-fixing plants to the production system, will boost soil fertility. Trees also help to reduce soil erosion and sequester carbon. Shade trees in coffee agroforestry systems boost and sustain surface soil humidity while decreasing direct light intensity reaching the coffee plant, which contributes significantly to increased coffee yield. Growing coffee beneath shade trees is critical not only for the sustainability of coffee farms, but also for environmental protection in ecologically sensitive areas. Costa Rica produces higher-quality coffee beans because Arabica coffee is grown in the shade (Muschler, 2001) [48]. Coffee production in shade is used to produce coffee in a sustainable manner with the least quantity of agrochemicals. Although coffee is a shade-loving plant, it can be grown without shade in perfect conditions and with large pesticide inputs. However, many countries are now paying attention to such coffee shade agroforestry systems due to the susceptibility of coffee plants to climate change and fluctuation, as well as people's growing health and environmental consciousness. Shade trees create ideal circumstances for excellent coffee growing by reducing light intensity and soil temperatures, increasing humidity and retaining soil moisture.

Coffee is one of the country's most important plantation crops. Unlike other places in India, coffee is grown in a traditional agroforestry setting beneath the shade of native tree canopy, allowing for a high degree of diversity (mixed cropping) with black pepper, orange, banana and other plantation crops.

This strategy has secured the farm's longevity while also preserving biodiversity and providing a variety of ecological benefits. In short, Indian coffee is the most environmentally benign and sustainable production system, contributing to the preservation of biodiversity in the ecologically vulnerable Western and Eastern Ghats. A lot of work has been put into improving its contribution to sustainable coffee production by selecting the best coffee shade tree and implementing shade tree management practices. Despite its importance and the government's efforts, there has been an increase in destruction on the tree reserve as coffee growers have tended to reduce shade cover, change their management strategies and shift towards monoculture to intensify their cultivation systems and increase yield (Anon, 2011) [2] and such high deforestation rates have had an impact on climate variability and a negative effect on coffee production practice. In recent years, the thinning of shade cover/monoculture, combined with shifting weather circumstances, has had a substantial impact on coffee production. Coffee output and quality are highly influenced by natural ecosystem services and seasonal climatic circumstances (Raghuramulu and Rudragouda, 2017) [61]. Evidence of climate fluctuation affecting coffee output has been explored in various other coffee-growing countries, including Brazil, Vietnam and Costa Rica. Indicated that the effects of climate change on Arabica coffee have already been documented in Brazil. For example, in 2020-2021, dryness and frost combined to damage approximately 1.5 million square kilometers of agriculture and may have destroyed nearly 600 million kg of coffee beans. Furthermore, acceptable areas for Robusta coffee in Vietnam's Central Highlands and Indonesia would be reduced by up to 36 per cent under the low climate effect scenario and 83 per cent under the high impact scenario. According to a research estimate, climate change might lower world Arabica coffee production by 45.2 per cent and Robusta coffee production by 23.5 per cent. Furthermore, the global area suitable for coffee production could shrink by half. This condition might harm the livelihoods of more than 25 million smallholder coffee growers in 60 tropical nations. Colombia's coffee production fell 30 per cent between 2008 and 2012 due to severe rainfall and coffee leaf rot. As a result, studying the performance of coffee produced under various shade management regimes is critical and it is necessary at this point to emphasize its importance in light of the current changing climate.

Hence, in the review of literature the work done on similar aspects of coffee and shade been reviewed under the following sub headings.

- Ecology of coffee
- Effect of natural shade on growth and yield of coffee
- Effect of natural shade on photosynthesis, stomatal conductance, transpiration and leaf temperature
- Effect of shade on pests, diseases and weeds
- Effect of shade on Biochemical components and beverage quality attributes

Ecology of coffee

Coffee thrives as an understory shrub in the tropical high rain forest in southwest Ethiopia, which is its natural environment. With an average annual temperature of 20 °C and an altitude of 1600-2800 m, this region experiences well-spread rainfall ranging from 1600 mm to over 2000 mm, with a dry season lasting three to four months that coincides with the coolest time of year (DaMatta and Ramalho, 2006) [15]. Coffee does not experience high temperatures or a vapour pressure deficit because it is an understory plant that is always shaded (Maestri and Santos Barros, 1977) [42]. One of the climatic elements that significantly affect coffee physiology is temperature. Arabica coffee can tolerate temperatures of 15 °C at night and 25 to 30 °C during the day, but it's ideal mean temperature is between 18 and 22 °C. Higher temperature than the ideal 22 °C caused berries to develop and ripen more quickly, which produced coffee beans of lower quality. Long-term exposure to temperatures above 30 °C may cause growth retardation and other abnormalities including leaf yellowing. Abortion of flowers may result from high temperatures during flowering, particularly when coupled with dryness. On the other hand, frost damage caused by low temperatures below 18 °C inhibits growth (DaMatta, 2004, Rudragouda *et al.*, 2017) [16, 61].

Since coffee exhibits traits of shade-adapted plant species, such as the capacity to photosynthesize in low light, a high leaf area to woody structure ratio and the lack of a fruit thinning mechanism to control fruit load, it is classified as such (Franck *et al.*, 2007) [22]. However, the vast range of radiation circumstances in which coffee can be cultivated indicates that coffee leaves exhibit a high degree of flexibility in their response to irradiance. According to DaMatta (2004) [16], coffee is consequently regarded as a shade-adapted plant rather than a normal shade plant. Coffee has become more popular in agroforestry systems due to its adaptation to shade, particularly in India and Central America (Vaast *et al.*, 2005) [78]. Over the years, there has been discussion on whether or not shade trees are good for coffee. However, coffee has been shown to benefit from shade, particularly in less-than-ideal circumstances (Vaast *et al.*, 2007, 2008; van Kanten and Vaast, 2006) [22, 77, 79]. Because it develops in tropical regions with rich biodiversity, the shaded coffee system has significant ecological and economic value (Soundari *et al.*, 2016) [70]. Coffee plants were shielded by shade trees from harmful environmental conditions including low relative humidity and hot soil temperatures.

Effect of natural shade on growth and yield of coffee

In contrast to unshaded plantation circumstances, when the crop alternates between years with high flowering and mild flowering, coffee plantations with shade tend to flower and produce a decent crop every year, resulting in a biennial production trend. Since unshaded coffee bushes have a shorter life expectancy than shaded bushes, the other issue with unshaded production is environmental degradation, specifically through soil erosion, the use of high external inputs and chemical residues, which become serious issues that reduce productivity and/or environmental quality and necessitate frequent replanting. Coffee yield can be positively impacted by shade. Particularly in less than ideal circumstances, shade trees produce a microclimate that encourages coffee growth and output. Because it preserves soil, water and biodiversity, shade is crucial for maintaining coffee productivity (Vaast *et al.*, 2007 and Rudragouda *et al.*, 2017) [7, 61].

According to research done in Central America, low to medium elevations benefit from 30 to 50 per cent shade (Beer *et al.*, 1998) [6]. Additionally, Soto-Pinto *et al.* (2000) [69] found that yield was positively impacted by shade levels between 23 and 38 per cent. Additionally, according to Vaast *et al.* (2006) [79], shade decreases biennial or alternating bearing.

Acacia abyssinica, *Cordia africana* and *Albizia schimperiana* produced the highest and most consistent coffee yield results. Such leguminous trees contributions to improving soil fertility condition and supplying moderate light intensity through their feathery leaves may be the cause of this (Kufa *et al.*, 2007) [36].

Due to increased vegetative growth and carbon reserves in branches and roots, coffee plants growing in shade suffer from less severe dieback (Wintgens, 2004) [17]. According to Siahaan Adriani S.A. (2020) [63], coffee planted in an agroforestry system yields more fruit than coffee grown in an open environment.

Arabica coffee produced under shade trees yields higher seed weight (148 g/1000 seeds) and better seed quality than those grown without shade (134 g/1000 seeds), according to Bote and Struik (2011) [9]. In order to hasten the development of fruit and flowers, coffee plants without shade will enhance the absorption of carbohydrates from the leaves and stems, which will cause damage to the roots and leaves (molt). Additionally, plants that were shaded had a higher physiological and biochemical capacity for producing large amounts of dry matter, which would enable them to sustain high coffee yields over time. In addition, Somporn *et al.* (2012) [67] found that when the shade level was gradually raised in comparison to full light, there was a substantial increase ($p<0.05$) in bean weight, bean size and fruit yield per plant.

Growing coffee in an agroforestry system with African mahogany, teak and Australian cedar raises the soil's organic matter and Phosphorus content while also increasing coffee yield (Jacome *et al.*, 2020) [29]. Long-term stability in coffee output was seen under shaded ecosystem (Cerda *et al.*, 2020) [12]. Coffee grown in shade had a much larger canopy diameter or bush spread (216.7 cm), whereas coffee grown in the absence of shade had a bush spread of 158.3 cm. Similarly, coffee grown in shaded conditions had higher numbers of branches per plant, fruits per branch and seed weight than coffee grown in unshaded conditions (Siahaan Adriani S.A., 2020) [63].

Muschler (2001) [48] found that under unpruned *Erythrina poeppigiana*, fruit weight and bean size rose dramatically when shade intensity was increased from 0 per cent to more than 80 per cent. In unshaded Caturra and Catimor, huge beans (width > 6.7 mm) made up 49 and 43 percent of the coffee, respectively; in thick permanent shade, these percentages rose to 69 and 72 percent. This implied that Catimor had a greater shade benefit than Caturra. Coffee shade affected the plant's physical yields, including the number of branches, nodes per branch and fruit per node, as well as its organoleptic characteristics, including bean size, color, shape and make, acidity, astringency, bitterness, body, flavor and overall quality (Diriba *et al.*, 2021) [19]. On the contrary, coffee grown in the sun has a higher metabolism and inappropriate morphological growth, which exposes the coffee plant to early death, branch dieback, excessive fruit production, fluctuating fruit production, heavy reliance on chemical fertilizers, insecticides, herbicides and fungicides and requires more management. These might have a negative impact on organic coffee yields and lowered the market's top perineum price. The yield of bigger beans increased by 6.25 per cent and berries by 5.6 per cent when 100 non-*Grevillea* shade trees were planted per hectare (Boreux *et al.*, 2016) [8].

Tree biodiversity and its implications on changes in coffee production over a gradient of intensification (from diversified multispecies to *Grevillea robusta* dominated shade) were the subject of a 2017 study by Nesper *et al.* Coffee production and quality (in terms of bean size) suffered from decreased tree diversity. These outcomes were consistent across management approaches (conventional vs. organic farming and irrigation) and a wide rainfall gradient (1060 mm yr^{-1} to 4370 mm yr^{-1}).

According to Franck *et al.* (2005) [23], coffee grown in shade has been shown to yield more than coffee grown in the sun. Shade also encourages the growth of larger individual leaves, plant lifespan and a decrease in leaf specific mass, which results in a lower carbon demand for a similar leaf area index (LAI). *Erytherina absinica* may be useful for shading coffee plants in order to maximize these crucial coffee production parameters. Coffee plant development and productivity are known to benefit from the influence of shade trees such as *Cordia africana* and *Erytherina absinica* on microclimatic conditions (Diriba *et al.*, 2021) [19].

Effect of natural shade on photosynthesis, stomatal conductance, transpiration and leaf temperature

Many studies have shown that high temperatures and irradiance can significantly impair the photosynthetic processes in coffee trees. According to Kumar and Tieszen (1980) [37], photosynthetic rates significantly decreased as air temperatures increased above 26 °C. According to other research, coffee plants exposed to air temperatures higher than 25 °C may experience high temperature stress, which is defined as a temperature increase that lasts longer than a critical threshold and damages plant growth and development irreversibly (Luo *et al.*, 1999) [41]. According to Nunes *et al.* (1993) [51], for every degree Celsius that the temperature rises, the photosynthetic rate decreases by 10 per cent. By increasing photorespiration, high temperatures can reduce net carbon gain (Ramalho *et al.*, 2013) [57]. Photo-inhibition, which lowers coffee leaves' capacity for photosynthesis, is linked to high radiation levels (Nunes *et al.*, 1993; Ramalho *et al.*, 1997) [51, 55]. Numerous biochemical processes involved in plant growth and development are temperature-sensitive (Oliveira *et al.*, 2010) [52]. Consequently, coffee trees exposed to such temperatures that are not sheltered, open, or in the sun have a considerable reduction in production. Coffee plants were shielded by shade trees from harmful environmental conditions including low relative humidity and hot soil temperatures. Additionally, shade caused the coffee plants to behave differently physiologically, improving photosynthesis and increasing the leaf area index, which allowed them to perform better than they could in full sunlight (Bote and Struik, 2011) [9].

Since coffee is highly sensitive to variation in leaf temperature, particularly above 25 °C, coffee trees cultivated in direct sunlight had a decrease in stomatal conductance when temperatures rose above this point (Dinorah *et al.*, 2021) [18]. According to Weidner *et al.* (2000) [81], coffee leaves kept in permanent shade exhibited higher stomatal conductance rates than those exposed to full sun. According to other research, stomatal conductance rates under shade were higher in the morning and decreased in the afternoon (Mohotti and Lawlor, 2002; Vaast *et al.*, 2007) [45, 7]. High temperatures and a vapour pressure deficit that cause stomatal closure have been blamed for this.

According to Baliza *et al.* (2012) [4], coffee trees with 35-50 per cent shade exhibited the highest stomatal conductivity. Compared to shaded plants, coffee in unshaded plantations typically experiences higher levels of water stress. According to research conducted in Central America and India during periods of extreme drought, shade trees' ability to reduce stress outweighed the negative effects of competing for water (Muschler, 2004; Somashekhargouda *et al.*, 2022) [49].

According to Van Kanten and Vaast (2006) [79], trees that received full sun had a tendency to transpire more than trees that received shade, suggesting that they were under more environmental stress. However, scientists also found that coffee plants planted in shade used more water per day than those grown in full sun because of their higher vegetative development. Additionally, under these circumstances, the water usage of related shade trees had little impact on the amount of soil water available for coffee, however this might have been because of the heavy rainfall (more than 2,500 mm). However, too much shade lowers the quality of the radiation that is delivered, which also has an impact on growth and photosynthesis (Franck and Vaast, 2009; Baliza *et al.* 2012) [21, 4].

The concept of photosynthetic maintenance in shaded coffee plants has been confirmed by Charbonnier *et al.* (2017) [13]. Coffee plants grown in shade had a 50 per cent increase in light-use efficiency despite a 60 per cent decrease in irradiance below the canopy of the shade trees. Additionally, the total aboveground net primary productivity (leaves, fruit, wood, etc.) did not differ statistically from that of the plants grown in full sun. This illustrates how coffee plants may be able to increase their photosynthetic efficiency in order to make up for the decrease in sun irradiation in a shady environment. In support of this theory, Martins *et al.* (2013) [43] showed that, when measured on a mass basis, coffee plants grown in 90 per cent shade cover had a similar amount of net photosynthesis to those planted in full sun. Additionally, this study found differences in the kinetics of photosynthesis, demonstrating that leaves grown in shade demonstrated faster photosynthetic induction than their counterparts grown in the sun. This variation is probably due to an adaptive reaction to use the light energy from sun specks. Coffee cultivated in shade may be able to maximize its capacity for carbon assimilation in low light conditions due to its enhanced photosynthetic ability, which is probably related to *Coffea arabica's* evolutionary background in forests and understory. In contrast to self-shaded, lower-canopy coffee leaves in the same plant, well-illuminated leaves from the upper portion of the canopy occasionally displayed a higher net carbon assimilation rate (A), which is linked to a higher electron transport rate (Araujo *et al.,* 2008) [3]. The study found that the stomatal and mesophyll conductance of coffee leaves in the sun and shade was similar regardless of leaf position, with no discernible differences. But when it comes to adapting to low-light conditions, morphological (such as changes in specific leaf area and leaf inclination) or anatomical plasticity is probably more important. Only mature coffee leaves could acclimate to harsh conditions for *Coffea arabica* (produced under controlled conditions), according to Campa *et al.* (2017) [11], who took leaf age into account. It was discovered that the developing and expanding leaves had weak antioxidant defenses, ineffective photo-protection systems and a low capacity to export sucrose in the presence of increasing light levels. These findings imply that *Coffea arabica* cv. Naryelis's young leaves are somewhat sensitive to high light levels, even though the cultivar was chosen for full sun and open environments. These results are consistent with other studies that demonstrate the high acclimation plasticity of freshly-matured coffee leaves following a shift from deep shade to full sun exposure. These findings are linked to modifications in the lipid profile of chloroplast membranes, the reinforcement of photosynthetic components and anti-oxidative and photo-protective mechanisms (Ramalho *et al.,* 1997, 2000, 2013) [55, 56, 57]. Unexpectedly, coffee leaves frequently respond to other stresses like heat (Rodrigues *et al.,* 2016) [60] and drought (Dubberstein *et al.,* 2020) with these high irradiance stress responses, which may worsen oxidative stress conditions (as a secondary stress). This suggests that some elite coffee genotypes are adaptable to environmental constraints, which should be investigated for breeding purposes. The climatic component that most affects the physiology of arabica coffee is temperature. This species prefers temperatures between 18 °C and 22 °C (Descroix and Snoeck, 2004) [17].

Unshaded plantations can have air, leaf and soil temperatures that are significantly higher than those in shaded plantations—sometimes by more than 10 °C (Muschler, 2004) [49]. Because they tower over coffee, shade generally serves as a buffer to the coffee microclimate. For instance, Mexico's maximum temperature during the hot season was lowered by an average of 5.4 °C under shade, while the minimum temperature rose by upto 1.5 °C (Barradas and Fanjul, 1986) [5]. In India, the temperature was lowered by upto 2.0 °C during the same period (Rudragouda *et al.,* 2017) [61].

Shade trees do act as a buffer against large temperature swings. Beer *et al.* (1998) [6] noted that temperatures in Mexico were 2 °C higher and 5 °C lower than the minimum ambient temperature during the hot season. Shade trees in Costa Rica raised coffee leaf temperatures by 0.5 °C at night and decreased global radiation by 40 per cent to 50 per cent of the peak temperature (Siles, 2007) [64]. Extreme fluctuations in leaf temperature and humidity can be reduced in shaded plantation systems (Kirkpatrick 1935; Barradas and Fanjul 1986) [35, 5]. When plants are exposed to extreme heat stress throughout the day, an increase in shade cover may result in a drop in temperature (Lin, 2007) [40].

According to Vaast *et al.* (2006) [79], coffee trees grown in full sun and coffee trees grown in shade had leaf temperatures that differed by 4 °C for inner leaves and 2 °C for outer leaves. In climatically marginal coffee production conditions, shade is crucial and as temperature stress increases, more shade is required (Beer *et al.,* 1998) [6].

Given that climate change is linked to less rainfall and more dramatic temperature variations, growing coffee beneath the natural shade of trees may be a crucial coping strategy for small-holder producers. Because of the slower rate of evapotranspiration from the soil and coffee layer, systems with greater shade have improved moisture availability (Lin, 2007) [40].

Effect of shade on pests, diseases and weeds

By moderating the vast variations in soil and air temperatures and increasing moisture, the shaded coffee habitat in an agroforestry system (AFS) may alter the environment for weeds, illnesses and insect pests. Additionally, the fall of litter increases mulch and soil organic matter. For other creatures, such as pests, illnesses and their natural rivals, the shade trees further expand the diversity of habitat (Hietz, 2005; Muschler, 2004) [28, 49].

The coffee berry borer (*Hypothenemus hampei*), shot hole borer (*Xylosandrus compactus*), coffee white stem borer (CWSB) (*Xylotrechus quadripes*) and mealybugs (*Planococcus citri* and *Planococcus lilacinus*) are among the major pests in India. Black rot or Koleroga, which is caused by *Koleroga noxia* and coffee leaf rust (CLR), which is produced by *Hemileia vastatrix*, are the two major diseases (Anon, 2023 - Coffee Guide CBI) [2].

In terms of tree species, epiphytes, mammals, birds, reptiles, amphibians and arthropods, the shaded coffee environment in agro forestry system (AFS) supports biological diversity (Udawatta *et al.,* 2021) [72]. By reducing pest domination through direct and indirect competition, for instance, coffee-AFS may help coffee production by providing ecological services. Additionally, ants, lady beetles, parasitic and predatory wasps and microorganisms like entomopathogenic fungi are among the many natural enemies of pests and illnesses that are drawn to coffee plants (Kiran, 2018; Perfecto *et al.,* 2021; Venzon, 2021) [34, 54, 80].

However, coffee monoculture cultivation lacks the proper conditions and nourishment to sustain a high population of these natural enemies in the field. Today, researchers are still working to understand the ecological interactions in coffee agroecosystems related to common pests and diseases like the coffee berry borer (*Hypothenemus hampei*), the white stem borer (*Xylotrechus quadripes*), the shot hole borer (*Xylosandrus compactus*), the fungus *Hemileia vastatrix*-caused CLR and the black rot or Koleroga-caused *Koleroga noxia* (Cerda *et al.,* 2020; Hajian-Forooshani *et al.,* 2020; Uma, 2023) [12, 27, 73].

The prevalence of pests and diseases varies depending on farm management, shade tree species, shade density and site characteristics (e.g., altitude) (Karp *et al.,* 2013) [31]. Coffee under AFS has less pests and diseases because there are more birds, ants, wasps and other predators there and the microclimate is different in the shaded area than in the open or sun fields (Johnson *et al.*, 2010; Uma *et al.,* 2013) [30, 73].

Recent research has revealed that some characteristics of shade trees, such canopy openness and leaf area, significantly correlate with CLR incidence levels (Gagliardi *et al.,* 2021) [24] and can account for the majority of microclimate conditions (Merle *et al.,* 2022) [44]. Due to either synergistic or antagonistic effects on different cropping systems, these findings highlight the significance of shade tree selection in a coffee AFS and could provide the "missing link" to explain the dynamics of the AFS-CWSB, SHB and CLR.

Due to its additional floral nectars, the Inga sp., a frequent shade tree species in coffee-AFS, has been associated with improved natural pest management for the coffee plant near its canopy (Rezende *et al.,* 2014) [58]. It has been demonstrated that the destructive shot hole borer and black coffee twig borer are slowed down by the large, densely covered canopies of sap-exuding shade trees. However, *Albizia chinensis,* a shade tree, eliminates this impact (Bukomeko *et al.,* 2018) [10].

Compared to coffee trees in full sun, those under the shade of fruit trees were significantly less vulnerable to coffee berry disease (Mouen *et al.,* 2007) [46]. It was recently shown that coffee leaf miner (CLM) can stay on coffee leaves over the chilly fall and winter months due to the so-called "shelter effect" of rubber shade trees (Righi *et al.,* 2013) [59]. Overall, CLM caused less damage to the coffee plant in the shade, despite the fact that more leaves were mined there. These studies demonstrate the substantial effects of diseases and pests on coffee production, which in turn affects farmers' livelihoods. They also emphasize the significance of choosing shade trees based on their antagonistic or synergistic effects on important coffee pests or pathogens.

Kimemia (2004) [33] observed that weed species and occurrences were decreased by natural shade, especially from *Mimosa scrabella*. He ascribed this to the leaf fall, which prevented weed development by forming mulch. The low amount of weeds under *Mimosa scrabella* may have been caused by the potential presence of allelopathic chemicals. To better understand and forecast future outbreaks, more study is required to clarify the relationships between pests, diseases and weeds and coffee-shaded systems, particularly along varying shade, temperature and altitude gradients (Liebig *et al.,* 2019) [39].

Biochemical components and beverage quality attributes

According to Kathurima and Njoroge (2012) [32], green coffee is made up of a wide variety of chemical components that react and interact during the coffee processing process to create an even more complex and varied final product. Although coffee bean density, size and beverage and bean biochemical quality attributes are intrinsic, their manifestation is greatly influenced by genetic diversity and the environment (Leroy *et al.,* 2006) [26].

Caffeine, lipids, trigonelline, sugar and chlorogenic acids are the main biological components of coffee. One of the important alkaloids present in the leaves, seeds, or fruits of several plants is caffeine (1, 3, 7-trimethylxanthine). Coffee, cocoa beans and tea leaves are common sources of caffeine (Mumin *et al.,* 2006) [47]. It is conceivably the most widely used pharmacologically active drug worldwide. Caffeine is a key component of coffee since it has been linked to the beverage's energizing effects (Franck *et al.,* 2005) [23].

Shade has been shown to improve coffee quality by numerous writers (Geromel *et al.,* 2008; Vaast *et al.,* 2006; Muschler, 2004) [25, 79, 49]. Shade delayed ripening by one month, increasing the size and improving the coffee bean's biochemical makeup (Vaast *et al.*, 2006; Sanz-Uribe *et al.*, 2017) [79, 62]. Larger beans are often linked to higher cup quality and higher costs in global markets. While un-shaded coffee trees frequently drop more than 20 per cent of their berries to the ground, Muschler (2004) [49] discovered that shade dramatically decreased the ratio of falling berries. This has been linked to the tree canopy's physical protection of ripe berries from the impact of rainfall as well as the enhanced capacity of shaded plants to hold onto ripe fruit. Additionally, it has been observed that shade lowers the percentage of rejects, which include dry, infected, or withered berries. Compared to unshaded coffee plants, shaded plants produce a higher-quality product because it encourages slower, more balanced filling and uniform ripening of berries (Muschler, 2001) [48]. According to Bote and Struik (2011) [9] and da Silva Neto *et al.* (2018) [14], shade also reduces tree stress, which promotes slower fruit ripening, better bean filling those results in larger beans and ultimately higher cup quality. Studies on the effects of shade on *canephora* coffee are far less common than those on arabica coffee.

Found that rainfall and the shade trees chosen had a significant impact on the size of Robusta beans. The percentage of larger-than-normal bean size (coffee grading AA corresponding to >7 mm diameter) was higher in Robusta intercropped with *Artocarpus heterophyllus*, *Dalbergia latifolia* and *Lagerstroemia microcarpa* under low rainfall conditions than in those interplanted with *Grevillea robusta*. However, during heavy rainfall, the percentage of AA beans produced by Robusta interplanted with *A. heterophyllus* or *G. robusta* was lower. According to a different study, the density of non-Gevillea shade trees had a significant and favorable impact on the percentage of AA beans, but not that of *G. robusta* (Boreux *et al.*, 2016) [8].

By measuring certain chemical components in green beans, such as sugars (like sucrose), lipids, chlorogenic acids (CGA) and caffeine, the quality of the coffee can be determined (Leroy *et al.,* 2006) [26]. It is unclear how light affects sucrose because it has been shown to rise in both full sun and shade (Worku *et al.*, 2018) [83]. Chlorogenic acid was the most common phenolic acid in all samples examined, according to Somporn *et al.* (2012) [67]. It was highest in beans grown in lychee shade, followed by 60 per cent shade, 70 per cent shade, 50 per cent shade and full sun, in that order. Coffee beans grown in 60 per cent shade showed the greatest levels of total sugar (fructose, glucose and sucrose), with fructose being the most common sugar.

Different enzymatic activity are thought to be the cause of the variance in bean biochemical contents seen in coffee beans grown in full sun versus those grown in shade. Higher activity of sucrose synthase and sucrose-phosphate synthase were found in the pericarp and perisperm tissues isolated from matured cherries of the *Coffea arabica* plant when exposed to shade as opposed to full sun (Geromel *et al.*, 2006) [26]. The decrease in sucrose and the rise in reducing sugars seen in shaded conditions

may be explained by the high activity maxima of these two enzymes in developing beans (endosperm).
According to Somporn *et al.* (2011) [68], bean extracts of *Coffea arabica* cv. Catimor grown in shadow exhibited stronger antioxidant activities than those from plants grown in full sun, as determined by DPPH (1,1-Diphenyl-2-picrylhydrazyl) radical-scavenging activity assays. Alves *et al.* (2018) [1] examined the polyphenol oxidase (PPO) activity in Robusta, an enzyme that is frequently linked to high-quality cups. The findings of sensory tests showed that coffee plants cultivated in shade had lower PPO activity than beans obtained in full light.
Another important factor influencing cup quality is the environmental circumstances around coffee cultivation. It was discovered that favorable quality characteristics like acidity, fruitiness and flavor quality were associated with and characteristic of coffees grown at higher elevations and in cool climates (Bertrand *et al.*, 2012) [7]. As a result, there is considerable fear that rising temperatures (linked to anticipated climate change) will probably have a detrimental effect on the quality of coffee grown in the mid- and low-lands. According to Worku *et al.* (2018) [83], coffee cultivated in shade had an acidity rise of 0.22 points for every 100 meters of altitude gain, whereas coffee grown in the absence of shade had no influence of altitude on cup acidity.
Shade and elevation had a significant and beneficial impact on cup quality organoleptic qualities (acidity, body, raw total, flavor and cup total values) as well as grade in coffee arabica produced under a variety of forest covers and densities (Tassew *et al.*, 2021) [71]. According to who investigated the impact of shade composition on the quality of Indian Robusta coffee, a higher proportion of *Grevillea robusta* foreign species led to a decline in cup quality, as well as in aroma and body.

Conclusion
Shaded coffee cultivation is a cornerstone of sustainable farming, offering a range of ecological, agriculturaland economic benefits. In traditional agroforestry systems, shade trees enhance soil fertility, conserve moistureand sequester carbon, while also reducing the intensity of direct sunlight and raising soil humidity. These trees help buffer against extreme climate conditions, leading to improved coffee yields, better bean qualityand reduced reliance on agrochemicals. Coffee grown under shaded conditions typically boasts larger, denser beans with superior biochemical qualities, resulting in higher market value and better cup quality. Additionally, shaded coffee systems play a crucial role in biodiversity conservation and ecosystem support, especially in regions like India. However, challenges such as deforestation and climate change threaten these benefits. Despite these hurdles, shaded agroforestry systems, by improving microclimates and supporting agricultural diversification, offer a sustainable solution for climate-resilient coffee production, ensuring environmental sustainability while enhancing farmer livelihoods.

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