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Climate stress, coffee physiology and India's export competitiveness: A review of emerging trade challenges and opportunities

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Abstract
India's coffee sector plays a pivotal role in the country's agricultural exports and rural economy, with over 70% of its annual production destined for international markets. However, the sector faces growing challenges from climate-induced stressors such as rising temperatures, erratic rainfall and prolonged droughts. These environmental changes negatively impact coffee physiology particularly in *Coffea Arabica* by impairing photosynthesis, reducing stomatal conductance and relative water content and inducing oxidative stress. The resultant effects include yield instability, poor bean quality and increased production costs, all of which diminish India's export competitiveness, especially in premium markets. At the same time, India has distinct advantages that offer pathways for adaptation. Traditional shade-grown agroforestry systems, genetic diversity in coffee germplasm and region-specific branding initiatives such as Geographical Indication (GI) tagging position India well to transition toward climate-resilient production. Interventions including climate-resilient varietal development, improved post-harvest practices, organic and specialty certification and policy support can enhance the sector's sustainability and market performance.
This review synthesizes recent research on climate stress impacts on coffee physiology and evaluates trade-related vulnerabilities and opportunities. It advocates for integrated strategies encompassing research, agronomic innovation and market diversification to ensure the long-term resilience and competitiveness of Indian coffee in the global arena.

Keywords: Coffee physiology, *Coffea Arabica*, climate change, export competitiveness, agroforestry, drought stress, India, specialty coffee, GI tagging, sustainable trade

1. Introduction
Coffee is one of the most widely traded agricultural commodities globally, contributing significantly to the livelihoods of over 25 million farming households across tropical and subtropical regions (FAO, 2020) [10]. In India, coffee cultivation is predominantly carried out in the Southern States of Karnataka, Kerala and Tamil Nadu, with emerging areas in Andhra Pradesh and the Northeastern hill regions. The country is renowned for its unique cultivation method—shade-grown coffee within traditional agroforestry systems which enhances biodiversity and contributes to ecosystem services (Bhagwat *et al*., 2008; Nath *et al*., 2023) [1, 17]. India is a major producer and exporter of both *Arabica* (*Coffea Arabica*) and Robusta (*Coffea canephora*), exporting over 70% of its annual production to international markets (ICO, 2021) [11].
However, the Indian coffee sector is increasingly challenged by the impacts of climate change, which threatens not only production but also quality and export reliability. Key climate-related stressors include rising mean temperatures, erratic rainfall patterns, extended dry spells and increased frequency of extreme weather events such as unseasonal heavy rains and droughts (Bunn *et al*., 2015; Moat *et al*., 2017) [2, 14]. These climatic shifts disrupt the delicate physiological balance required for successful coffee cultivation, particularly in *Arabica*, which is more sensitive to environmental stressors than Robusta (DaMatta *et al*., 2007; Kath *et al*., 2020) [8, 12].
Climate stress affects coffee plants at multiple physiological levels, including photosynthesis, stomatal conductance, leaf water potential, flowering phenology and fruit development. For instance, temperatures exceeding 30 °C during flowering and bean development stages lead to abnormal fruit formation, flower drop and poor bean filling,

ultimately reducing yield and quality (DaMatta *et al*., 2019; Rodrigues *et al*., 2016) [5, 13]. Similarly, prolonged water deficits impair carbon assimilation and trigger oxidative stress, which in turn prompts the plant to upregulate its antioxidant defense systems (Tadesse *et al*., 2018) [20]. Understanding these physiological responses is critical for developing drought-resilient cultivars and adaptive agronomic strategies.

From a trade perspective, climate-induced reductions in yield and fluctuations in bean quality directly influence India's competitiveness in the global coffee market. The premium *Arabica* segment, where India faces stiff competition from countries like Ethiopia, Colombia and Brazil, is especially sensitive to quality variations resulting from environmental stress (Mohanraj *et al*., 2022) [15]. Additionally, supply chain disruptions, pest and disease outbreaks triggered by climate variability and rising input costs are emerging as significant trade risks.

Despite these challenges, there are also opportunities. India's traditional shade-grown coffee systems present an inherent climate-buffering advantage. With strategic interventions such as genotype improvement, sustainable agroforestry intensification, precision irrigation and climate-smart certification, Indian coffee can improve its adaptive capacity while enhancing market value (Muthappa *et al*., 2022; Nath *et al*., 2023) [17, 16].

This review critically examines the physiological impacts of climate stress on coffee cultivation in India and explores the implications for export competitiveness. It highlights recent scientific findings, trade trends and policy interventions, aiming to provide insights into pathways for climate-resilient and economically viable coffee production.

2. Climate Stress and Coffee Physiology

The physiology of coffee plants is intricately linked to climatic conditions, particularly temperature and water availability. As perennial crops cultivated predominantly in tropical highland ecosystems, coffee plants require a narrow range of climatic parameters for optimal growth and bean development. However, climate variability and long-term changes in temperature and precipitation patterns are disrupting this balance, leading to increased stress, reduced productivity and compromised quality in both *Arabica* (*Coffea Arabica*) and Robusta (*Coffea canephora*) cultivars. Understanding the physiological responses of coffee to climate stress is vital for developing adaptive strategies aimed at ensuring sustainable production and export reliability.

2.1 Temperature and Water Stress

Temperature and water availability are two of the most critical environmental factors influencing coffee growth, development and yield. *Arabica* coffee performs best in cooler environments with mean annual temperatures ranging between 18°C and 24°C (DaMatta *et al*., 2007) [8]. When temperatures exceed 30°C, particularly during flowering and fruit development, key physiological processes such as floral initiation, pollination and bean filling are adversely affected. This leads to outcomes such as incomplete bean development, increased fruit drop and lower bean density factors that directly reduce both yield and market value (Rodrigues *et al*., 2016; DaMatta *et al*., 2019) [5, 8].

In addition to heat stress, altered rainfall patterns such as delayed monsoons or prolonged dry spells impose significant water stress on coffee plants. Water scarcity during the flowering phase can inhibit bud expansion, reduce fruit set and delay maturity, ultimately affecting harvest quality and quantity (Bunn *et al*., 2015) [2]. Moreover, frequent drought events reduce soil moisture availability, which impairs the plant's capacity to absorb nutrients and maintain cellular turgor pressure.

Robusta coffee, while more tolerant of higher temperatures, is also vulnerable to water stress, particularly during prolonged dry periods. In regions such as southern India, changing monsoonal dynamics have already resulted in reduced yields and increased variability in coffee production (Mohanraj *et al*., 2022; Muthappa *et al*., 2022) [15, 16].

2.2 Impact on Physiological Parameters

Climate stress induces a cascade of physiological changes in coffee plants, affecting processes such as photosynthesis, transpiration and oxidative metabolism. Under high-temperature and drought conditions, photosynthetic rates decline due to stomatal closure, which limits carbon dioxide uptake and reduces carbon assimilation. Studies have demonstrated that net photosynthesis (Pn) decreases significantly in drought-sensitive coffee genotypes during periods of water stress, resulting in lower biomass accumulation and reduced yield potential (Chaves *et al*., 2009; Martins *et al*., 2016) [3, 13].

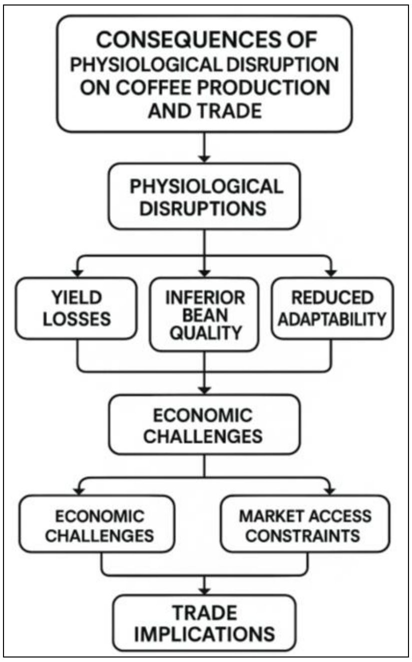
Stomatal conductance (gs) a key indicator of transpiration and gas exchange also declines sharply under drought conditions. Reduced stomatal aperture leads to lower evaporative cooling and higher leaf temperatures, exacerbating thermal stress. Genotypic variations in stomatal regulation have been observed, with lines such as Sln.6 and S.274 showing variable drought tolerance under field conditions in India (Yadukumar *et al*., 2020) [23].

Relative Water Content (RWC), a measure of plant hydration and turgor, decreases under moisture-deficient conditions. Genotypes that maintain higher RWC under stress typically demonstrate better osmotic adjustment and resilience. Such physiological indicators are increasingly used in screening programs to identify drought-tolerant varieties (Tuberosa, 2012; Rahman *et al*., 2019) [21, 18].

In addition to these primary responses, plants activate antioxidant defense mechanisms to cope with the oxidative stress induced by drought and heat. Enzymes such as superoxide dismutase (SOD), catalase (CAT) and peroxidase (POD) play a central role in scavenging reactive oxygen species (ROS) and protecting cellular structures. Tadesse *et al*. (2018) [20] observed significant upregulation of antioxidant enzyme activity in drought-tolerant *Arabica* cultivars, suggesting their role as potential biochemical markers for stress adaptation. Similar findings have been reported in Indian and Ethiopian coffee germplasm, highlighting the genetic diversity available for breeding stress-resilient cultivars (DaMatta *et al*., 2022; Mohanraj *et al*., 2022) [6, 15].

The combined effect of these physiological disruptions under climate stress contributes to yield instability, reduced bean size and compromised cupping quality factors that influence both domestic production and export competitiveness.

Consequences of Physiological Disruptions on Coffee Production and Trade



3. India's Export Competitiveness in Coffee Trade

India's position as a key player in the global coffee market is shaped by its unique agroforestry cultivation practices, diverse climatic zones and a growing focus on quality differentiation. Despite contributing a modest share of around 3-4% to global coffee production, India exports nearly 70% of its total coffee output, earning substantial foreign exchange and supporting rural livelihoods in major growing states such as Karnataka, Kerala and Tamil Nadu (ICO, 2021) [11]. However, climate-related challenges are increasingly undermining the reliability and profitability of India's coffee exports. This section explores both the current export landscape and emerging trade risks linked to climate stress.

3.1 Current Export Scenario

India produces two main varieties of coffee: *Arabica* (*Coffea Arabica*) and Robusta (*Coffea canephora*), with the latter accounting for nearly 65% of the country's total output. While Robusta is more widely cultivated due to its higher yield and resistance to pests and climatic extremes, *Arabica* coffee commands a premium price in international markets because of its superior flavor profile and lower caffeine content (DaMatta *et al*., 2007; Kath *et al*., 2020) [8, 12]. The country's export portfolio is therefore heavily reliant on maintaining quality standards and consistent volumes.

The major export destinations for Indian coffee include Italy, Germany, Belgium, Russia and several Middle Eastern and Southeast Asian countries. Italy alone imports over 20% of Indian coffee, primarily for use in espresso blends (ICO, 2021) [11]. To improve brand recognition and product traceability, the Coffee Board of India has implemented several strategic initiatives, such as:

Geographical Indication (GI) tagging for region-specific coffees like *Monsooned Malabar*, *Coorg Arabica* and *Bababudangiri Arabica*.

Promotion of specialty coffee segments through certifications, traceability systems and participation in global coffee expos.

Support for organic and eco-certified coffee production, which appeals to health-conscious and environmentally aware consumers.

These initiatives have helped Indian coffee establish a niche in the premium and specialty markets. However, the long-term sustainability of these advantages is being increasingly challenged by climate-related disruptions.

3.2 Climate-Induced Trade Risks

The export competitiveness of Indian coffee is under growing threat from climate-induced biophysical and economic pressures. One of the most immediate challenges is yield instability. Unpredictable rainfall, prolonged droughts and temperature anomalies disrupt flowering, fruit set and bean development leading to significant fluctuations in output. This not only affects year-on-year supply volumes but also introduces inconsistencies in bean size, weight and appearance, which are critical to quality grading and price realization (Bunn *et al*., 2015; DaMatta *et al*., 2019) [2, 5].

Furthermore, bean defects such as black beans, cherry drop and "foxy" flavors have become more frequent due to climate stress and poor post-harvest drying conditions. These quality issues often result in downgrading or outright rejection of shipments, especially in the specialty coffee market where sensory attributes are tightly regulated (Mohanraj *et al*., 2022) [15].

Another major concern is the escalation of production costs. Farmers are increasingly investing in irrigation infrastructure to cope with erratic rainfall, shade tree management to buffer against rising temperatures and integrated pest and disease control, as climate change is expanding the range and severity of pests like white stem borer and coffee berry borer (Vega *et al*., 2009) [22].

These additional costs, coupled with stagnant or volatile global coffee prices, are eroding profit margins, especially for smallholder growers who dominate the Indian coffee landscape. The economic strain is further exacerbated by the lack of timely insurance coverage and access to adaptive technologies.

In the context of international trade, quality fluctuations and inconsistent volumes pose reputational risks for Indian coffee exporters. Buyers in high-value markets, particularly those dealing in specialty or single-origin coffees, demand uniformity and traceability. Climate stress-induced inconsistencies could therefore jeopardize India's access to premium segments and lead to a loss of market share to more climate-resilient producers like Brazil, Vietnam, or Colombia (Moat *et al*., 2017; Kath *et al*., 2020) [14, 12].

Moreover, supply chain disruptions such as labour shortages during extreme weather events, delayed harvests, or logistical bottlenecks further compound trade risks. This calls for urgent investment in climate-smart production systems, real-time weather monitoring and export infrastructure modernization to preserve India's competitive edge.

4. Opportunities for Climate-Resilient Coffee Trade

Despite the growing risks associated with climate change, India's coffee sector holds considerable potential to adapt and thrive through proactive interventions. Building resilience into coffee production and trade systems requires a multipronged approach involving genetic improvement, sustainable agroforestry practices, market diversification and policy support. This section outlines key opportunities for enhancing India's coffee trade competitiveness in a changing climate.

4.1 Breeding for Climate Resilience

One of the most promising long-term strategies for climate adaptation lies in developing and deploying resilient coffee varieties. Genetic variability exists within both *Coffea Arabica* and *Coffea canephora* germplasm, particularly in Ethiopian landraces and Indian elite lines, which show differences in physiological and biochemical stress responses (DaMatta *et al*., 2022; Tadesse *et al*., 2018) [6, 20].

Traits such as high relative water content (RWC), efficient stomatal regulation, improved antioxidant enzyme activity (SOD, CAT, POD) and heat and drought tolerance during flowering and bean filling stages have been identified as critical markers in selecting genotypes suitable for future climates (Yadukumar *et al*., 2020; Martins *et al*., 2016) [23, 13]. The Coffee Board of India and research institutions like Central Coffee Research Institute (CCRI) are working on breeding programs incorporating these traits, although the adoption among farmers remains slow and requires scaling.

4.2 Shade-Grown Agroforestry Systems

India's traditional shade-grown coffee systems offer inherent ecological advantages in mitigating the effects of climate stress. Incorporating native and diversified shade tree species not only buffers microclimatic extremes (e.g., reducing soil temperature and evapotranspiration) but also enhances soil fertility, carbon sequestration and biodiversity conservation (Bhagwat *et al*., 2008; Nath *et al*., 2023) [1, 17].

Recent research shows that well-managed agroforestry systems contribute to improved water-use efficiency, natural pest control and long-term sustainability of coffee landscapes. Agroforestry also opens avenues for payment for ecosystem services (PES) and carbon credit trading, which could provide alternative income sources to farmers while rewarding climate-smart practices (Muthappa *et al*., 2022; Nath *et al*., 2023) [16, 17].

4.3 Market Innovations and Value Addition

To maintain global competitiveness, India must explore value addition and market innovation in its coffee sector. Opportunities include specialty coffee production with traceability and single-origin branding, organic and eco-certification to target premium markets, blockchain-based traceability systems to enhance transparency in the supply chain and climate-resilient certification labels, similar to Rainforest Alliance or UTZ, which attract conscious consumers (Fairtrade International, 2018). Additionally, post-harvest processing improvements (e.g., controlled fermentation, solar drying) can significantly enhance cup quality and reduce climate-induced defects, particularly in *Arabica* .

4.4 Policy and Institutional Support

Government and institutional support are crucial to enable smallholder farmers to transition towards climate-resilient coffee systems. India has introduced several schemes through the Coffee Board, such as subsidies for micro-irrigation systems, support for rejuvenation and replanting programs and capacity-building through farmer field schools and training in climate-smart practices

There is a growing need to integrate real-time weather advisories, crop insurance schemes and risk-mitigation funds to buffer farmers against extreme events. Public-private partnerships (PPP) involving cooperatives, exporters and certification bodies can also enhance access to finance and global markets.

In addition, India could benefit from aligning its coffee sector with international climate frameworks like the Koronivia Joint Work on Agriculture (UNFCCC) and leverage climate finance for adaptation and low-emission development.

4.5 Diversification and Regional Expansion

To reduce dependence on a few traditional growing belts, India has begun promoting coffee cultivation in non-traditional regions, such as Araku Valley (Andhra Pradesh) and parts of the Northeast. These areas often have favorable altitudes and rainfall regimes and are suitable for organic and tribal cooperative farming, providing new opportunities for inclusive, climate-resilient growth (Coffee Board of India, 2021).

5. Conclusion and Way Forward

The Indian coffee sector stands at a critical juncture, where the increasing impacts of climate change are challenging both the ecological resilience of plantations and the economic viability of exports. Climate stress, manifested in the form of elevated temperatures, erratic rainfall, prolonged droughts and extreme events, significantly affects the physiology of coffee plants reducing photosynthesis, impairing water-use efficiency and inducing oxidative damage. These physiological disruptions ultimately translate to reduced yields, inferior bean quality and inconsistencies in export performance.

The situation is particularly concerning for *Arabica* coffee, which, despite its high market value, is more sensitive to heat and drought compared to Robusta. As a result, India's ability to remain competitive in global coffee markets especially in the high-value specialty and organic segments is increasingly threatened by climate-induced production variability and quality declines (DaMatta *et al*., 2019; Mohanraj *et al*., 2022) [5, 15].

Nevertheless, the sector also possesses inherent strengths and emerging opportunities. India's traditional shade-grown agroforestry systems, rich genetic diversity and institutional support frameworks provide a strong foundation for building climate resilience. Adaptation strategies such as breeding climate-resilient cultivars, intensifying agroforestry, adopting smart irrigation and improving post-harvest practices can significantly buffer the impacts of climate stress.

On the trade front, diversification into non-traditional growing regions, investment in value-added processing and adoption of digital traceability systems can help enhance market visibility and trust. Government-backed GI tagging, organic certifications and climate-smart branding further provide avenues for improving market differentiation and export revenue (Nath *et al*., 2023; Coffee Board of India, 2021) [17].

For a sustainable and competitive future, coordinated action is required on multiple fronts:

- **Research and Development (R&D):** Accelerate breeding programs using physiological and biochemical stress markers.
- **Extension Services:** Strengthen farmer training in climate-smart practices and adaptive agroforestry.
- **Market Integration:** Promote digital platforms, climate-resilient certifications and direct-to-consumer models.

- **Policy Interventions:** Expand insurance coverage, incentivize low-emission farming and improve climate data accessibility.

Ultimately, the transformation of India's coffee sector into a climate-smart, high-value export system will depend on its ability to integrate science, policy and market innovation. By leveraging its ecological traditions and modern technologies, India can not only mitigate the risks of climate change but also redefine its position in the global coffee economy.

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