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Climate change and its impact on coffee production: A review on regional adaptation and mitigation strategies in Indian context

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ABSTRACT

Coffee production is highly influenced by climatic variations. Among the climatic variables temperature and rainfall are more influencing the coffee yield through their effect on crop growth, flowering and quality. This review examines the impacts of climate variability on coffee production along with adaptation and mitigation practices reported in the existing literature. The review covers how climatic variations change coffee yield and quality, pest and disease incidence, production costs and the suitability of coffee-growing regions. Practices like shade management, soil and water conservation, micro irrigation, diversification of crop, integrated pest and disease management, post-harvest processing, residue management and the use of climate-resilient varieties help farmers to reduce climate-related production risks. The effects of climate change and the effectiveness of adaptation and mitigation measures are specific to regions. It depends on local climate, altitude, soil conditions, and production systems. Further it was identified that research on climatic effects on coffee quality and *Robusta* production systems is limited. Therefore, greater attention to local studies and research on *Robusta* production and coffee quality is required to develop suitable strategies and to support sustainable and climate-resilient coffee production.

Keywords: Coffee, Climate change, Agroforestry, Shade management, *Arabica*, *Robusta*, Carbon sequestration

Introduction

Coffee is a plantation crop with lifespan of about 20 to 35 years (Pohlan *et al.*, 2010) [1]. Farmers start harvesting coffee commercially five years after planting the coffee. Around the world two main types of coffee are grown: *Arabica* (*Coffea arabica*) and *Robusta* (*Coffea canephora*). *Arabica* makes up 60 percent of coffee produced globally and the *Robusta* makes up the remaining 40 percent (ITC, 2021) [2]. Coffee production varies from one region to another because each area has specific climate conditions and different farming methods. These differences influence the quality and grade of the coffee that is produced. From different grades of coffee variety of products are produced. This opens up opportunities for processing and value addition. As coffee is labour intensive crop creates jobs and income at every step along the production and marketing. Moreover, coffee is one of the most widely traded agricultural products in the world, supporting the livelihoods of millions of farmers and playing an important role in the economies of many coffee-producing countries. According to the Food and Agriculture Organization of the United Nations (FAO) the total value of global coffee production in 2024 was estimated at nearly US\$25 while value of world trade in coffee beans is above US\$34 billion. The annual revenue of coffee industry was estimated at more than US\$200 billion. Due to the importance of coffee industry in generating employment and income and providing livelihood security to 25 million households, coffee is economically and socially important (FAO, 2025) [3]. Despite the growth in coffee industry, its production is increasingly affected by climate and weather variability. Coffee requires favourable temperature in the range of 14-28 °C and annual rainfall of 1,400-2,300 mm (FAO, 2000) [4]. Coffee is very sensitive to variations from these optimum range. The growth, flowering, fruit development and maturation stages of coffee are influenced by temperature, rainfall and altitude. Among these factors temperature and rainfall have the major impact on coffee production and yield. When these climatic conditions alters coffee output can fall in coffee-producing countries, which leads to a drop in global supply. The demand for coffee in international market shows a stagnation and almost equal to 10.51 million tonnes (ITC, 2025). Hence the fluctuations in the supply decides price determining force and climate change is having a gigantic role in production. Along with those pests and diseases further challenges coffee production. However, the ways climate variability impacts coffee production differ from one region to another. In addition to production and marketing risks coffee quality is also affected by climate change by a change in the chemical composition of coffee. Therefore climate change can affect not only coffee

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fee production but also coffee quality, coffee prices and the lives of coffee-growing farmers (Bunn *et al.*, 2015 [5]; Pham *et al.*, 2019; FAO, 2025) [3].

The future of coffee production systems is uncertain because of climate change. It is now very important for farmers to adopt adaptation measures to keep coffee output stable and to secure the livelihood of people who rely on the coffee sector. Therefore coffee farmers must use strategies that help them deal with changing weather conditions and reduce coffee losses. Adaptation methods such as shade tree management, soil and water conservation and better farm management practices can help lower climate related risks. Meanwhile mitigation strategies such as agroforestry, using environmentally friendly coffee production practices can help reduce the environmental impact of coffee. This study brings the review of research papers and together the effects of climate variability on the different coffee production systems. This paper looks at how coffee farmers are adapting to these challenges, the practical measures they can adopt to reduce their impacts, and the way forward for building a more resilient and sustainable coffee sector.

Methodology

A literature review was carried out to examine how climate change affects coffee production and how these effects are managed through adaptation and mitigation strategies. For this purpose, relevant studies were identified through keyword searches on google scholar, J-gate, Web of Science, PubMed, and other reliable institutional sources. The keywords included 'coffee', '*Coffea Arabica*', '*Coffea Canephora*', 'climate change', 'coffee yield', 'agroforestry', 'shade management', 'adaptation', 'carbon sequestration', and 'mitigation'.

Then the literature was screened based on the relevance to the objectives of the review. Studies on impacts of climate change on coffee, agroforestry, soil and water conservation, irrigation, crop diversification, integrated pest and disease management, climate-resilient varieties, carbon sequestration, and greenhouse gas reduction were in-

cluded. The review included earlier studies providing foundational evidence and recent research on climate change impacts and response strategies were considered. The selected literature was organised into major themes and synthesised to identify key climate risks and adaptation strategies along with research gaps in coffee production systems.

Global coffee production and production systems

Production and growth rate

Global coffee production has grown over time. According to the USDA-FAS, (2025) [6] estimation in 60 kg bags units, the world coffee production is 178.85 million bags in 2025-26 to approximately 10.73 million tonnes. Brazil is the leading coffee-producing country with an estimated production of 63.0 million bags, followed by Vietnam with 30.8 million bags and Colombia with 13.8 million bags. Indonesia and Ethiopia rank fourth and fifth with 12.45 and 11.56 million bags, respectively. Uganda ranks sixth with 6.88 million bags while India ranks seventh with 6.05 million bags. Together the major producing countries contribute a significant share of global coffee production. Changes in their production levels important for the availability and prices of coffee in the international market.

Brazil Vietnam Colombia Indonesia Ethiopia Uganda India Honduras

Country

Growth rate of coffee production is fluctuating over the years. Global coffee production increased considerably by 5.8 per cent in 2023–24 reaching about 178 million bags. It shows a positive growth rate in recent years except in 2019-20 and 2021-22. During these years the coffee production declined by 0.9 percent in former year and 1.7 per cent in the later year. The decline in production was mainly associated with weather conditions in some major producing regions along with variations in crop yield. Global coffee production growth was almost stagnant in 2022–23 (ICO, 2023) [7].

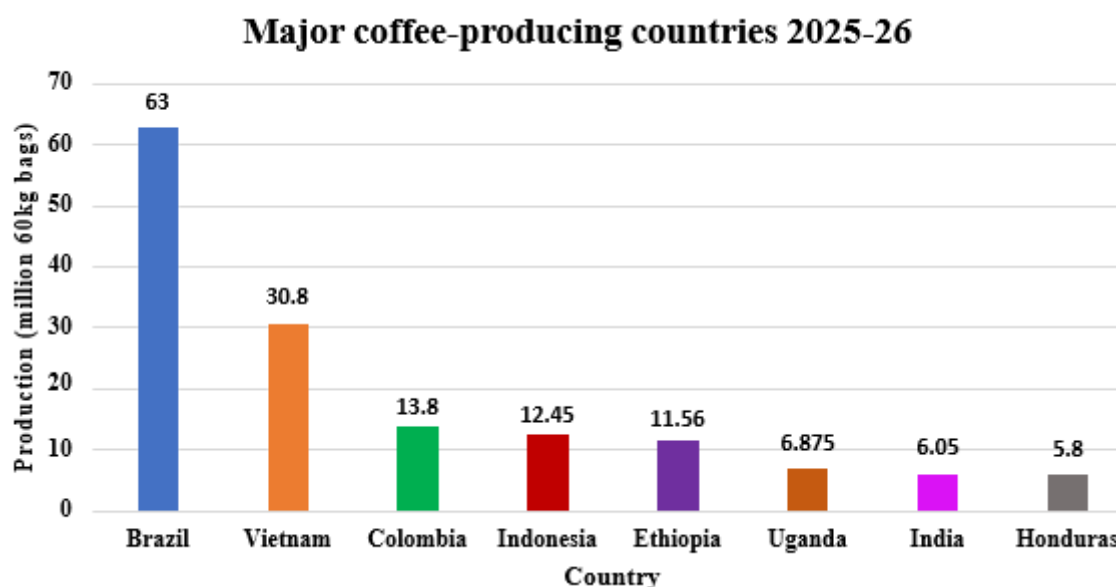


Figure 1. Major coffee producing countries 2025-26.

Arabica production and growth rate

From 2018-19 arabica growth rate shows a consecutive rise in one year followed by fall in next year till 2021-22. In 2022-23 growth rate was stabilized and increased by 8.8 per cent accounting to 102.2 million bags of arabica production in 2023-24. The fluctuations in *Arabica* production are caused by weather, crop cycles and changes in the producing countries, especially in South America. According to the

International Coffee Organization (ICO), the decline in *Arabica* production during 2021–22 was mainly linked to reduced output in South America, particularly in Brazil and Colombia.

Robusta production and growth rate

The International Coffee Organization (ICO) reports that global *Robusta* production, measured in 60 kg bags grew from 70.3 million bags in 2018-19 to 75.8 million bags in 2023-24 a rise of about 7.8 percent over the period. The Compound Annual Growth Rate

(CAGR) for *Robusta* is 1.5 percent per year. *Robusta* production is also fluctuating. The production was increased by 2.1 percent in 2023-24 after many years of uncertainty in production. *Robusta* made up 42.6 percent of world coffee production in 2023-24 up from 41.4

percent in 2018-19 showing an increase in its share of the global supply (ICO, 2023) [7]. The ICO notes that Asia and Oceania are the major *Robusta* producing areas, with Vietnam, Brazil, Indonesia, Uganda and India, among the top producers.

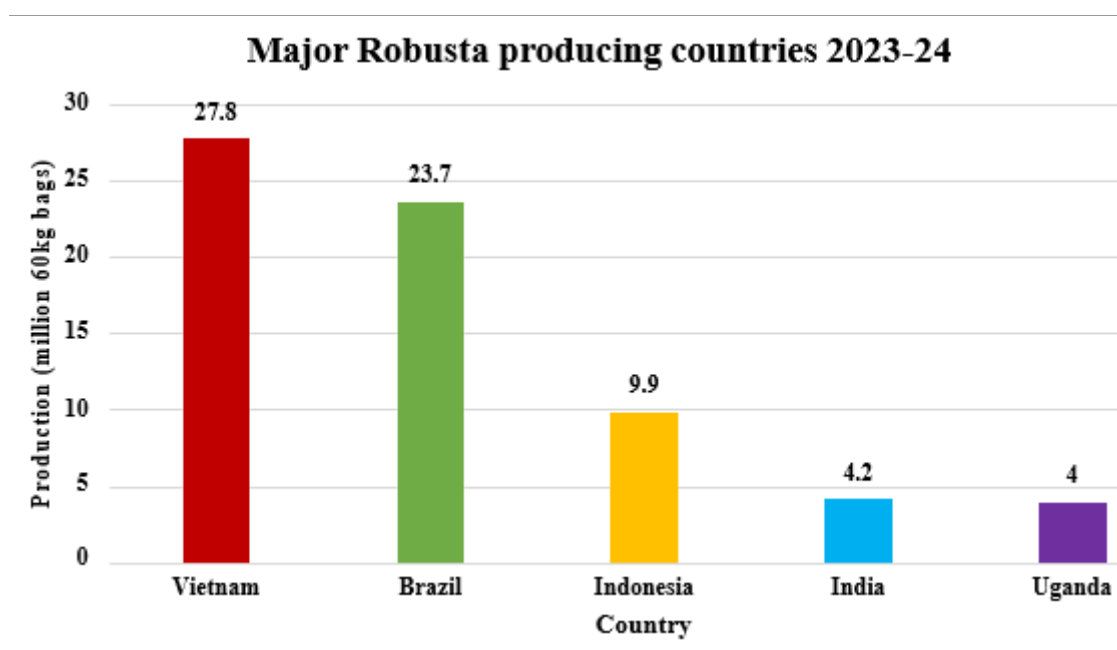


Figure 2. Major *Robusta* producing countries 2023-24

3.4 Production system

Coffee is cultivated under a diverse range of production systems. The coffee production system differs in the level of shade, crop diversity, management intensity and use of external inputs. These systems range from traditional multi-layered agroforestry systems to canopy open monoculture system. In traditional systems, coffee is grown in the existing forest vegetation with limited disturbance and low use of external inputs. In traditional and commercial polyculture systems, coffee is grown along with shade trees, fruit trees, and other economically useful crops. Monoculture systems are a more intensive system in which coffee is cultivated as the main crop but maintained under a simple shade canopy. In contrast, a more intensive type of coffee system represents unshaded monoculture. In this type of system, coffee is cultivated with little or no shade. It has high plant density along with greater use of fertilizers and other inputs (Moguel *et al.*, 1999; Jha *et al.*, 2014) [9, 8].

In India, coffee is mostly cultivated under shade, this practice makes the production of coffee distinct from many other coffee-producing countries. The Coffee Board of India states that Indian coffee is grown under two-tier mixed shade canopy consisting of evergreen leguminous and non-leguminous trees. Coffee is intercropped with other crops such as pepper and fruit trees, making many Indian coffee farms a form of diversified agroforestry rather than a simple monoculture. Besides this, in areas like Wayanad and Araku Valley small-holder and tribal coffee farmers use low-input or follow natural farming practices, with limited use of chemical fertilizers and plant-protection chemicals (GoK, 2026; Karki *et al.*, 2021) [10]. Hence, coffee plantations in India are broadly characterized by intercropped coffee grown as shade-based agroforestry system. (Coffee Board of India, 2026) [11].

Climatic impacts on coffee production systems

The direct effects of Climate change on coffee production includes heat and moisture stress, whereas through changes in pest and disease pressure, pollination services, coffee quality, production costs, and prices it indirectly affects yield of coffee. Recent studies identified that *Robusta* is less sensitive to climate than *Arabica*. But *Robusta* has limited climate envelope and its production is may be at with rise

in temperature (Bunn *et al.*, 2015; Pham *et al.*, 2019; Davis *et al.*, 2026) [5, 12, 13]. Such impacts are also regionally variable because the impact of temperature and precipitation on coffee production are contingent upon altitude, soil moisture, shade management, variety, and time of occurrence of climatic stress (Bilen *et al.*, 2023; Byrareddy *et al.*, 2024) [14, 15]. The recent trends in *Robusta* coffee production also underline the resilience ability of the crop.

Effect of climate on production and productivity of coffee

Yield is one of the important economic parameters that are affected by climate change. Key climatic parameters that influence the physiological processes of coffee such as photosynthesis, flowering, fruit development, bean filling and maturation are temperature and precipitation. Climate change impacts coffee production not just at the time of the final harvest but it alters the timing and synchrony of phenological stages. The relationship between temperature and rainfall is especially important for the flowering of coffee (Ramirez *et al.*, 2010; Unigarro *et al.*, 2025) [16]. Flowers are stimulated by a dry period, but may become dormant if dry period is prolonged, after which rainfall stimulates flowering. Drought and erratic rainfall can cause flower drop and poor fruit set, as well as poor bean fill. However, if intense rainfall occurs during the flowering period, flower drop and reduced pollination and fruit set will occur. With an increase in temperature evapotranspiration could be improved and lead to water stress situation, reduced photosynthetic activity and impaired reproductive development. In this condition, yield and productivity of coffee is greatly affected. The findings of Bilen *et al.* (2023) [14] in the systematic review indicate that out of 42 studies assessing the direct impacts of climate change on coffee yield, 35 studies reported negative impacts, suggesting coffee is highly affected by climate change.

Coffee yield is most dependent on climatic factors, namely temperature. A reduction in the yield of *Robusta* coffee of 14 per cent (350-460 kg per hectare) has been observed for every 1 °C increase in mean temperature. This result indicates that even though it can withstand the heat better than *Arabica*, *Robusta* coffee is still susceptible to higher temperatures and is likely to suffer significant losses in yield under warmer conditions (Kath *et al.*, 2020) [17]. A study by Byrareddy *et al.* (2024) [15] also revealed temperature as the key cli

matic factor driving *Robusta* yield, in particular post-flowering maximum temperature. The mean increase in maximum temperature from 23 °C to 28 °C resulted in reduction in yield of around 700 kg ha⁻¹. With an increase in temperature by 1 °C, yield is reduced by 140 kg ha⁻¹. A regional model estimated an average decline of 10-20 per cent of yield under a 2 °C global warming scenario. Other than temperature, yield reduction of 400 kg ha⁻¹ was observed with decreasing post-flowering rainfall from 3000 mm to 2000 mm. A stepwise multiple regression analysis revealed that the maximum temperature, relative humidity and rainfall had a significant association with *Robusta* yield (Jayakumar *et al.*, 2016) [18]. Further, blossom showers also affect *Robusta* yield compared to total annual rainfall, highlighting the importance of timing rather than total rainfall intensity (Jayakumar *et al.*, 2017) [19].

In *Arabica* coffee higher night-time temperatures has negative physiological impacts and poor reproductive development. For each 1 °C increase in the minimum temperature of the *Arabica* coffee, a yield reduction of 137 ± 16.87 kg ha⁻¹ was recorded (Bunn *et al.*, 2015) [5]. Noronha *et al.* (2026) [20] found that hot days during the grain filling stage are especially critical. Lack of water at critical periods of plant development impedes vegetative growth, flowering, berry development and filling. Excessive rain during harvest however, affects the crop condition and harvest. According to Xiao *et al.* (2025) [21], the rainfall in the flowering period and the berry ripening period positively influenced the coffee yield, while the rainfall during the harvesting period negatively affected coffee yield. Therefore, the intensity and timing of climatic factors influence the production of *Arabica* coffee

Occurrence of pests and diseases

Climate change creates favourable conditions for the development of pests and reproduction of pathogens. Warmer temperatures speed up insect development by increasing number of generations per year. At the same time, changes in rainfall and humidity favour the growth of fungal pathogens. Climate change indirectly affects the distribution and severity of the pests and diseases. Coffee plantations are vulnerable to coffee berry borer and coffee white stem borer (*Xylotrechus quadripes*) infestation influencing suitability of coffee producing areas (Pham *et al.*, 2019; Bilen *et al.*, 2023; Magrach *et al.*, 2015) [12, 14, 22]. Reddy *et al.* (2022) [23] observed that the white stem borer of coffee was positively related to maximum temperature, minimum temperature and negatively related with rainfall and relative humidity in Karnataka. In India, heavy infestation by white stem borer can cause 17.8-20.0 per cent economic yield loss in coffee (Pandey *et al.*, 2022) [24]. Various diseases such as *Hemileia vastatrix* (coffee rust) have strong relationship with temperature, rainfall and humidity. Coffee leaf rust dynamics have been seen to be strongly related to minimum temperature and vapour pressure deficit in recent ten year study carried out at Central Coffee Research Institute, Karnataka. Without adequate control, losses due to coffee leaf rust can reach up to 30 per cent of yield (Machenahalli *et al.*, 2026) [25]. Disease pressure is more likely to impact the coffee production system in *Arabica* than *Robusta*, but can increase the chemical and labour requirements. The effects of the climatic variables on the incidence of pests and diseases in *Arabica* and *Robusta* are represented in Table 1.

Table 1. Influence of climatic variables on pest and disease incidence in *Arabica* and *Robusta* coffee

Aspect	<i>Arabica</i>	<i>Robusta</i>	Reference
Temperature sensitivity	<i>Arabica</i> has a narrower climatic range and is more sensitive to temperature changes.	<i>Robusta</i> is relatively more tolerant than <i>Arabica</i> ; however, climate change can still alter pest and disease dynamics in <i>Robusta</i> -growing areas.	Bunn <i>et al.</i> (2015); Bilen <i>et al.</i> (2023); Davis <i>et al.</i> (2026)
Major disease	Coffee leaf rust is an important disease of <i>Arabica</i> . Its development is influenced by temperature, humidity, and moisture conditions. It can cause 30 per cent yield loss if not managed.	<i>Robusta</i> is affected by fungal diseases, including black rot, stalk rot, leaf spot, and berry diseases, particularly under prolonged and wet conditions.	Bilen <i>et al.</i> (2023); Toniutti <i>et al.</i> (2017); Machenahalli <i>et al.</i> (2026); Davis <i>et al.</i> (2026)
Major pests	Coffee white stem borer, coffee berry borer, and leaf miner are important pests associated with <i>Arabica</i> causing 17.8 to 20.0 per cent yield losses. Climatic conditions can influence their activity and distribution.	Coffee berry borer and other insect pests affect <i>Robusta</i> and cause 40 to 80 per cent production loss. White stem borer has also been reported in <i>Robusta</i> plantations, although <i>Arabica</i> is its preferred host.	Reddy <i>et al.</i> (2022); Haraprasad <i>et al.</i> (2001); Jaramillo <i>et al.</i> (2009); Ranjeeth Kumar <i>et al.</i> (2022); Bilen <i>et al.</i> (2023); Pandey <i>et al.</i> (2022)
Rainfall effect	Excessive or erratic rainfall can increase canopy wetness and humidity, favour fungal disease development and influence pest and pathogen dynamics.	Prolonged and erratic rainfall can maintain canopy wetness and favour fungal diseases and berry infections.	Pham <i>et al.</i> (2019); Bilen <i>et al.</i> (2023); Machenahalli <i>et al.</i> (2026)
Indian	In Karnataka, white stem borer	In Kodagu, white stem borer	Reddy <i>et al.</i>

(continued on next page)

Aspect	<i>Arabica</i>	<i>Robusta</i>	Reference
evidence	emergence was positively associated with maximum and minimum temperature and negatively associated with rainfall and relative humidity.	adult emergence showed a positive relationship with maximum temperature and a negative relationship with rainfall.	(2022); Machenahalli <i>et al.</i> (2026); Ranjeeth Kumar <i>et al.</i> (2022)
Overall implication	<i>Arabica</i> is generally more vulnerable to climate-related pest and disease risks because of its greater climatic sensitivity and susceptibility to important pests and diseases.	<i>Robusta</i> 's greater heat tolerance does not mean complete resistance to climate-related pest and disease risks. Evidence specific to <i>Robusta</i> remains more limited than for <i>Arabica</i> .	Bunn <i>et al.</i> (2015); Bilen <i>et al.</i> (2023); Davis <i>et al.</i> (2026)

Change in quality of coffee

Climatic parameters have an influence on the physical, chemical and sensory characteristics of the coffee beans. They alter the bean-filling time and development of secondary metabolites like caffeine, chlorogenic acids, lipids, sugars and volatiles. Secondary metabolites in coffee beans contribute to aroma, flavour, acidity, body and overall quality of the cup of coffee (Sarzynski *et al.*, 2023) [26]. Higher altitudes and decreased light exposure helps in developing better sensory properties in coffee beans. Coffee quality is also influenced by water stress. The moderate water stress during fruit filling was beneficial and excess water stress and rain may negatively impact quality. Increased temperature may shorten bean filling time by speeding up bean maturity. This process changes the composition of sugars, lipids, and in the coffee bean, resulting in low quality beans (Ahmed *et al.*, 2021) [27]. Piato *et al.* (2020) [28] reported that shade management in *Robusta* coffee plantations can have an impact on yield and quality. Based on the results of the meta-analysis, the moderate shade level promoted better growth and productivity, while the high shade levels (around 30 per cent and above) were linked with decreased beverage quality. Climate adaptation by managing shade must therefore take into account both temperature protection and providing sufficient light.

Effect on the suitability and geography of an area

Climate change is gradually reshaping where coffee can be grown, making some traditional coffee-growing areas less suitable while opening up new opportunities in regions that were previously considered unsuitable for coffee cultivation. Bunn *et al.* (2015) [5] estimated that climate change would lead to a loss of about 50 per cent of the geographic space suitable for growing coffee worldwide by 2050, mostly at low latitudes and low elevations. This suggests the potential for a change in coffee growing systems to the higher elevations. Despite its higher heat tolerance, their analysis indicated that *Robusta* may lose a significant proportion of its areas as well. Some of the high impact scenarios resulted in estimated global losses in the suitability of the *Robusta* areas of around 54 per cent. Similar findings were identified by Magrach *et al.* (2015) [22], *Robusta* could lose approximately 55 ± 6 per cent of its current suitable area by 2050. But, areas such as Amazon Basin and Southeast Asia will be better adapted to producing *Robusta* coffee, leading to a growth in the total area. These projections are regional in nature, however, scenarios at the global level may not necessarily reflect the scenarios that would happen at the district level because the future suitability for the district is dependent on future temperatures and climate.

Effect on pollination services

The pollination services are especially significant in *Robusta*, which is self-incompatible in nature and requires cross pollination. Pollinator abundance, species distribution and activity can be impacted by extreme weather. Excessive rain on the flowering period can disrupt insect activity and prevent pollination from taking place. Significant changes in pollinator numbers and locations due to extended periods of drought and temperatures can lead to reduced fruit set and yields. Imbach *et al.* (2017) [29] estimated that bee richness would reduce by 8-18 per cent in future climate suitable areas for coffee.

However, the study was conducted on *Arabica* plantations in Latin America, not on Indian *Robusta* plantations. This shows the importance of need to consider the effects of climate change on ecosystem services along with the direct effects on the coffee plant. Therefore, protecting shade trees and the surrounding vegetation can help regulate temperatures within coffee plantations and reduce moisture stress in coffee plants.

Price risk

Coffee production can decline during periods of drought, heavy precipitation, frost, extreme heat, pest and disease attacks. International prices rise when supply decreases and demand is relatively constant. Conversely, when production increases, the price of the coffee may fall. So, international prices for coffee are sensitive to climate change. International prices for coffee rose 38.8 per cent in 2024. This increase was due to interruptions in coffee supplies associated with unfavourable weather in key producing nations (FAO, 2025) [3]. During 2023-24, dry weather in Vietnam and excess rainfall in Indonesia caused a decrease in coffee production of 20 per cent and 16.5 per cent respectively. The lower production in Brazil was due to hot and dry weather, which lowered the production estimate from a projected 5.5 per cent year-on-year growth to a 1.6 per cent decline. The losses created a tighter global supply and pushed up the international prices.

A year later, in December 2024, prices of *Arabica* rose 58 per cent, while *Robusta* prices increased 70 per cent (FAO, 2025) [3]. Thus, poor weather conditions in the key producing countries can impact farm-level production and the global coffee supply, trade and prices. A production shock can lead to higher market prices, but a single farmer whose production is affected has less coffee to sell. If the farmer's production is reduced then the higher market price does not mean that the farmer is getting a better return. Farmers may also face higher adaptation costs affecting smallholder coffee growers. In a comparative review in India, Patil *et al.* (2025) [30] pointed out that increased temperatures, variability in rainfall, pest and disease, and changes in agroecological zones are the factors that can influence production costs, stability of the supply chain, and price volatility in the international market.

Switching to adaptation strategies raises production costs for farmers. Farmers incur additional costs for irrigation and mulching to manage drought and heat stress. Frequent monitoring and increased plant protection chemical usage as climate change increases pest and disease incidence, increase production costs. Thereby decreasing the profits from coffee plantations. Koutouleas *et al.* (2022) [31] noted that there are costs associated with agroforestry and shade management, such as the cost of establishing and maintaining shade trees, irrigation infrastructure, drainage, pruning, and managing pests.

Coffee production adaptation strategies

Coffee farming adaptation to climate change is a change in farm management procedures. Coffee is produced as a perennial crop that has a long production life, so adaptation means that both short-term (intra-farm) and long-term (intra-production-system) changes are required. There are various options for adapting to climatic risks and ensuring the productivity and resilience of coffee farming systems.

Agroforestry and scientific shade management

Agroforestry is a land-use system that combines perennial woody plants and agricultural crops on the same land (FAO, 2018) [32]. Coffee is typically grown in shade and shade-tree management is a key aspect of coffee-based agroforestry systems. Based on the observation on 314 coffee farms in Chikmagalur, Coorg, Wayanad, shade management is also considered to be an important factor in the climate adaptation of Indian *Robusta* system (Byrareddy *et al.*, 2024) [15]. Proper shade helps to control the temperature, light intensity and evapotranspiration in the plantation altering the microclimate. Fallen leaves from shade tree add organic matter to soil and aids in enhancing the nutrient uptake by the plants. They prevent soil erosion, improve water infiltration and help to support biodiversity. They are useful in minimizing exposure of coffee plants to heat and short-term moisture stress. It has been estimated that the losses due to climate effects on production can be reduced by about 31 per cent, losses in pest and disease incidence by 24 per cent, and loss in quality by 19 per cent by proper shade management (Patil *et al.*, 2025) [33]. More shade intensity can inhibit photosynthesis and raise humidity in the coffee plantation. This results in reduction of coffee production and increase the presence of pests and diseases. An adequate canopy density is necessary to get good light penetration into the plantation. So, proper pruning of shade trees prior to the rainy season can help to manage canopy cover and assure desirable microclimatic conditions. Along with proper density, type of shade trees also matters. Native shade trees promote soil health and ecological integrity. In Agroforestry coffee systems, combining a variety of native shade trees have been reported to promote more diverse tree species growth and increases carbon storage compared to those dominated by exotic shade species (Guillemot *et al.*, 2018; Koutouleas *et al.*, 2022; Bhagwat *et al.*, 2005; Pham *et al.*, 2019) [35, 31, 34, 12]. In the Western Ghats of India, coffee plantations are typically agroforestry production systems. They enhance the resilience of coffee plantations to some climate stresses than other production systems. The advantages of agroforestry, however, are only realized if shade trees are managed appropriately. If shade canopy is too dense, or if it is a type of tree that does not grow well with coffee, it can compete with the coffee plants for light, water and nutrients. Thus, it is important to select shade tree species along with maintenance of appropriate shade levels. So that the productivity and biodiversity of coffee is preserved in the face of a changing climate (Nesper *et al.*, 2017; Guillemot *et al.*, 2018; Jha *et al.*, 2014) [36, 35, 8].

Soil-moisture conservation

Sloping land has a high risk of soil erosion and nutrient losses during monsoons. Soil and moisture conservation practices are necessary measures in these areas. Long dry spells in post monsoon period may limit soil moisture available to plants. Hence mulching, contour trenches, terracing, cover crops, basin management and addition of organic matter should be adopted. They help to increase water infiltration, decrease surface runoff and soil erosion, and increase water holding capacity of soil. To minimize surface runoff, contour planting and terracing on moderate to steep slopes, and staggered trenches or cradle pits across the slope are recommended. Mulching and use of cover crops help prevent moisture loss due to evaporation and keep the soil temperature more stable. Organic matter aids in improving soil structure and water holding capacity (Coffee Board, 2026) [37]. Mulching, terracing and other soil-moisture conservation techniques were found to be likely to benefit coffee farmers, however, these practices are labour intensive and may be restricted in adoption among smallholder farmers (Patil *et al.*, 2025) [33]. It is also important to note that soil and water conservation is critical in minimizing soil loss; research along the Western Ghats indicates significant erosion hazards in monsoon dominated mountain areas (Achu *et al.*, 2023) [38]. Water scarcity was also found to be an important source of vulnerability in regional studies, with improved irrigation and soil-based management resilience of farms can be achieved (Anjitha *et al.*, 2024) [39].

Supplemental irrigation and efficient water management

Water availability during critical times in the coffee's development cycle is important to productivity. It requires optimum rainfall of 1500 to 2000 mm per year (Unigarro *et al.*, 2025) [16]. The most critical stages in coffee for irrigation are flowering, fruit set or backing period, fruit expansion and filling of a bean. Water requirement in *Robusta* coffee is of special significance. Considerable variation in the timing of flower-bud initiation, flowering, and fruit setting can be observed across regions. In the major *Robusta* production areas of Karnataka and Kerala flowering occurs during the dry season. The Coffee Board suggests the blossom showers of 25-40 mm for *Robusta* in February-March followed by backing showers (50-75 mm) in March-April. They play a key role in providing successful flowering and holding newly set fruit. Watering can be given by sprinklers during these periods to enhance blossom and fruit set in *Robusta*. Drip or micro-irrigation can deliver water close to the root zone to further improve water-use efficiency. Thus, access to reliable water sources, rainwater harvesting and improved irrigation systems can decrease reliance on rainfall and boost coffee yield. Murugan *et al.* (2022) found future climate scenarios are likely to cause significant changes in both temperature and precipitation over the Western Ghats hotspots of coffee production. They found drought, irrigation-water scarcity, pest and disease issues, and soil degradation to be the primary problems growers reported. The study suggested to enhance the density and diversity of shade-trees, multiple canopies and irrigation and fertigation in dry regions as adaptation measures.

Diversification and mixed cropping

Crop diversification can enhance the resilience of the coffee production system and farmers when their coffee production or price is impacted by climatic and market shocks, by generating an alternative source of income and food. The study in Kodagu, India, revealed that intercrops like pepper, cardamom and arecanut added 16-31 per cent to the farmer's income, highlighting the economic significance of coffee agroforestry diversification (Chethana *et al.*, 2009) [40]. Economic considerations should not be the only factor in choosing companion crops; their climatic control properties should be considered as well. Plants that offer appropriate shade, soil cover, nutrient cycling, moisture conservation and mitigating water stress are beneficial. Chengappa *et al.* (2017) [41] found that diversification of the coffee production systems corresponded with reduced perceived climate risk. Crop diversification can also contribute to less food insecurity apart from providing income security (Anderzen *et al.*, 2020) [42]. A strategy for diversification with compatible crops depending on the local climate, soil conditions, and water availability, also the canopy needs of the coffee should be developed. A good diversified system can generate extra income sources and enhance soil health and a more favourable microclimate for coffee production. Diversification of coffee, especially by intercropping with banana was identified as an adaptation strategy by Patil *et al.* (2025) [33], which can help alleviate heat stress and generate extra income.

Integrated pest and disease management (IPDM)

Climate change can alter the distribution, development, and severity of coffee pests and diseases. Integrated pest and disease management (IPDM) combines regular monitoring and early detection of pests and diseases with cultural, biological, mechanical, and chemical methods. These methods help in maintaining pest and disease populations below economically damaging levels. Adopting resistant varieties, optimum shade management, pruning, field sanitation, conservation of natural enemies, biological control agents, and timely application of need-based plant protection products can reduce crop losses while limiting excessive dependence on chemical pesticides. Such an integrated approach provides greater flexibility to respond to changes in pest and pathogen behaviour under future climatic risks (Valladares *et al.*, 2018) [43]. Strengthening climate-based pest and disease surveillance and developing location-specific IPDM strategies will therefore be important

for improving the resilience of coffee production systems (Coffee Board of India, 2021) [44].

Developing climate-resilient varieties and rootstocks

5.6. Developing climate-resilient varieties and rootstocks

Adaptation measures such as agroforestry, shade management and soil-moisture conservation can be implemented immediately in the farm and benefits can be seen in short term. whereas, genetic improvement is a long-term adaptation strategy. Breeding programmes should target on developing varieties and clones with greater tolerance to climate stresses without compromising coffee yield and quality.

Research institutions should focus on region-specific breeding programmes taking into account local climate and production conditions. Researcher attention should be placed on developing and evaluating locally suitable varieties, clones and rootstocks that are better adapted to future changes in temperature, rainfall and pest and disease pres-

sure. Strengthening coordinated research networks among breeding institutions, universities, extension agencies and coffee growers could speed up the identification, testing and dissemination of climate-resilient planting materials.

India already has established breeding programme through the Coffee Board and Central Coffee Research Institute. For *Robusta*, the development and dissemination of clones with improved water-use efficiency and greater tolerance to heat and water deficit are relevant. Recent experimental evidence from the Central Coffee Research Institute showed that grafting *Robusta* scions onto selected *Arabica* rootstocks can improve physiological performance under water-deficit conditions. Hence, rootstock selection can be a potential adaptation technology in developing resilient varieties (Kumar *et al.*, 2025) [45]. The *Arabica* breeding programme aims to combine characteristics like high productivity and quality with pest and disease resistance. Along with these traits, higher adaptability of varieties makes the coffee production climate resilient.

Table 2. Integrated pest and disease approaches in major pest and diseases of coffee.

Pest/disease	Major IPDM approaches	References
Coffee berry borer	Monitoring, field sanitation, removal of remaining berries, attractant-based monitoring/trapping, biological control and integration of control measures	Damon (2000); Aristizabal <i>et al.</i> (2016); Rodriguez- Gallo <i>et al.</i> (2024); Rimbing <i>et al.</i> (2023)
White stem borer	Monitoring, tracing and removal of infested plants, cultural and mechanical control and timely integrated management	Venkatesha and Dinesh (2012); Kumar <i>et al.</i> (2020)
Coffee leaf rust	Resistant varieties, monitoring, shade management and chemical control using recommended fungicides	Narayana (2013); Boudrot <i>et al.</i> (2016); Rodriguez- Gallo <i>et al.</i> (2024)
Multiple pests and diseases	Crop-loss assessment, identification of pest and disease drivers, ecological regulation and sustainable crop-health management	Avelino <i>et al.</i> (2018)

Table 2. Adaptation strategies to climate change in coffee cultivation

Adaptation strategy	Major practices	Role in climate adaptation	Key references used
Agroforestry and scientific shade management	Suitable shade- tree selection, optimum shade density, pruning	Regulates canopy temperature and evapotranspiration; reduces heat and short-term moisture stress; improves soil organic matter, infiltration and biodiversity; supports yield and quality of coffee	FAO (2018); Byrareddy <i>et al.</i> (2024); Patil <i>et al.</i> (2025); Guillemot <i>et al.</i> (2018); Nesper <i>et al.</i> (2017)
Soil-moisture conservation	Mulching, contour trenches, terracing, cover crops, basin management, addition of organic matter	Reduces runoff, erosion, and evaporation; improves infiltration, soil structure, water-holding capacity, and soil moisture during dry periods	Coffee Board (2026); Patil <i>et al.</i> (2025); Achu and Thomas (2023); Anjitha <i>et al.</i> (2024)
Supplemental irrigation and efficient water management	sprinkler irrigation, drip/micro-irrigation, rainwater harvesting and storage	Maintains water availability during flowering, fruit set, fruit expansion and bean filling; reduces dependence on erratic rainfall and helps stabilize coffee yield	Coffee Board; Murugan <i>et al.</i> (2022)
Diversification and mixed cropping	Intercropping with pepper, cardamom, arecanut, banana, fruit trees and other compatible crops	Provides additional income and food; reduces dependence on coffee; can improve soil cover, nutrient cycling, moisture retention and microclimate	Chethana <i>et al.</i> (2009); Chengappa <i>et al.</i> (2017); Anderzen <i>et al.</i> (2020); Patil <i>et al.</i> (2025)
Integrated pest and disease management (IPDM)	Monitoring and early detection	Helps respond to climate- induced changes in pest and	Valladares <i>et al.</i> 2018; Coffee Board of India (2021)

(continued on next page)

Adaptation strategy	Major practices	Role in climate adaptation	Key references used
Climate-resilient varieties and rootstocks	Breeding and selection for drought, heat, pest and disease tolerance; improved clones and rootstocks; grafting	disease incidence; reduces crop losses and dependence on pesticides; improves preparedness through surveillance Provides long-term adaptation by improving tolerance to climatic stresses while maintaining yield and quality	Kumar <i>et al.</i> (2025); Coffee Board of India (2026)

Mitigation strategies in coffee production

Coffee production is a source of GHG emissions at different stages, including cultivation, harvesting, processing, transport, roasting and consumption. The carbon footprint of primary coffee production is estimated at 2.18 kg CO₂e per kg of green coffee beans. Fertiliser production and application, particularly nitrogen fertilisers, contributes around 65-100 per cent of emissions in most production systems (Cornelius *et al.*, 2025) [46]. The manufacture process requires energy, resulting in CO₂ emissions. Meanwhile, their application to the soil can lead to N₂O emissions, further increasing the carbon footprint of coffee production (San Martin Ruiz *et al.*, 2021) [47].

Site-specific fertilizer application and slow-release fertilizers can help lower N₂O emissions by improving nitrogen use efficiency. Sarkis *et al.* (2023) [48] found that replacing conventional urea with other types of urea fertilizers containing urease inhibitor and ammonium nitrate reduced N₂O emissions by 50.6 per cent and 78.5 per cent, respectively. Other emissions come from the fuel and energy used on farms, the manufacture and transport of farm inputs, soil disturbance, and clearing existing vegetation when new coffee areas are established.

Post-harvest processing is also a source of GHG emissions in coffee production. Wet processing uses energy for pulping, drying, and other operations. Wet processing can therefore have a notable effect on the overall climate impact of coffee (Cheron-Bessou *et al.*, 2024) [49]. Wastes from coffee processing such as pulp and husk can be composted and returned to the farm, where they can supply nutrients and reduce the need for external inputs. Further processing of coffee, such as roasting, grinding, packaging, and transportation, emits greenhouse gases. Roasting and grinding require heat and electricity. At the consumer level, the fuel or electricity used to prepare coffee contributes further emissions. Barreto Peixoto *et al.* (2023) [50] showed that fertiliser use, wastewater from wet processing, and coffee preparation can make up a considerable part of emissions across the coffee chain. This highlights the need to address emissions at different stages of coffee production and consumption, rather than focusing only on farm-level practices.

Recent evidence from India also shows that emissions can occur during post-harvesting of coffee. A life-cycle study of *Robusta coffee* in Wayanad, Kerala, estimated a carbon footprint of 0.62 kg CO₂e per kg of green coffee when local transport, processing, packaging, roasting and grinding were considered (Iglesias *et al.*, 2025) [51]. In this scenario, roasting accounted for about 78 per cent of the assessed footprint. In another scenario, where green coffee was transported from India to the Netherlands, the carbon footprint was estimated at 0.38 kg CO₂e per kg of green coffee. Sea transport contributed about 66 per cent of this footprint. However, this estimate does not represent the entire farm-to-consumer footprint, as cultivation and harvesting were not included in the study (Iglesias *et al.*, 2025) [51].

Agroforestry is an important mitigation option in coffee production because it can help reduce greenhouse gas emissions and increase carbon storage in the farm. Cornelius *et al.* (2025) [46] reported a median CO₂ removal rate of 17,676 ± 3,971 kg CO₂ ha⁻¹ year⁻¹ in agroforestry systems, compared with 6,990 ± 3,405 kg CO₂ ha⁻¹ year⁻¹ in unshaded coffee systems. The trees in coffee agroforestry systems add biomass that can store carbon both above and below the soil. Research has found that shaded coffee systems generally store more

carbon than coffee grown without shade. In Uganda, coffee grown with trees had higher soil organic carbon stocks than coffee monocultures, showing that shade trees and other vegetation can increase carbon storage in the soil (Tumwebaze *et al.*, 2016) [52].

Shade-tree biomass was an important significant factor affecting the total carbon stored by coffee farms in Puerto Rico, and shade trees stored more carbon than those without them (Lugo-Perez *et al.*, 2023) [53]. In the Western Ghats of India, native coffee agroforestry systems stored same amount of carbon as nearby forests. Agroforestry systems with exotic *Grevillea robusta* had lower carbon storage and less tree diversity (Guillemot *et al.*, 2018) [35]. Tree density and the biomass of shade trees decide the amount of carbon storage in agroforestry systems. Therefore, well-managed and diversified shade-tree systems can help mitigate climate change in the coffee landscape through higher carbon storage and reducing the net amount of carbon released into the atmosphere.

Reducing these emissions is crucial because coffee is a globally traded perennial crop cultivated over a large area and climate change is simultaneously increasing the vulnerability of coffee production. Agroforestry-based coffee production systems lower GHG emissions from coffee production while improving the environmental sustainability and resilience of production systems. Therefore, mitigation in coffee production should follow a whole-value-chain approach, combining efficient fertilizer and nutrient management, maintenance and restoration of shade trees and agroforestry systems, improvement of soil carbon management, reduced dependence on fossil fuels, efficient water and energy use, improved wastewater and coffee-residue management, renewable energy use, low-emission processing technologies, and efficient transportation and packaging. These practices can lower GHG emissions while improving soil health, supporting biodiversity, using resources more efficiently, and promoting the long-term sustainability of coffee production.

Conclusion

Climate variability poses problems for coffee farming. It affects coffee production, increases the risk of pests and diseases, lowers coffee quality, drives up production costs and makes prices unstable. Farmers can reduce these risks by using adaptation methods like agroforestry, shade management, soil and water conservation, supplemental irrigation, Integrated pest and disease management and planting coffee varieties that work well in changing climates. These strategies are region specific. Their benefits depend on climate, altitude, soil type, farming practices and how crops are managed. The review also identifies that while a lot is known about Arabica coffee there is still little research on Robusta-based systems. More region-specific studies are needed to find smart ways to help farmers adapt and manage climate risks in different parts of the world.

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