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Impact of climate change on coffee price: A comparative review with focus on India and other major coffee-growing countries

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Abstract
Coffee is among the most economically significant agricultural commodities globally, cultivated in over 70 countries and sustaining the livelihoods of more than 125 million people, many of whom are smallholder farmers. However, the sector faces mounting risks from climate change, including rising temperatures, erratic rainfall, increased pest and disease prevalence, and shifting agroecological zones. These changes threaten not only yield and bean quality but also the economic viability of coffee production, particularly in vulnerable regions. This paper provides a comparative analysis of the biophysical and economic impacts of climate change on coffee production and pricing, with a focus on India and four major coffee-producing countries: Brazil, Vietnam, Colombia, and Ethiopia. Drawing from current scientific literature and institutional data, the review examines key climate stressors temperature rise, hydrological variability, pest outbreaks and their consequences on crop performance, input costs, supply chain stability, and international price volatility. The analysis reveals that India, despite its relatively smaller global market share, faces climate risks comparable to those in other developing producer nations due to its reliance on arabica coffee in fragile hill ecosystems and the limited adaptive capacity of smallholders. In contrast, Brazil and Vietnam exhibit stronger institutional responses and technological capacity for adaptation. The review concludes with policy recommendations for enhancing climate resilience in India's coffee sector, emphasizing research, finance, infrastructure, and integrated governance. Strengthening these areas will be essential for ensuring long-term sustainability and competitiveness in the face of escalating climate challenges.

Keywords: Climate change, coffee production, price volatility, agricultural policy, climate resilience

1. Introduction

Coffee is among the most economically significant agricultural commodities in the world, serving as a primary export product for more than 50 developing countries and a source of livelihood for approximately 125 million people, many of whom are smallholder farmers (International Coffee Organization [ICO], 2020) [12]. The two most commercially important species *Coffea arabica* (arabica) and *Coffea canephora* (robusta) have distinct ecological requirements and market dynamics, but both are highly sensitive to climatic conditions. Arabica, which commands higher market prices due to its superior flavor profile, requires cooler temperatures (optimal range 18-22 °C) and higher elevations, while robusta is more heat-tolerant, thriving at temperatures between 22-30 °C and at lower elevations (DaMatta *et al*., 2007; Bunn *et al*., 2015) [8, 26].

The cultivation of coffee is inherently climate-dependent. Optimal coffee growth depends on specific combinations of temperature, precipitation, humidity, altitude and soil conditions. Even small deviations from these optimal conditions can lead to yield reductions, increased pest and disease prevalence, and compromised bean quality (Ovalle-Rivera *et al*., 2015) [26]. In recent decades, the effects of climate change including rising average temperatures, shifting precipitation patterns, more frequent extreme weather events, and the increased incidence of pests and pathogens have begun to disrupt traditional coffee-growing regions across the globe (Jaramillo *et al*., 2011; Bunn *et al*., 2015) [15, 26]. These disruptions not only impact local agricultural economies but also reverberate through global coffee supply chains, leading to significant price volatility.

The economic impacts of climate-induced disruptions to coffee production are multifaceted. On the supply side, climate change affects the amount and quality of coffee harvested, which can lead to decreased exports, increased production costs, and long-term shifts in suitable cultivation zones. On the demand side, price volatility triggered by unpredictable supply shocks undermines market stability and can disproportionately affect low-income producers who lack the financial resilience to absorb losses or adapt to new conditions (Zhang *et al*., 2020) [27]. Coffee markets are particularly sensitive to such disruptions due to the crop's relatively inelastic demand and the time lag between planting and production, which limits short-term supply adjustments (ICO, 2022) [28].

India, while not the largest coffee producer globally, holds a unique position in the international coffee market. As of 2023, India contributed about 3-4% of global coffee production, with Karnataka, Kerala, and Tamil Nadu being the major producing states (Coffee Board of India, 2023) [6]. Indian coffee is distinguished by its predominantly shade-grown cultivation and frequent intercropping with spices such as pepper and cardamom, contributing to its distinctive flavor and ecological sustainability. However, Indian coffee cultivation is not immune to the impacts of climate change. In recent years, growers have reported irregular monsoon patterns, prolonged dry spells, increased incidence of white stem borer in arabica coffee, and post-harvest diseases linked to unseasonal rainfall (Ninan & Sathyapalan, 2005; Bhadra *et al*., 2021) [24, 4]. These environmental stressors have led to inconsistent yields, quality degradation, and fluctuating farm-gate prices.

While climate change is a global phenomenon, its effects on coffee production and pricing are region-specific, influenced by local agroecological conditions, adaptive capacity, infrastructure, and policy support. For instance, Brazil and Vietnam currently the top two global producers benefit from extensive mechanization, climate-resilient varietal research, and export-oriented supply chains. In contrast, smallholder-dependent systems in Ethiopia and India face significant constraints in terms of capital, access to climate services, and institutional support (Laderach *et al*., 2017; Moat *et al*., 2017) [17, 19].

This review aims to synthesize recent scientific findings on how climate change is influencing coffee production and pricing across major producing regions, with a specific focus on India in comparison with other leading coffee-exporting countries such as Brazil, Vietnam, Colombia, and Ethiopia. By analyzing both biophysical and economic dimensions, this review contributes to a deeper understanding of how global and regional coffee markets are being reshaped by climate forces. The review also highlights adaptation strategies and policy responses that could help buffer against future price shocks and promote more sustainable, resilient coffee systems.

2. Biophysical Impact of Climate Change on Coffee Production

The biophysical impacts of climate change on coffee cultivation are multifaceted, involving changes in temperature regimes, precipitation patterns, relative humidity, extreme weather events, and biological stressors such as pests and diseases. These factors interact with local agroecological conditions to influence plant physiology, crop yields, and quality. As perennial crops with narrow climatic requirements, *Coffea arabica* and *Coffea canephora* (robusta) are particularly susceptible to such changes, making them useful indicators of climate sensitivity in tropical agriculture (Bunn *et al*., 2015; Ovalle-Rivera *et al*., 2015) [26].

2.1 Temperature Rise and Heat Stress

Among the most consistent climatic trends globally is the increase in average temperatures. Arabica coffee is highly temperature-sensitive, performing optimally within a narrow range of 18-22 °C. Exposure to temperatures above this threshold, especially during flowering and fruit development stages, can cause physiological stress, resulting in reduced photosynthetic efficiency, accelerated fruit ripening, poor bean filling, and ultimately lower cup quality (DaMatta *et al*., 2007) [8]. Robusta, while more heat-tolerant, also shows signs of stress when temperatures exceed 30 °C, particularly when accompanied by water scarcity.

Climate models predict that by 2050, up to 50% of the land currently suitable for arabica production may become unsuitable due to temperature increases alone (Bunn *et al*., 2015) [26]. In Brazil, for instance, average annual temperatures have increased by about 1.4 °C since the 1970s, significantly affecting arabica-growing regions such as Minas Gerais and Espírito Santo (DaMatta *et al*., 2019) [9].

In India, temperature anomalies during pre-monsoon months have affected flowering synchronization in arabica, leading to poor fruit set and uneven ripening (Coffee Board of India, 2023) [6]. Nighttime temperature increases are of particular concern, as they disrupt metabolic recovery in coffee plants, exacerbating heat stress.

2.2 Precipitation Variability and Hydrological Stress

Coffee cultivation requires not only adequate rainfall (typically 1200-2200 mm annually) but also consistent distribution throughout the growing season. Changes in rainfall patterns, including delayed monsoons, erratic rainfall, and extended dry periods, have been reported across all major coffee-producing regions (Ovalle-Rivera *et al*., 2015; Laderach *et al*., 2017) [26, 17]. Inadequate rainfall during the flowering season leads to incomplete anthesis, while excess rain during harvest promotes fungal infections and hampers post-harvest drying.

In India, irregular monsoon patterns particularly the increasing frequency of short dry spells followed by intense rainfall have led to both drought stress and waterlogging, which are harmful to root health and bean development (Bhadra *et al*., 2021) [4]. In Latin America, El Niño-Southern Oscillation (ENSO) events have been linked to lower yields due to droughts in Colombia and floods in Peru.

Hydrological stress also affects nutrient uptake, increases susceptibility to diseases like *Phoma* and *Colletotrichum*, and exacerbates the effects of other stressors such as heat and pests (Avelino *et al*., 2015) [3].

2.3 Increased Incidence of Pests and Diseases

Climate change is also intensifying the prevalence, geographical spread, and seasonal activity of coffee pests and diseases. The most notable among these is the coffee berry borer (*Hypothenemus hampei*), which has expanded its range to higher altitudes and latitudes due to warmer temperatures (Jaramillo *et al*., 2011) [15]. Once restricted to lower elevations (<1200 m), the pest is now found in coffee plantations over 1600 m in Colombia, Ethiopia, and Kenya.

The coffee leaf rust (*Hemileia vastatrix*), a fungal disease, thrives under high humidity and moderate temperatures (~21-25 °C). The devastating 2012-2013 outbreak in Central America was facilitated by atypically warm and wet weather, resulting in up to 40% yield losses in affected areas (Avelino *et al*., 2015) [3].

In India, the spread of white stem borer (*Xylotrechus quadripes*) has intensified due to warmer winter temperatures and lower relative humidity during larval stages, especially affecting arabica plantations in Karnataka (NCAER, 2020) [22]. Management becomes increasingly difficult as pest cycles desynchronize from conventional spraying schedules.

2.4 Declining Quality and Cup Profile

Apart from yields, climate change negatively impacts the sensory quality of coffee an increasingly important parameter in specialty markets. High temperatures accelerate the maturation of coffee cherries, leading to lower accumulation of sugars and aromatic precursors. This results in reduced bean density, undesirable acidity, and bland flavor notes (Laderach *et al*., 2017) [17].

Water stress during bean filling leads to uneven ripening and defective beans, while fungal infections during the post-harvest phase introduce off-flavors. In Ethiopia and Kenya, shifts in altitude-based suitability zones have been associated with decreased aromatic complexity, even in regions known for high-quality arabica (Moat *et al*., 2017) [19].

2.5 Shifting Agroecological Zones

As climate envelopes shift, traditional coffee-growing zones may become unsuitable, while new areas may emerge as viable. However, migrating coffee production to higher altitudes or latitudes is often constrained by land availability, forest conservation concerns, and lack of infrastructure.

In India, higher elevation zones in the Western Ghats and the Northeastern states like Arunachal Pradesh and Nagaland have shown emerging suitability under future climate projections (Coffee Board of India, 2023) [6]. However, such shifts pose challenges related to land rights, ecological fragility, and socio-economic feasibility.

Globally, adaptation through migration is more feasible in countries like Brazil and Vietnam due to relatively better infrastructure and land tenure systems. In contrast, Ethiopia and parts of India face greater institutional and ecological constraints to shifting production (Zhang *et al*., 2020) [27].

3. Comparative Analysis of Regional Climate Vulnerability: India vs. Brazil, Vietnam, Colombia, and Ethiopia

The vulnerability of coffee-producing countries to climate change varies considerably depending on their geographic location, species cultivated, socio-economic conditions, and institutional capacities. While the overall threat of climate change to global coffee production is well-established, the magnitude and nature of its impacts are highly region-specific. This section compares the climate vulnerability of India with that of Brazil, Vietnam, Colombia, and Ethiopia the world's major coffee-growing countries across key biophysical and socio-economic dimensions.

3.1 Framework for Comparative Vulnerability Assessment

Vulnerability to climate change is typically assessed through three interconnected dimensions: exposure, sensitivity and adaptive capacity (IPCC, 2014) [14].

Exposure refers to the degree to which a region is subjected to climatic variability (e.g., droughts, rising temperatures).

Sensitivity captures how strongly a region's agricultural systems are affected by that exposure.

Adaptive capacity reflects the ability of a system or society to adjust, cope, or transform in response to climate risks. This framework provides a useful basis for comparing coffee-producing countries.

3.2 Brazil

3.2.1 Exposure & Sensitivity

Brazil is the world's largest coffee producer, contributing over 35% of global output, with coffee grown mainly in Minas Gerais, Espírito Santo, São Paulo, and Bahia. These regions have experienced significant climate variability in recent decades. The 2014 and 2021 droughts, coupled with a frost event in 2021, caused major declines in arabica yields (DaMatta *et al*., 2019) [9]. These extreme weather events have become more frequent and severe, raising concerns about long-term suitability in traditional arabica zones.

3.2.2 Adaptive Capacity

Brazil has relatively high adaptive capacity due to its advanced research institutions (e.g., Embrapa), large commercial plantations, access to irrigation infrastructure, and strong export-oriented market systems. However, smallholders remain more vulnerable, particularly in northeastern regions (Laderach *et al*., 2017) [17].

3.3 Vietnam

3.3.1 Exposure & Sensitivity

Vietnam is the second-largest coffee producer globally, primarily cultivating robusta in the Central Highlands (e.g., Dak Lak, Lam Dong). While robusta is more heat-tolerant, Vietnam is increasingly facing risks related to rising night-time temperatures, water stress due to over-irrigation, and shifting rainfall patterns during the flowering and harvesting seasons (Nguyen *et al*., 2016) [23].

3.3.2 Adaptive Capacity

Vietnam has strong institutional support for agriculture, including government subsidies, irrigation programs, and replanting initiatives. However, heavy dependence on groundwater and monoculture systems increases ecological vulnerability. Continued expansion into forested areas also exacerbates environmental degradation.

3.4 Colombia

3.4.1 Exposure & Sensitivity

Colombia is a top exporter of high-quality arabica coffee, grown in the Andes at altitudes of 1200-2000 meters. The country has seen increased temperatures and rainfall variability, leading to more frequent and intense outbreaks of coffee leaf rust (*Hemileia vastatrix*) (Avelino *et al*., 2015) [3]. These outbreaks have periodically devastated yields, especially in zones where rainfall coincides with flowering.

3.4.2 Adaptive Capacity

Colombia has moderate adaptive capacity. The National

Federation of Coffee Growers (FNC) has developed rust-resistant varieties like Castillo and provided extension services. However, smallholder reliance on rainfed agriculture and lack of climate insurance limits resilience in many rural areas (Laderach *et al*., 2017) [17].

3.5 Ethiopia

3.5.1 Exposure & Sensitivity

Ethiopia is the genetic home of *Coffea arabica* and one of Africa's top coffee exporters. Coffee is primarily grown in forested highlands under shade canopies. Recent studies suggest that suitable arabica zones in Ethiopia may shrink dramatically by 2050, with a projected 39-59% loss in current viable land (Moat *et al*., 2017) [19]. Rising temperatures, erratic rainfall, and pest pressure have already reduced productivity in some areas.

3.5.2 Adaptive Capacity

Ethiopia has relatively low adaptive capacity. Most coffee is cultivated by smallholders with limited access to improved seeds, extension services, or credit. Infrastructural limitations and political instability further constrain the capacity to respond to climatic stress. Nonetheless, Ethiopia's rich coffee gene pool offers long-term adaptation potential through conservation and breeding.

3.6 India

3.6.1 Exposure & Sensitivity

India ranks as the 6th largest coffee producer, with cultivation concentrated in the Western Ghats (mainly Karnataka, Kerala, and Tamil Nadu). The country grows both arabica and robusta, with the latter dominating due to its better tolerance to rising temperatures. In recent years, Indian coffee plantations have faced increasingly erratic monsoons, dry spells, and post-monsoon flooding. Notably, arabica is declining in area due to increased vulnerability to pests such as the white stem borer and reduced profitability (Bhadra *et al*., 2021; Coffee Board of India, 2023) [4, 6].

3.6.2 Adaptive Capacity

India's adaptive capacity is mixed. On one hand, the Coffee Board of India supports research on drought- and pest-resistant varieties, and there are well-established intercropping and shade-grown systems that provide some buffer against heat and pests. On the other hand, the fragmented nature of landholdings, weak access to crop insurance, and limited irrigation in some regions constrain the ability of smallholders to respond effectively to climatic shocks (NCAER, 2020) [23].

3.7 Summary Comparison

Country	Dominant Species	Major Risks	Adaptive Capacity	Suitability Outlook (2050)	Smallholder Vulnerability
Brazil	Arabica & Robusta	Drought, frost, heat stress	High (but uneven)	Major shifts; southern regions under threat	Moderate to high
Vietnam	Robusta	Water stress, rising temps	High (institutional)	May retain suitability with irrigation	Moderate
Colombia	Arabica	Leaf rust, rainfall shifts	Moderate	Mid-altitude zones at risk	Moderate to high
Ethiopia	Arabica (wild)	Heat, pest expansion	Low	Up to 59% loss in current zones	High
India	Arabica & Robusta	Erratic monsoon, pests	Moderate (mixed access)	Low-altitude arabica decline; robusta stable	Moderate to high

3.8 Key Takeaways

- India's vulnerability profile shares similarities with Colombia and Ethiopia, particularly in terms of arabica sensitivity and smallholder dependence.
- Unlike Brazil and Vietnam, India lacks widespread irrigation infrastructure and large-scale commercial plantations, limiting rapid adaptation.
- However, India's diverse agroforestry systems, if supported by research and policy incentives, could become a model for sustainable coffee production under climate change.
- Countries like Brazil and Vietnam illustrate how investments in climate-smart agriculture and technology adoption can reduce vulnerability even in exposed regions.
- Ethiopia's unique position as a genetic repository underscores the need for global cooperation in conservation and breeding for climate resilience.

4. Economic Implications: Effects on Coffee Pricing and Global Markets

The impacts of climate change on the coffee sector extend beyond biophysical stress, influencing market dynamics, trade patterns, production costs, and ultimately, the economic livelihoods of producers and consumers alike. As a globally traded commodity with relatively inelastic demand and a long production cycle, coffee is especially vulnerable to supply-side shocks. These disruptions can translate into price volatility, altering producer incomes and affecting global trade balances. This section explores the relationship between climate-driven production variability and its influence on coffee prices, with a comparative lens on India and other key exporting nations.

4.1 Climate-Induced Production Shocks and Price Volatility

Coffee prices have historically shown high volatility due to fluctuations in production, demand, and speculative activity. However, climate change has intensified the frequency and severity of supply disruptions, particularly in major producing countries like Brazil and Colombia. For instance, the Brazilian drought and frost events in 2021 led to a sharp decline in output, causing arabica prices to surge by more than 60% over a six-month period on global commodity exchanges (International Coffee Organization [ICO], 2022) [12].

These production shocks often trigger speculative trading in futures markets, amplifying price movements. The resultant volatility disproportionately affects smallholders, who typically lack financial buffers or access to hedging instruments. For importing countries, sharp price increases raise retail costs and may reduce consumption, especially in price-sensitive markets.

India, while not a dominant player in global pricing, is exposed to international price fluctuations due to its export-oriented coffee sector. Indian coffee is sold in both auction and direct export markets, and global prices heavily influence domestic farm-gate prices. Thus, climate-related output variability in Brazil or Vietnam can indirectly impact Indian producers, even if domestic yields are stable.

4.2 Regional Comparison of Price Sensitivity

Country	Export Share in Global Market	Climate Risk Type	Price Sensitivity	Impact on Domestic Economy
Brazil	~35%	Drought, frost	Very High	High export dependency
Vietnam	~18%	Water stress, heat	High	Strong government buffers
Colombia	~10%	Rainfall variability	Moderate-High	Moderate export reliance
Ethiopia	~3-4%	Heat, pests	Moderate	Critical for national income
India	~3-4%	Erratic monsoon	Moderate	Important for regional economy

Brazil's production volume means that climate events there often set global price trends. Vietnam, while large in volume, benefits from government price stabilization and low-cost robusta production, which cushions farmers against sudden income losses. In contrast, Ethiopia's economy is highly dependent on coffee exports, making it economically vulnerable even to small production shocks. India, although not as exposed at the macro level, sees significant regional impacts in states like Karnataka, where coffee farming is a primary income source.

4.3 Rising Production Costs and Market Competitiveness

Climate change not only affects yields but also increases the cost of production. Growers must invest more in irrigation, shade trees, disease control, and climate-resilient varieties. These costs are rising particularly fast for arabica producers, who face increased pressure from pests such as coffee berry borer and white stem borer under changing temperature and humidity conditions.

In India, the cost of inputs such as fungicides, irrigation infrastructure, and labor has increased substantially over the past decade. Farmers are also reporting higher post-harvest losses due to unseasonal rains during the drying period, necessitating investments in mechanical dryers and covered processing facilities (Coffee Board of India, 2023) [6]. These added costs are not always reflected in higher farm-gate prices, particularly in years when global prices are low.

For smaller economies like Ethiopia and regions of India, this cost-price imbalance can reduce coffee's profitability, prompting farmers to abandon or switch crops. This has broader implications for land-use patterns and rural economies.

4.4 Climate Change and Quality Premiums

In specialty coffee markets, quality premiums offer a buffer against low commodity prices. However, climate stress particularly heat and irregular rainfall—can compromise bean quality by affecting sugar accumulation, acidity, and aromatic complexity (Laderach *et al*., 2017) [17]. Countries like Colombia and Ethiopia, which rely heavily on the specialty market, are increasingly vulnerable to losing quality premiums under adverse climate conditions.

India, which produces both commodity and specialty-grade coffees, has seen growing interest in premium markets. However, inconsistent quality due to weather-related stressors threatens India's ability to expand in this segment. Investment in post-harvest processing, quality certification, and origin branding is essential to safeguard and grow this niche.

4.5 Trade and Supply Chain Implications

Global coffee trade is structured around long, complex supply chains involving farmers, cooperatives, exporters, importers, roasters, and retailers. Climate disruptions affect each of these actors. Delayed harvests, logistical bottlenecks from weather events, and rising insurance premiums can raise the cost of doing business, especially for exporters in climate-sensitive regions.

In India, heavy post-monsoon rains have delayed harvesting and drying, affecting the supply chain flow from plantation to port. The result is not only missed export windows but also increased cost due to storage, spoilage, and demurrage charges (NCAER, 2020) [22].

In Brazil and Vietnam, large estates and processing facilities provide scale economies and better infrastructure to absorb these shocks. In contrast, India's fragmented smallholder structure lacks such resilience, making its coffee sector more susceptible to climate-induced supply chain inefficiencies.

4.6 Smallholder Livelihoods and Income Security

Coffee is a key source of income for over 250,000 farming families in India and millions worldwide. The long-term viability of coffee as a livelihood depends on price stability, input costs, access to finance, and climate predictability. With climate change introducing greater variability, many farmers especially arabica growers face mounting uncertainty.

In Ethiopia and parts of Colombia, climate-induced yield losses have led to income declines, outmigration, and even shifts to illicit or less climate-sensitive crops. In India, similar trends are emerging, with some growers switching to pepper, areca nut, or dairy as alternative income sources (Bhadra *et al*., 2021) [4].

The economic risk is amplified by limited access to formal credit, insurance, or market information. Developing and scaling financial safety nets, such as weather-indexed crop insurance and minimum support prices, is vital to securing coffee-based livelihoods under climate uncertainty.

4.7 Global Economic Feedbacks

Finally, price fluctuations and supply instability in the coffee market have broader macroeconomic effects. For exporting countries, reduced coffee income affects foreign exchange reserves, fiscal revenues, and rural employment. For importing countries, particularly those dependent on high-quality arabica, supply constraints may drive inflation in the retail sector and alter consumption patterns.

The global coffee industry must now grapple with both market and environmental uncertainty. Ensuring economic sustainability under climate change will require coordinated action by governments, producer organizations, trade bodies, and private sector actors to create more transparent, inclusive, and resilient value chains.

5. Policy Recommendations for Enhancing Climate Resilience in India's Coffee Sector

India's coffee industry faces increasing challenges due to erratic weather, rising temperatures, shifting monsoon patterns, and pest infestations. These challenges disproportionately affect smallholder farmers, many of whom rely on coffee as a primary source of income. Despite some institutional support through the Coffee Board of India, there remain significant gaps in climate adaptation, infrastructure, financing, and long-term sustainability planning. To ensure the resilience and competitiveness of India's coffee sector, a coordinated and forward-looking policy approach is essential.

5.1 Strengthen Climate-Resilient Research and Development

There is an urgent need to prioritize the development of climate-resilient coffee varieties. Research institutions such as the Central Coffee Research Institute (CCRI) should expand breeding programs focused on traits like drought tolerance, heat resistance, and pest resilience (Coffee Board of India, 2023) [6]. In particular, resistant arabica strains that can thrive in warmer, drier conditions would help stabilize production in highland regions.

Government policy should increase funding for:

- Genomic-assisted breeding
- Pest forecasting systems
- Long-term ecological monitoring of plantation ecosystems

Furthermore, partnerships with international institutions can accelerate the transfer of adaptive technologies and knowledge.

5.2 Expand Access to Climate-Smart Farming Practices

The adoption of climate-smart agricultural practices remains limited in India's coffee sector due to knowledge gaps and financial constraints. Extension programs should be revamped to promote:

- Soil moisture conservation techniques (e.g., mulching, contour bunding)
- Efficient irrigation systems (e.g., drip or sprinkler-based)
- Integrated pest and disease management (IPDM)
- Shade tree diversification for microclimate buffering

A decentralized extension system possibly in partnership with NGOs and farmer cooperatives should be established to deliver these solutions at scale. Mobile-based advisory services can also be used to disseminate localized weather updates and agronomic recommendations.

5.3 Promote Coffee Agroforestry and Biodiversity Conservation

India's traditional shade-grown coffee systems, particularly in Karnataka and Kerala, offer a natural advantage in adapting to climate stress. These systems improve water retention, reduce heat stress, and support pollinators and beneficial insects. However, there is growing pressure to shift towards higher-yield monocultures, which increases ecological vulnerability.

5.3.1 Policy should incentivize

- Maintenance and restoration of native shade trees
- Conservation of forest patches within and around coffee plantations
- Certification programs that reward biodiversity-friendly practices (e.g., Rainforest Alliance, UTZ)

In addition, agroforestry models should be promoted through demonstration plots and financial incentives, especially in vulnerable areas facing rapid environmental degradation.

5.4 Improve Access to Finance and Climate Insurance

One of the major barriers to adaptation is the limited financial capacity of smallholders. Most coffee farmers in India lack formal credit access and face difficulties in recovering from climate-related losses.

The government should introduce

- Weather-indexed crop insurance specifically tailored for coffee
- Subsidized loans and credit guarantees for climate-resilient infrastructure (e.g., irrigation, drying yards)
- Risk-sharing mechanisms for exporters and producer cooperatives during climate shocks

Public-private partnerships can also play a role in building affordable insurance products by leveraging satellite data and historical weather models.

5.5 Upgrade Post-Harvest Infrastructure

Post-harvest losses in India's coffee sector are increasing due to unpredictable rainfall during harvest and drying periods. Many smallholders still rely on open drying yards, which are susceptible to spoilage during untimely rains.

Policy should support

- Construction of covered drying platforms and solar dryers
- Investment in community-level storage and pulping units
- Capacity-building for quality grading and cupping

State governments and the Coffee Board could co-finance these investments under rural infrastructure schemes or convergence with MGNREGA in coffee-growing districts.

5.6 Strengthen Market Access and Price Stabilization Mechanisms

Volatility in global coffee prices often leads to income instability for Indian growers. While India has traditionally depended on private traders and exporters, more inclusive market mechanisms can offer greater income stability.

5.6.1 Policy interventions could include

- Minimum Support Price (MSP) benchmarks for arabica and robusta during extreme downturns
- Price risk management training for farmer groups and cooperatives
- Expansion of direct trade platforms, such as e-auctions and digital marketplaces
- Encouraging geographical indication (GI) branding for regional coffees to capture niche markets

These measures can also help Indian coffee fetch better premiums in domestic and export markets.

5.7 Integrate Climate Policy into Coffee Governance

Finally, climate considerations should be formally integrated into India's national coffee strategy. This requires:

- Developing a National Climate Adaptation Plan for Coffee
- Aligning coffee sector policies with India's National Action Plan on Climate Change (NAPCC)
- Mandating climate risk assessments in all Coffee Board development programs

Cross-sector coordination with forestry, water, and rural development ministries is also essential for a holistic approach to adaptation.

Summary Table: Policy Actions and Responsible Agencies for Climate-Resilient Coffee in India

Policy Action	Responsible Agencies / Stakeholders	Reference
1. Develop climate-resilient and pest-tolerant coffee varieties	Central Coffee Research Institute (CCRI), Indian Council of Agricultural Research (ICAR)	Coffee Board of India, 2023 [6]; ICAR, 2021 [10]
2. Increase funding for research on pest forecasting and climate modeling	Ministry of Agriculture & Farmers Welfare (MoAFW), Department of Science & Technology	ICAR, 2021 [10]; NCAER, 2020 [22]
3. Promote climate-smart agricultural practices (e.g., efficient irrigation, soil conservation, IPDM)	Krishi Vigyan Kendras (KVKs), State Agriculture Departments, Coffee Board	MoAFW, 2022; Bhadra *et al*., 2021 [18, 4]
4. Launch mobile-based agro-advisory and early warning systems	Indian Meteorological Department (IMD), Digital India Initiative, Coffee Board	IMD, 2022; Coffee Board of India, 2023 [11, 6]
5. Incentivize biodiversity-friendly, shade-grown coffee systems	Ministry of Environment, Forest and Climate Change (MoEFCC), NABARD	MoEFCC, 2015; Laderach *et al*., 2017 [20, 17]
6. Promote GI-tagged regional coffee and agroforestry-linked branding	Coffee Board of India, APEDA, Ministry of Commerce & Industry	APEDA, 2021; NITI Aayog, 2020 [2, 25]
7. Introduce weather-based crop insurance schemes tailored to coffee	Agriculture Insurance Company of India (AIC), NABARD, PMFBY Implementing Agencies	AIC, 2020; NABARD, 2021 [1, 21]
8. Provide subsidized loans and grants for climate-resilient infrastructure (e.g., irrigation, shade trees)	NABARD, State Cooperative Banks, Coffee Board	NABARD, 2021; MoAFW, 2022 [21, 18]
9. Support infrastructure for post-harvest management (e.g., covered drying yards, solar dryers)	Coffee Board of India, State Governments, Rural Infrastructure Development Fund (RIDF)	NCAER, 2020; Coffee Board of India, 2023 [22, 6]
10. Expand digital and physical marketplaces for direct trade and e-auctions	Coffee Board, Ministry of Commerce, State Marketing Boards	Coffee Board of India, 2023; APEDA, 2021 [6, 2]
11. Establish Minimum Support Price (MSP) benchmarks during periods of market volatility	Ministry of Agriculture, NITI Aayog, Coffee Board	NITI Aayog, 2020 [25]
12. Draft a dedicated National Adaptation Plan for coffee under the climate policy framework	MoEFCC, Coffee Board, Ministry of Agriculture	MoEFCC, 2015; ICAR, 2021 [20, 10]
13. Integrate climate resilience into Coffee Board development schemes and production-linked subsidies	Coffee Board of India, MoAFW	Coffee Board of India, 2023; MoAFW, 2022 [6, 18]
14. Facilitate public-private partnerships for insurance, research, and value chain resilience	NABARD, Private Sector (Agri Tech, Finance), NITI Aayog	NABARD, 2021; NITI Aayog, 2020 [21, 25]
15. Strengthen farmer producer organizations (FPOs) and local extension systems for climate-focused capacity building	State Agriculture Departments, NGOs, Farmer Cooperatives	Bhadra *et al*., 2021; MoAFW, 2022 [4, 18]

6. Conclusion

Climate change has emerged as one of the most formidable challenges to global coffee production, with far-reaching biophysical and economic consequences. From rising temperatures and erratic rainfall to expanding pest pressures and soil degradation, the environmental threats to *Coffea arabica* and *Coffea canephora* cultivation are no longer theoretical they are already reshaping the geography, quality, and sustainability of the crop. This review demonstrates how these challenges translate into yield instability, increased production costs, and market volatility, affecting both producers and consumers worldwide.

The comparative analysis reveals significant regional disparities in climate vulnerability and adaptive capacity. While countries like Brazil and Vietnam are better positioned to mitigate risks due to their institutional strength and investment in technology, nations such as India, Colombia, and Ethiopia face steeper obstacles, particularly for smallholder farmers. India's unique position producing both arabica and robusta under ecologically rich, shade-grown systems offers both challenges and opportunities. Its vulnerability to monsoon variability and pest outbreaks underscores the urgency of systemic adaptation measures, but its diversified agroforestry traditions and emerging specialty market potential provide a valuable foundation for resilience.

Addressing the climate risks to India's coffee sector requires a multi-pronged strategy that includes scientific innovation, infrastructure investment, inclusive policy frameworks, and targeted financial instruments. Strengthening research on climate-resilient varieties, promoting sustainable farming practices, expanding insurance and credit access, and enhancing market infrastructure will be critical in protecting farmer livelihoods and ensuring long-term sectoral viability.

Ultimately, safeguarding the future of coffee both in India and globally demands not only technological and agronomic solutions, but also policy coherence, international cooperation, and a commitment to sustainable development rooted in equity, resilience, and ecological stewardship.

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