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EXPLORING TEA: CULTIVATION, ECONOMIC IMPACT, AND NAVIGATING CLIMATE VARIABILITY CHALLENGES

Bidisha Hazarika[1], Pompi Dutta[2]*, Mriganko Kakoti[3], Brishti Saikia[4], Lipika Talukdar[5], Milon Jyoti Konwar[6] and Manuranjan Gogoi[1]

[1]Department of Tea Husbandry & Technology, AAU, Assam, India
[2]Department of Agricultural Economics, AAU, Jorhat, Assam, India
[3]Department of Agrometeorology, AAU, Jorhat, Assam, India
[4]A.P.A.R.T., A.A.U., Jorhat, Assam, India
[5]Advanced centre for IFS Research, Assam Agricultural University, Jorhat, Assam, India
[6]A.A.U. A.R.R.I., Titabar, Assam, India
*Corresponding author E-mail: pompi.dutta@aau.ac.in
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ABSTRACT

Tea stands as a primary source for the globally consumed non-alcoholic beverage, with its cultivation dating back five millennia in China. The industry has now expanded to over 58 countries, including major producers like China, India, Kenya, and Sri Lanka. Tea plays a pivotal role in global economies, rural development, and poverty alleviation, serving an impressive 4.5 billion consumers worldwide. Projected annual growth of 4-5.5% anticipates the global tea market to exceed USD 73 billion by 2024. In India, tea holds a central position in the economy, cultural heritage, and social fabric, cultivated extensively across diverse regions. However, climate change poses formidable challenges to the tea industry, impacting temperature, precipitation, and extreme weather events, thereby threatening its sustainability. Research findings reveal disruptions in the delicate balance crucial for optimal tea growth, affecting flavor profiles, chemical composition, and nutritional content. While increased CO_2 levels benefit photosynthesis, challenges like reduced sunlight and unpredictable rainfall negatively impact yield. Thus, a comprehensive and integrated approach is imperative, involving adaptation measures, sustainable farming practices, and socio-economic programs to ensure the resilience and longevity of the tea industry. Collaborative efforts are crucial in addressing the multifaceted challenges posed by climate change in the tea sector, safeguarding the entire production ecosystem and livelihoods.
***Keywords*:** Climate, Tea, Economy.

Introduction

Tea plants (*Camelia sinensis)* serve as the botanical source for the most widely consumed non-alcoholic beverage in the world tea (Pan *et al.,* 2022). Originating in south-western China approximately 5000 years ago, these plants are now cultivated in more than 58 countries, covering an estimated land area of 4.37 million hectares (Global Market Report: Tea, 2018). Notably, China, India, Kenya, and Sri Lanka have consistently been the leading global tea producers (Kumarihami *el al.,* 2018) (Fig. 1). Tea plays a crucial role in the economies, rural development, food security, and poverty alleviation of many developing nations. It caters to the thirst of approximately 4.5 billion consumers worldwide (Hazarika *et al.,* 2023). The tea industry is expected to experience growth at a compound annual rate of 4% to 5.5% from 2017 to 2024 (Keelery *et al.,* 2020). In 2017, the retail value of the global tea market was estimated at around USD 50 billion, and projections indicate an increase to over USD 73 billion by 2024 (Prikhodko *el al.,* 2022).

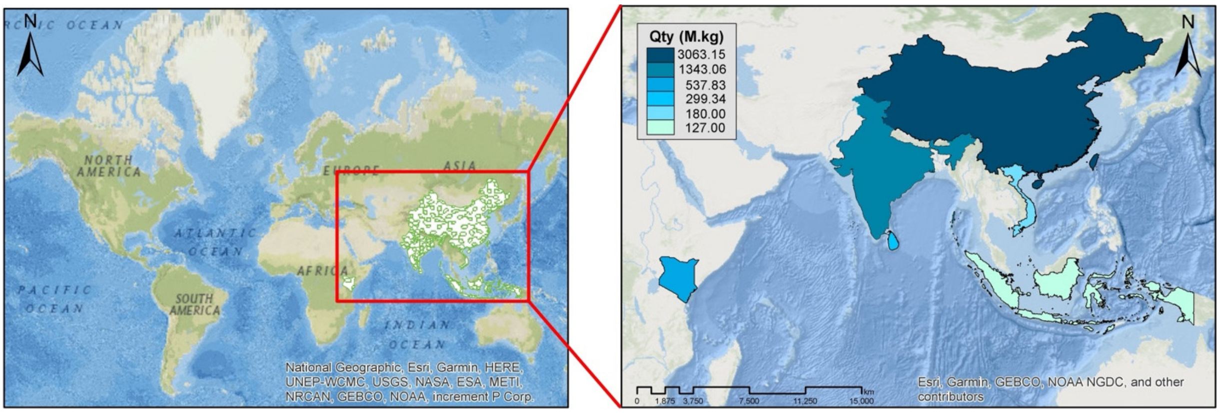

Fig. 1: Top five countries in terms of tea production

Tea stands as a cornerstone in the Indian economy, serving as a major employer and foreign exchange earner (Hazarika *et al.,* 2023). Its rich cultural significance is deeply ingrained in daily life, symbolizing social connections and heritage. The global competitiveness of the tea industry, driven by diverse varieties, enhances India's economic standing. Beyond its economic contributions, tea cultivation contributes to rural development, alleviating poverty, and attracts tourism with scenic plantations (Hazarika *et al.,* 2024). Tea plays a pivotal role in shaping India's economic, cultural, and social landscape. The extensive cultivation of tea across vast swathes of land in India further underscores its pivotal role, with 619773.70 ha of area dedicated to tea plantations, making it one of the largest tea-producing nations in the world. Himachal Pradesh and Uttarakhand boast the highest area under tea cultivation, followed closely by Assam and West Bengal (Hazarika *et al.,* 2023), highlighting the geographical diversity and significance of the industry in various regions of the country.

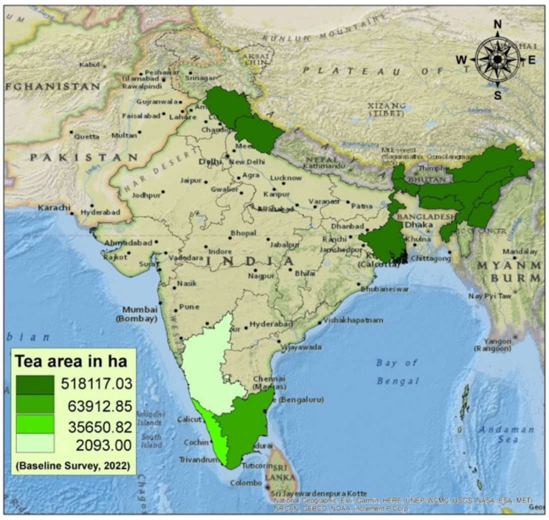

Fig. 2: State wise production of Tea

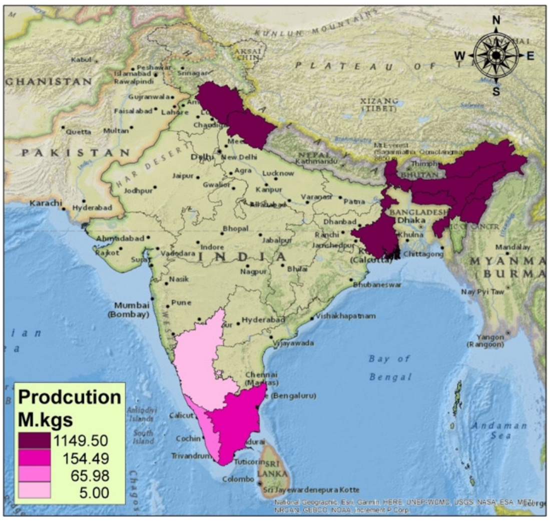

Fig.2: Major tea growing regions of India

On the other hand, climate change, induced by global warming, poses a significant global challenge. The world has witnessed a noticeable increase in changing climate, projected to escalate further (Robinson, 2020), impacting agriculture (Konwar *et al.,* 2022), including tea production (Hazarika *et al.,* 2023). Characterized by alterations in temperature, precipitation patterns, and extreme weather events, climate change threatens tea plants' growth, yield, and quality. Shifts in suitable growing regions may impact traditional tea-producing areas (Chhogyel *et al.,* 2020; Elith *et al.,* 2009). The heightened frequency and intensity of pests and diseases, coupled with variations in climate, pose threats to tea productivity (Hazarika *et al.,* 2023). Changes in tea leaf composition may affect flavour and health properties, influencing the economic viability of the industry and global supply chains (Bokuchava *et al*., 1980).

The social and environmental dimensions of climate change on tea cultivation are equally critical.

Smallholder farmers in tea-producing regions depend on cultivation for livelihoods, and climate variations may disrupt traditional practices, leading to income loss and community well-being risks (Deka *et al.,* 2022). Furthermore, climate change poses challenges to the environmental sustainability of tea production, impacting soil erosion, water scarcity, and ecological balance (Su *et al.,* 2017).

Tea plants, with their extended life span, are subject to various decadal impacts of climate change, as outlined in the literature (Boehm et al., 2016; Li *et al.,* 2017) . These include stresses such as severe drought, erratic and heavy precipitation, rising temperatures, heightened concentrations of CO_2, and other extreme weather events (Kadam *et al.,* 2014) . Examples of these events encompass floods, frosts, and storms. Moreover, climate change-related biotic (i.e., pests and diseases) and abiotic stressors (i.e., UV irradiation, nutrient deficiency, and ozone depletion) affect the sustainability of climate-smart tea systems (Marx *et al.,* 2017). In crop-producing areas, agrometeorological conditions are experiencing variability with climate change (Kakoti *et al.,* 2023). Uncertain and less predictable climate scenarios may no longer satisfy the eco physiological requirements of tea, thus posing risks, threats and limitations, as well as advantages in some locations for the tea sector (Jayasinghe *et al.,* 2021).

Recognizing these consequences, studying the effects of climate change on tea is imperative. Such research informs adaptive strategies, mitigates risks, and ensures the long-term sustainability of the global tea industry, guiding policymakers, farmers, and industry stakeholders toward resilient and sustainable practices. This article delves into the intricate relationship between climate change and tea, analysing its impact on flavour profiles, chemical composition, and nutritional content with the following a. Quantify the impact of climate change on tea quality parameters; b. Investigate adaptive strategies for mitigating climate change effects on tea production and c. Analyse the socio-economic implications of climate change on tea farming communities

The research employs exploratory and descriptive methodologies, focusing on qualitative analysis. As this study delves into the impact of climate change on tea quality, production and tea farming communities, the data utilized in this research is primarily sourced from secondary data.

Impact on Tea Quality

Climate change can have a significant impact on the flavor profiles of tea, affecting various aspects of tea cultivation, processing, and the final product (CIAT Report. 2011). Climate change might affect the functional quality of tea, primarily dictated by the levels of methylxanthine caffeine and various polyphenolic catechin compounds (Ahmed *et al.,* 2019; Kfoury *et al.,* 2019). These compounds play distinct roles in tea, contributing to its stimulant properties, antioxidant capabilities, anti-inflammatory attributes, and cardioprotective qualities (Lin *et al.,* 2003).

The growth of tea plants is intricately linked to specific temperature and altitude conditions that are deemed optimal for their development (Owuor *et al.,* 2011). These conditions are crucial for shaping the chemical composition of tea leaves, which, in turn, has a direct impact on the flavour of the resulting tea (Akhlas *et al.,* 2004). Climate change introduces alterations in both temperature and altitude, potentially disrupting the delicate balance required for optimal tea growth (Wijeratne *et al.,* 2007). The rise in temperatures associated with climate change can lead to accelerated chemical reactions within the tea leaves. This acceleration can, in turn, affect the equilibrium of various compounds responsible for the distinct aroma and taste of tea (Zheng *et al.,* 2019). Higher temperatures may influence the rate of biosynthetic processes within the tea plant, affecting the synthesis of volatile compounds, essential oils, and other flavour-contributing elements (Shi *et al.,* 2015). Additionally, shifts in altitude, which often accompany climate changes, can further influence atmospheric conditions, sunlight exposure, and soil characteristics, all of which contribute to the overall flavour profile of tea (Han *et al.,* 2017). Thus, the interplay between temperature and altitude is a critical factor in determining the chemical composition of tea leaves. Changes induced by climate change in these factors can disrupt the finely tuned processes that create the characteristic flavours in tea, leading to potential alterations in its sensory qualities (Ye *et al.,* 2022). Climate change poses a noteworthy challenge for the tea industry, as the subtle and cherished flavour intricacies appreciated by tea enthusiasts are closely linked to the intricate balance of environmental factors (Porter, 2010). The industry is increasingly concerned about how changes in these variables, such as temperature and altitude, may impact the distinctive qualities that make each tea unique and sought-after by discerning consumers.

Tea plants are highly dependent on a specific amount of rainfall to thrive and achieve healthy growth (Carr *et al.,* 1972). The availability of water is crucial for various physiological processes, nutrient absorption, and overall plant development. Changes in precipitation patterns, a notable aspect of climate change, can significantly influence soil moisture levels in tea plantations, giving rise to both challenges and potential issues (Han *et al.,* 2018). When there is a deviation from the usual rainfall patterns, it can lead to two primary concerns: drought or excess water (Paul *et al.,* 2023). In the case of insufficient rainfall, drought conditions may arise, negatively impacting the water supply available to the tea plants. This water scarcity can hinder the normal metabolic processes within the plants, affecting their growth and overall health (Farooq *et al.,* 2009). As previous studies have reported, drought caused tea plant crop losses of around 14–40% in different cultivation areas (Wijeratne *et al.,* 1998, Ng'etich *et al.,* 2001). In addition, extreme drought frequently leads to tea plant death; Studies (Burgess *et al.,* 1933) reported that drought caused 6–19% plant mortality in varieties of clonal tea cultivars.

The limited availability of water may also lead to stress, potentially causing a reduction in the synthesis of compounds responsible for the flavor profile of tea leaves. Conversely, excessive rainfall can result in waterlogged or flooded conditions in the tea plantation (Samynathan *et al.,* 2021). This excess water can adversely affect the root system, leading to issues such as root rot or nutrient leaching. Both of these conditions can compromise the health of the tea plants and, subsequently, influence the chemical composition of the leaves. The development of tea leaves is intricately linked to the availability of water, as it directly influences the plant's ability to absorb nutrients from the soil (Kowalska *et al.,* 2021). The concentration of flavour compounds in tea, including polyphenols and other aromatic substances, is closely tied to the plant's metabolic activity, which can be disrupted under water stress or waterlogged conditions (Cai *et al.,* 2018). In essence, changes in rainfall patterns due to climate change have the potential to disturb the delicate water balance essential for tea cultivation (D’Auria *et al.,* 2022). This, in turn, can impact the development of tea leaves and influence the concentration of flavour compounds, ultimately shaping the taste and quality of the final tea product (Zhai *et al.,* 2022). Adaptation strategies, such as improved irrigation practices or the selection of tea varieties resilient to varying water conditions, become crucial for mitigating the effects of changing precipitation patterns on tea flavour (Pokharel *et al.,* 2021).

Climate change introduces shifts in environmental conditions that can significantly impact the interactions between tea plants and their surrounding ecosystem (Jayasinghe *et al.,* 2021). Specifically, alterations in temperature and precipitation patterns can bring about changes in the distribution and behaviour of pests and diseases affecting tea crops. Rising temperatures can create more favourable conditions for the expansion and proliferation of specific pests that may not have been as prevalent in the past (Sutherst *et al.,* 2011). The altered climate can also contribute to the emergence of particular diseases, as precipitation patterns influence the growth and spread of pathogens that affect plants (Barua *et al.,* 2023) . To combat the increased threat of pests and diseases, farmers often resort to the use of pesticides (Hazarika *et al.,* 2023). However, the application of these chemicals to manage agricultural challenges can have unintended consequences. Pesticides not only target the pests and diseases but can also impact the overall composition of the tea plant and its surrounding ecosystem. Consequently, the use of pesticides has the potential to influence the flavour and sensory characteristics of the tea produced from these treated crops (Wang *et al.,* 2019). Thus, the intricate relationship between climate change, pest and disease dynamics, and pesticide usage underscores the complex challenges faced by tea cultivation. Adapting to these changes requires a careful balance between managing agricultural threats and preserving the distinct qualities that define the flavour profile of tea (Aaqil *et al.,* 2023). Overall, the specific impact of climate change on tea flavour profiles can vary based on regional climate patterns, tea varieties, and cultivation practices. Adaptation strategies in agriculture and careful monitoring of tea plantations are crucial to mitigate the potential adverse effects of climate change on tea quality.

Impact on Tea Production

Climate change presents both advantages and disadvantages for tea growth and development, with a significant impact expected on tea yield (Rwigema *et al.,* 2021). As a C3 crop, tea plants benefit from increased CO_2 levels, temperature, and rainfall (Li *et al.,* 2017). However, they also face challenges such as reduced sunny days, rainfall variability, and extreme weather events like droughts and floods (Rahman *et al.,* 2022). The record-high atmospheric CO_2 concentration in 2023, reaching 424 ppm according to NOAA's Global Monitoring Lab, has led to increased biomass production in tea leaves due to enhanced photosynthesis (Rebecca *et al.,* 2019). Elevated CO_2 levels improve photosynthesis in tea plants, boosting biomass production through increased photosynthesis and respiration (Wijeratne *et al.,* 2007).

The impact of climate change on tea yield varies across regions. While some cooler countries experience beneficial effects from rising temperatures, many tea-producing countries report reduced yields due to increased temperatures (Raj *et al.,* 2019). Tea growth is highly temperature-dependent, with temperatures beyond 12 °C and 30 °C being less favourable for tea bushes (Carr *et al.,* 1992; Jayasinghe *et al.,* 2020). Optimal photosynthetic rates occur at average temperatures between 18 °C and 20 °C, and deviations from this range can reduce yield by affecting evapotranspiration and altering the microclimate around tea bushes (Jayasinghe *et al.,* 2020) . Rainfall quantity and distribution also significantly affect tea production, with high, low, or uneven rainfall reducing yield (Lou *et al.,* 2021).

Global warming affects the hydrological cycle, leading to increased rainfall variability, floods, and soil erosion in tea fields (Sombroek *et al.,* 1996). Drought stress is another significant factor reducing tea yield by increasing dormant or unproductive buds (Cheruiyot *et al.,* 2007; Ng'etich *et al.,* 2001). Optimal conditions for tea yield include specific radiation intensity, humidity levels, and photoperiods (Mohotti *et al.,* 2000). However, solar radiation patterns have become unstable due to climate change, with fewer sunny days and more cloudy days potentially benefiting tea production (Ahmed, 2014). Additionally, light quality plays a role, with certain wavelengths inhibiting tea plant growth while others stimulate it (Fu *et al.,* 2015).

Possible effects on the economy

Climate change can have several significant effects on the economy, not just for tea but for various crops, crops like paddy which cover a large area in Assam (Dutta *et al.,* 2023) and eventually affect the economy of the state/region. It has been seen impacting various stages of tea production, from cultivation to processing and marketing. The global tea industry, deeply rooted in tradition and geography, is facing a significant challenge the impact of climate change on traditional tea-growing regions. The intricate interplay of temperature and humidity conditions is reshaping landscapes, rendering some areas unsuitable for tea cultivation (Jayasinghe *et al.,* 2019; Jayatilakha *et al.,* 2012; Kotikot *et al.,* 2020). This shift necessitates a re-evaluation of cultivation strategies, which might help in better growth of crops (Talukdar *et al.,* 2020), potential relocations of tea plantations to higher altitudes, and raises concerns about established supply chains. In this context, it becomes imperative to explore the multifaceted consequences and potential solutions for sustaining the tea industry in the face of climate-induced transformations.

Climate change is altering the climatic conditions that have long supported tea cultivation (Ahmed *et al.,* 2018). Traditional tea-growing regions may experience shifts in temperature and humidity (Kakoti *et al.,* 2023), adversely affecting the quality and quantity of tea produced. Increased temperatures can lead to stressed tea plants, affecting flavor profiles and overall yield. The need for adaptation is evident in all crops (Dutta *et al.,* 2023), prompting considerations for the relocation of tea plantations to higher altitudes or different geographical locations with more suitable climate conditions (Muench *et al.,* 2021).

A change in the supply structure in recent decades is the transformation from large plantations to smallholders (Chang *et al.,* 2015). In Assam for instance currently, the number of Small Tea Growers (STGs) is 122415 while during 2008 it was 64597 (Deka *et al.,* 2022). Tea cultivation is attractive to smallholders because it provides work and income throughout the year, requires relatively little investment, labour is available on a casual basis and the risk of complete crop failure is small (Duncan *et al.,* 2016). Now, with the sudden changes in the climate the tea growers are facing various issues, (Duncan *et al.,* 2016) found that monthly temperatures above 26.6 ºC had an adverse effect on the tea yield, and an additional one degree of temperature at an average monthly temperature of 28 ºC would reduce the yield by 3.8% in Assam, India. As agricultural yields decline, farmers may encounter a myriad of challenges. The production costs on smallholder tea farms have historically remained lower than those on larger estates, primarily due to treating the opportunity cost of farm household labour as nearly negligible (Deka *et al.,* 2021). Consequently, the proportion of national tea production contributed by smallholder farms has seen a significant rise (Herath *et al.,* 2009). However, these smallholder operations confront hurdles such as reduced traceability, lower quality, and limited participation in export-oriented supply chains that are adapting to heightened standards in terms of quality, social responsibility, and environmental sustainability.

The landscape is further complicated by the evolving challenges of climate change, introducing an additional layer of complexity to the profitability of smallholder tea farms. Sustaining profitability now hinges on the adaptation of strategies, which, unfortunately, comes with increasing costs. The rising expenses associated with mitigating climate change are beginning to reverberate through social facilities in tea estates, giving rise to serious socio-economic issues that are particularly critical in major tea-producing countries.

These socio-economic challenges encompass a spectrum of issues related to working conditions on tea plantations. They include persistently low wages, substandard housing, concerns regarding health and safety, a declining workforce with an upsurge in part-time child labour, the shift of regular employment to casual or short-term arrangements, gender-based discrimination, and a diminishing representation of workers. As the cost of climate change mitigation escalates, it intersects with these existing socio-economic challenges, creating a complex web of issues that demand comprehensive and sustainable solutions to safeguard the well-being of tea plantation workers and the industry at large.

Conclusion

Climate change is presenting a multifaceted and intricate challenge to the tea industry, influencing every stage of its production cycle, from cultivation to processing and marketing (87). The changing patterns of temperature and precipitation directly impact key aspects such as the flavor profiles of tea, overall yield, and the economic sustainability of tea production. The delicate balance of flavour compounds in tea leaves is being altered, and traditional growing regions are undergoing significant transformations, all of which contribute to the complexity of supply chains within the industry.

For smallholder tea farmers, these challenges are compounded by unique socio-economic issues, further intensified by the urgent need for adaptation strategies and the rising costs associated with mitigating the effects of climate change. The repercussions of climate change extend beyond the mere quality of the tea; they extend to the livelihoods and well-being of those involved in its cultivation.

Addressing these challenges requires a holistic and integrated approach. It involves implementing adaptation measures that account for the changing climate, adopting sustainable farming practices to ensure environmental resilience, and initiating socio-economic programs to support the communities engaged in tea production. This comprehensive strategy aims not only to maintain the high quality of tea but also to secure the welfare of the individuals whose lives are intricately tied to this industry.

In navigating these complexities, collaborative efforts among stakeholders, policymakers, and researchers are paramount. Only through a united and coordinated approach can we hope to ensure the resilience and longevity of this beloved beverage. It is not merely a matter of preserving tea; it is about safeguarding an entire ecosystem of production and livelihoods that sustains the industry and countless individuals dependent on it. The urgency of the situation calls for collective action to tackle the multifaceted challenges posed by climate change in the tea industry.

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