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Impact of climate change on plantation crops with special reference to tea (*Camellia sinensis* (L.) O. Kuntze) in India

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Climate change poses a serious threat to the sustainability and productivity of plantation crops in tropical and subtropical regions. In India, tea (*Camellia sinensis* (L.) O. Kuntze), a major plantation crop and economic driver, is particularly sensitive to changing climatic variables. This study analyzes the shifts in critical climatic variables across four major Indian tea-growing regions, viz., South Bank (Assam), Nagrakata (West Bengal), Anamallais (Tamil Nadu), and the High Ranges (Kerala) over a 30-year period (1996–2025). Using the Mann–Kendall trend test and Sen’s slope estimator, significant spatiotemporal climate variations like maximum and minimum temperatures (Tmax, Tmin), rainfall (RF), and relative humidity (RH) were analyzed. Data were segregated into demi-decadal and seasonal intervals to observe periodic and seasonal fluctuations. Findings showed that the South Bank and Nagrakata regions experienced a significant increase in Tmax ($p < 0.001$), with a rise of 1.1 °C–1.3 °C compared to long-term averages, while Tmin decreased significantly ($p < 0.001$) by 1.8 °C in South Bank. In the case of Nagrakata, although long-term RF increased ($p < 0.05$), total rainfall notably decreased by 88 mm in 2025, while in South Bank, the decrease was 364 mm. The morning and afternoon RH in both regions declined ($p < 0.05$), where the afternoon RH dropped by about 2%. In Anamallais, Tmax declined (τ -coefficient = -0.07), while winter Tmin increased. Notably, overall seasonal RF significantly increased ($p < 0.05$), alongside a significant rise in morning and afternoon RH ($p < 0.001$). Conversely, the High Range regions showed a widening temperature gap, with Tmin rising significantly ($p < 0.001$) in recent years. While overall seasonal rainfall increased ($p < 0.05$), the critical monsoon rainfall decreased, along with its morning RH ($p < 0.05$). These changing trends of the overall climatic pattern have a substantial impact on tea cultivation and its production. In order to safeguard this tea sector, the study discusses the urgent implementation of integrated adaptation and mitigation strategies, including the deployment of drought-tolerant cultivars, agroforestry for microclimate regulation, and multi-scalar policy frameworks to protect the millions of livelihoods tied to this labor-intensive industry.

KEYWORDS

adaptation, climate change, humidity, mitigation, rainfall, tea, temperature

1 Introduction

Tea (*Camellia sinensis* (L.) O. Kuntze) is a globally vital monoculture plantation cash crop and the primary livelihood for millions of people. India is the second-largest producer and third-largest exporter of black tea, with the industry supporting millions of livelihoods (Van Der Wal, 2008). Given its economic and social significance, this industry relies particularly on the Northeastern states of Assam and West Bengal (Darjeeling), as well as on the Southern states of Kerala and Tamil Nadu. These regions offer diverse agro-climatic conditions ranging from the fertile plains of the Brahmaputra Valley to the high-altitude terrains of Darjeeling, Anamallais, and Munnar, which contribute to both high productivity and distinctive tea quality. Of the following, Assam accounts for over 50% of the national production (Jain et al., 2007; Yinga et al., 2022), followed by West Bengal. The tea regions of Assam and Darjeeling are characterized by plains and varied high-altitude zones with seasonal dormancy and distinct flushes, whereas South Indian plantations are situated in steeper, rugged mountainous areas, with high-elevation landscapes under tropical conditions that support year-round harvesting.

Within this diverse geographical region, tea remains highly sensitive to climatic variability. Environmental factors strongly influence its growth, leaf productivity, and quality. Tea grows best in warm and humid conditions (>80% humidity), with an optimum temperature of 30 °C–32 °C during the active growth period (Aditya et al., 2023), along with 1,500–3,000 mm of evenly distributed rainfall (Gangopadhyay et al., 2016). However, deviations from these optimal conditions can severely affect tea physiology and productivity. Temperatures above 35 °C or below 13 °C cause physiological stress (Zakir, 2018), reducing photosynthesis and shoot growth, which can lead to summer scorching or winter frost damage (Ahmed et al., 2018). In Southern India, about 70%–75% of rainfall occurs during the Southwest monsoon (June–September), while the remaining 25%–30% comes from the Northeast monsoon (October–December; Varikoden and Revadekar, 2020).

This distinct seasonal rainfall pattern influences key cultural practices in tea cultivation, particularly pruning schedules. Pruning is regarded as a vital practice synchronized with rainfall patterns for maintaining bush height, promoting vegetative growth, and ensuring uniform crop distribution (Liang et al., 2024; Ramanjineyulu et al., 2024). In South India, major rejuvenation (hard) pruning is carried out during the pre-monsoon period (April–May), covering over 50%–60% of the area, followed by medium and light pruning during the post-monsoon period, while skiffing is typically done in October to postpone the pruning cycle (Rathour and Bhowmik, 2023). Additionally, relative humidity plays a crucial role in tea growth and productivity (Ahmed et al., 2018), and ongoing climate change is increasingly disrupting this delicate balance of weather parameters. As a result, the increasing instability of climatic conditions is emerging as a major constraint to tea production systems (Wang et al., 2024). Rising temperatures, erratic rainfall, and frequent extreme weather events are reducing suitable tea-growing areas, particularly in vulnerable regions like Assam (Roy et al., 2020; Babu et al., 2022). These changes have resulted in heat stress, drought-like conditions, crop damage, and yield instability, while also degrading tea quality

and increasing pest and disease incidence (Baruah and Handique, 2021; Edwin Raj et al., 2017). Thus, emphasizing the urgent need for long-term, multidisciplinary research to develop adaptive strategies for sustaining the Indian tea sector under changing climatic conditions is the need of the hour.

In this broader context, the vulnerability of tea cultivation extends beyond localized impacts to a global scale (Mittal et al., 2021). Ideal growing conditions for tea are increasingly at risk worldwide, including in major Indian regions such as Assam, West Bengal, Kerala, and Tamil Nadu. Despite these concerns, significant research gaps remain in addressing these challenges in an integrated manner. The primary lacuna addressed in this study is the critical gap in long-term, region-specific climate monitoring, impact assessment, and the development of adaptive strategies to sustain India's tea sector under climate change. Thus, our study focuses on the long-term (annual and seasonal) trends of climate change in India's major tea-growing regions using non-parametric statistical approaches, while identifying suitable adaptation and mitigation strategies. Understanding and visualizing these regional changes and their impacts on tea cultivation will thereby help ensure food security, protect livelihoods, and sustain the tea ecosystems.

2 Materials and methods

2.1 Study area

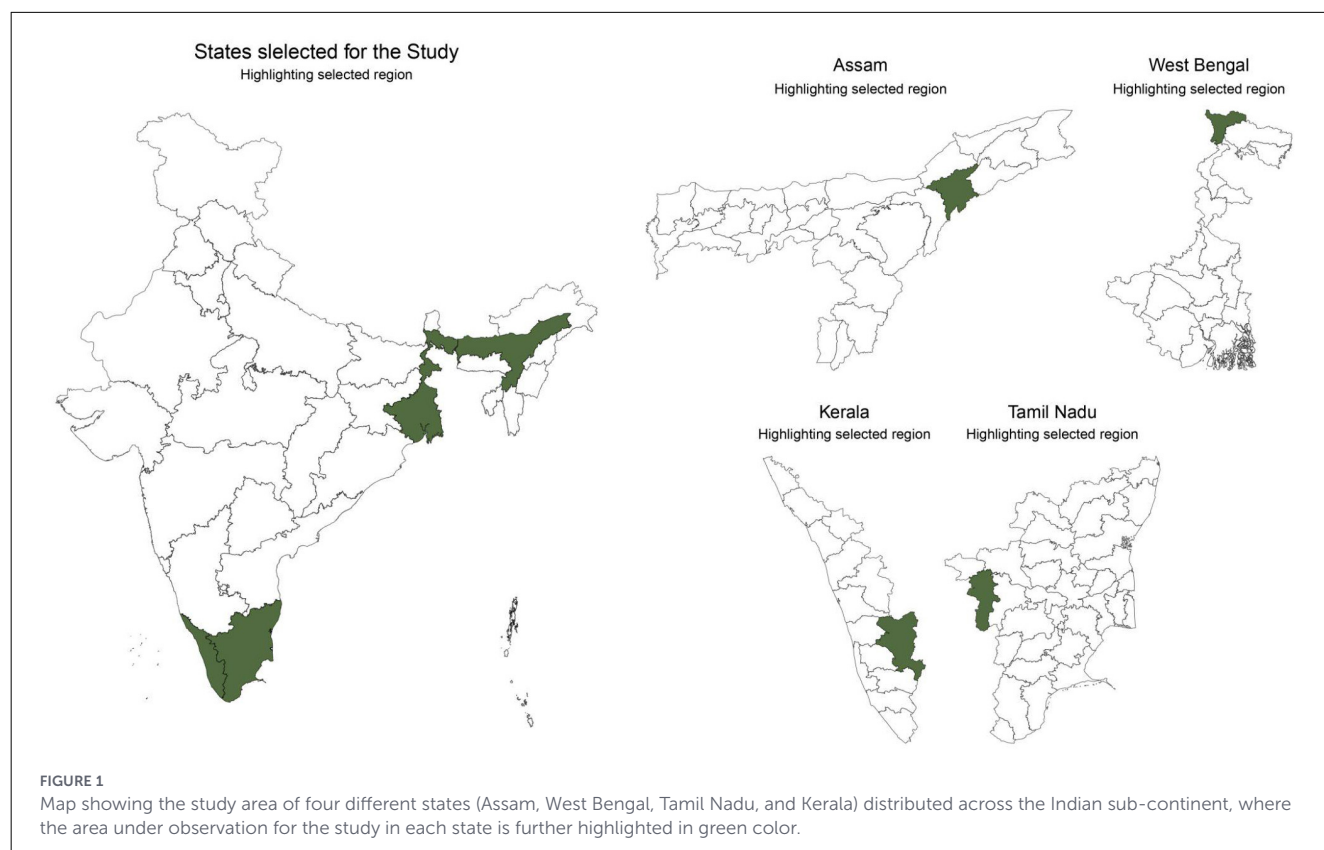
The study was conducted across four major tea-growing regions of India, viz., Assam, West Bengal, Tamil Nadu, and Kerala. For Assam and West Bengal, the research focused on the South Bank (26°43' N and 94°13' E, altitude: 116 m above sea level) and Nagrakata (26°53' N and 88°55' E, altitude: 226.6 m above sea level) regions, respectively. For Southern India, the study focused on the Anamallais (Valparai, 10°2' N, 76°8' E, and altitude: 1,065 m above sea level) region of Tamil Nadu and the High Ranges (Munnar, 10°09' N, 77°06' E, altitude: 1,600 m above sea level) region in Kerala (Figure 1).

2.2 Meteorological data collection

To understand the changing patterns and their impact on tea cultivation, historical climate data for over 30 years (1996–2025) were collected. The primary data for Assam and West Bengal were obtained from the meteorological stations of Tocklai Tea Research Institute, Jorhat, and North Bengal Regional Research Center, Nagrakata. Likewise, for Southern India, the primary data was collected from the UPASI Tea Research Institute, Valparai, and its Munnar Regional Center. The number of sites selected for the study depended on their long historical records and the availability of error and gap-free data.

2.3 Climatic variables considered for analysis

For this study, temperature, precipitation, and relative humidity parameters were considered due to their direct influence



on tea cultivation. Temperature was evaluated using both maximum (Tmax) and minimum (Tmin) temperature records, which provide insights into diurnal variability and temperature extremes. In case of precipitation, rainfall (RF) was considered, representing the total precipitation received over a given temporal scale, while relative humidity (RH) was analyzed for both the morning and afternoon periods to account for daily variations in atmospheric moisture content.

2.4 Analysis of climatic trends: non-parametric approaches

Initially, the historical data set from all four regions was evaluated to ensure quality and homogeneity. The Mann–Kendall (MK) trend test was utilized to determine the significance, while Sen's slope was used to determine the direction of temporal trends (Partal and Kahya, 2006; Yilmaz and Perera, 2015). Both MK and Sen's slope trend tests were individually applied for the four regions at 95%, 99%, and 99.9% confidence levels (Khalil, 2023). To study seasonal variations, the data were segregated into four seasons. For Assam and West Bengal, the primary data were segregated into pre-monsoon (March–May), monsoon (June–September), post-monsoon (October–November), and winter (January, February, and December). For Tamil Nadu and Kerala, the same were segregated into Southwest (SW) monsoon (June–September), Northeast (NE) monsoon (October–November), winter (December–February), and summer (March–May). Furthermore, demi-decadal (5-year interval) analyses were

conducted for all primary weather variables (Tmax, Tmin, RH, and total annual RF) to examine short-term, periodic fluctuations and to calculate mean distributions with standard deviations. Further, to visualize the shifts in the distribution of RF over time, decadal mean distributions of monthly RF were compared between the decade (1996–2005) and the most recent (2016–2025).

2.5 Statistical analysis and visualization

The study area map was prepared using Python version 3.14. The Mann–Kendall trend test, Sen's slope, and linear regression analysis were performed using R software version 4.5.2, with the “ggplot2” visualization and “trend” packages for the Mann–Kendall test. Significance levels were tested at $p < 0.05$. Line and radar plot representations were generated to visualize temporal and seasonal changes in selected parameters, respectively, using both R statistical software and GraphPad Prism version 9.5.

3 Results and discussion

3.1 Changing temperature patterns in tea growing regions

Climate change poses significant threats to tea cultivation because of its specific environmental parameters (Dutta, 2014), particular temperature ranges, rainfall patterns, humidity, and day length. In our study, the Mann–Kendall trend and Sen's

slope estimator of meteorological data (1996–2025) highlighted that India's tea-growing landscapes are experiencing a significant temperature shift, though the direction of change was not uniform across the country. Regionally, the South Bank, Assam, and the Nagrakata, West Bengal, exhibited a 30-year trend of rising Tmax, which showed a significant increase ($p < 0.001$) with Kendall's tau (τ) coefficients of 0.60 and 0.44, respectively. Similarly, the Tmin for both regions decreased significantly ($p < 0.001$) with τ -coefficients of -0.48 and -0.60 . The slopes for Tmax and Tmin were 0.06 and -0.06 for South Bank, respectively, while for Nagrakata they were 0.05 and -0.13 , respectively (Figures 2, 3). In contrast, the South Indian regions showed more fluctuations, where the Anamallais region of Tamil Nadu observed a Tmax and Tmin that steadily increased for a period, and later decreased (Figures 4, 5). Here, the Tmax has shown a significant upward trend ($p < 0.001$) with Kendall's tau (τ) coefficient of 0.22, whereas the Tmin was insignificant ($p > 0.05$) with Kendall's tau (τ) coefficient of -0.07 . Meanwhile, the High Range region of Kerala recorded an increasing gap between Tmax and Tmin. Here, the Tmax has shown a significant upward fluctuation ($p < 0.001$) with Kendall's tau (τ) coefficient of 0.41, whereas the Tmin has decreased significantly in recent years ($p < 0.001$) with Kendall's

tau (τ) coefficient of -0.39 . Bhagat and his co-workers observed that long-term trends from 1918 to 2014 had indicated rising Tmin by approximately 1.3°C in the tea-growing regions of Assam (Bhagat et al., 2016). Our findings showed similar long-term trends. It was observed that in recent years, Assam and Nagrakata have experienced an increase in Tmax (1.1°C – 1.3°C) when compared to their long-term average. Interestingly, in 2025, Tmin in Assam decreased by about 1.8°C , while in Nagrakata it increased by 1.3°C . These rapid fluctuations in temperature can severely affect tea yield and quality by influencing the polyphenolic catechin, methylxanthine, and other secondary metabolites (Ahmed et al., 2018).

Seasonal data highlighted that temperature sensitivity was highly region-specific. In the South Bank, Tmax increased significantly ($p < 0.001$), with an average τ -coefficient of 0.60, during all seasons, while Tmin decreased ($p < 0.001$, τ -coefficient of -0.48 ; Figure 6). In the case of Nagrakata, the overall seasonal Tmax increased ($p < 0.001$, τ -coefficient of 0.44), while the Tmin decreased significantly at $p < 0.001$ with a τ -coefficient of -0.60 (Figure 7). In the Anamallais, Tmax increased significantly ($p < 0.001$, $\tau = 0.22$), the Tmin of the region showed a decreasing trend over the last decade, with a τ -coefficient of -0.072 , while

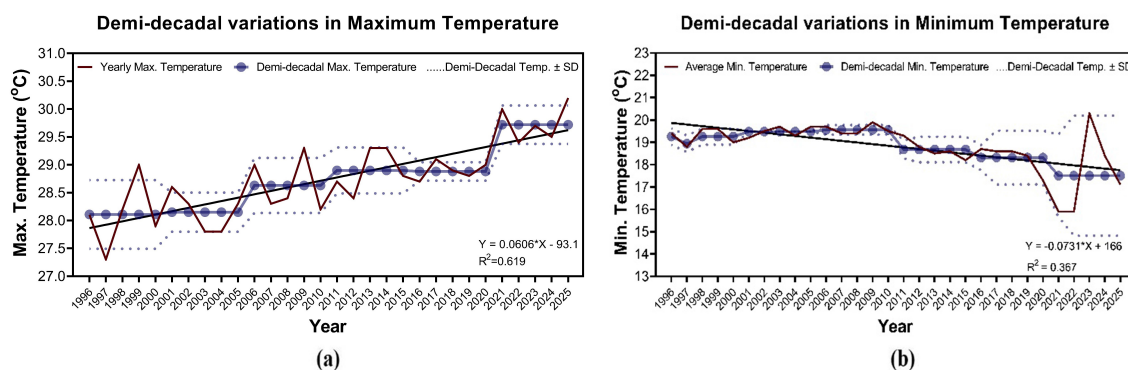


FIGURE 2

Demi-decadal analysis of average (a) Tmax and (b) Tmin in the South Bank, Assam (1996–2025), where the x-axis shows the years, and the y-axis represents temperature ($^\circ\text{C}$). The red line represents the yearly average temperature, while the blue line represents the demi-decadal average temperature, with upper and lower SD represented by dotted blue lines.

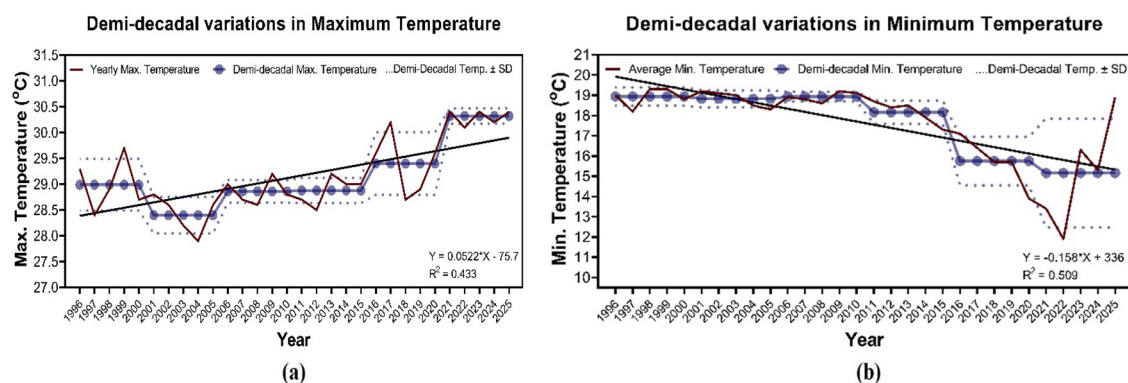


FIGURE 3

Demi-decadal analysis of (a) Tmax and (b) Tmin in the Nagrakata region of West Bengal (1996–2025), where the x-axis shows the years, and the y-axis represents temperature ($^\circ\text{C}$). The red line represents the yearly average temperature, while the blue line represents the demi-decadal average temperature, with upper and lower SD represented by dotted blue lines.

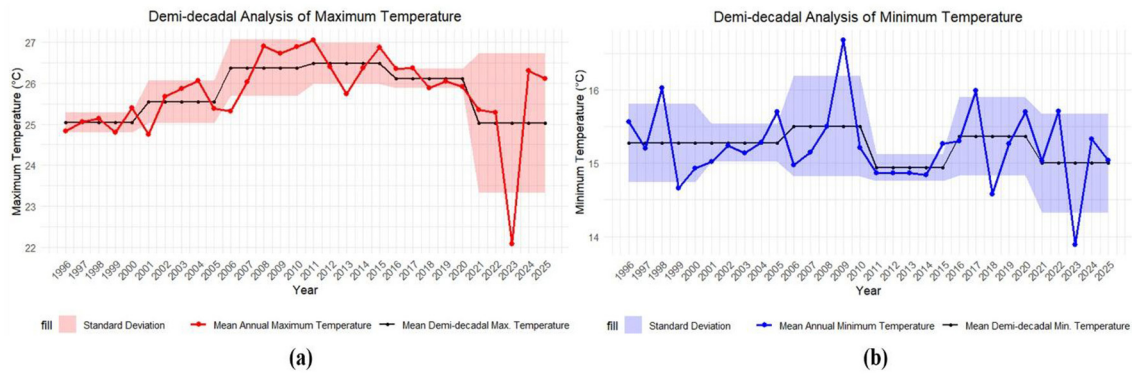


FIGURE 4

Demi-decadal analysis of (a) Tmax and (b) Tmin in the Anamallais (1996–2025), where the x-axis shows the years, and the y-axis represents temperature (°C). The red and blue lines represent the yearly average temperature, while the black line represents the demi-decadal average temperature, with upper and lower SD represented by dotted blue lines.

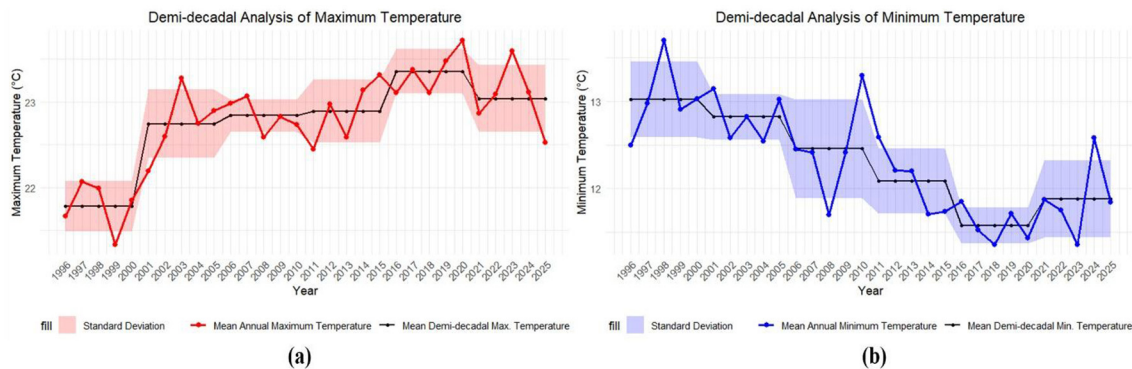


FIGURE 5

Demi-decadal analysis of (a) Tmax and (b) Tmin in the High Ranges (1996–2025), where the x-axis shows the years, and the y-axis represents temperature (°C). The red and blue lines represent the yearly average temperature, while the black line represents the demi-decadal average temperature, with upper and lower SD represented by dotted blue lines.

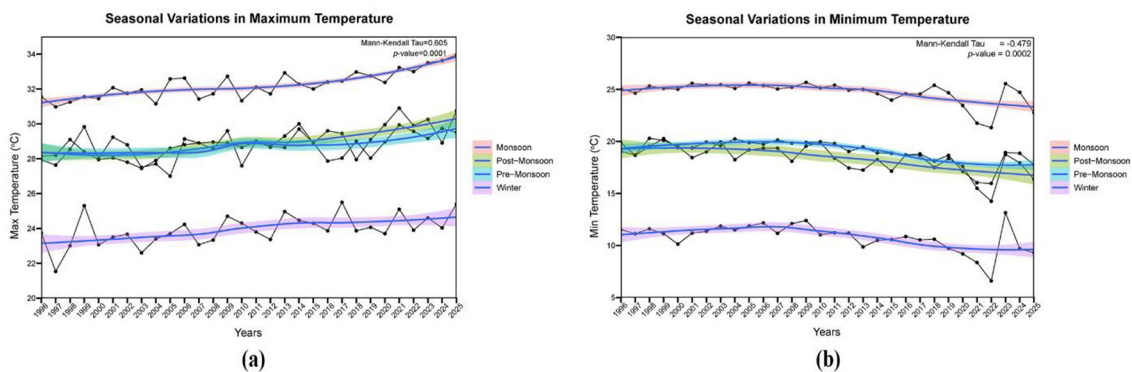


FIGURE 6

Seasonal variation of (a) Tmax and (b) Tmin in the South Bank region of Assam (1996–2025), where the x-axis shows the years, and the y-axis represents temperature (°C). The lines pink (monsoon), green (post-monsoon), blue (pre-monsoon), and purple (winter) represent the average seasonal temperature, with the upper and lower SD indicated by their colors.

the winter Tmin showed an increase over the same period (Figure 8). Conversely, in the High Range regions of Kerala, Tmax showed a steady increase during the summer and winter but recorded a decreasing trend during the Monsoons. Overall, the

average Tmin in this region declined throughout the seasons ($p < 0.001$, $\tau = -0.39$; Figure 9). In Northeast India, this seasonal temperature fluctuations demonstrates the vulnerability of tea plantations to temperature increase (1 °C), where a decrease of

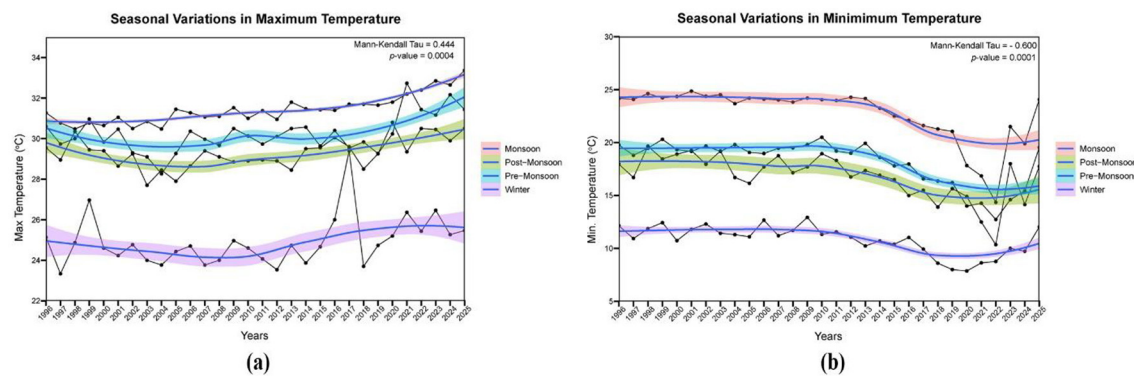


FIGURE 7

Seasonal variation of (a) Tmax and (b) Tmin in the Nagrakata region of West Bengal (1996–2025), where the x-axis shows the years, and the y-axis represents temperature (°C). The pink (monsoon), green (post-monsoon), blue (pre-monsoon), and purple (winter) lines represent the average seasonal temperature, with the upper and lower SD indicated by their colors.

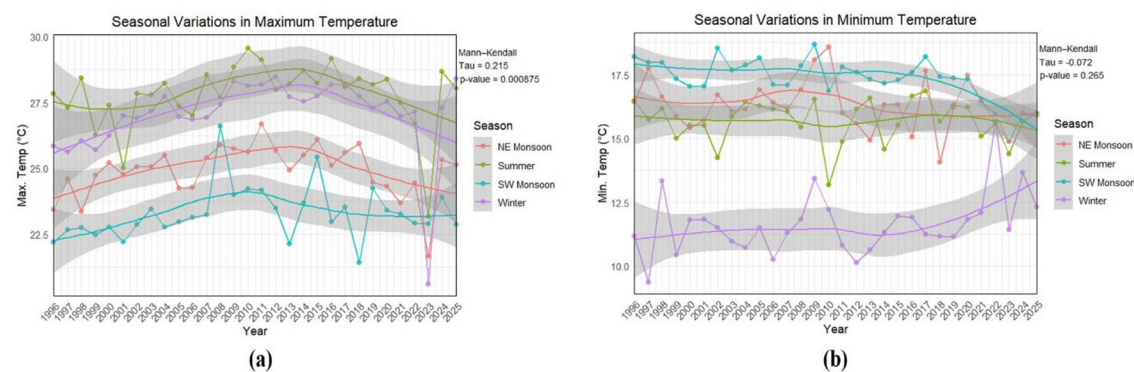


FIGURE 8

Seasonal variation of (a) Tmax and (b) Tmin in the Anamallais region of Tamil Nadu (1996–2025), where the x-axis shows the years, and the y-axis represents temperature (°C). The pink (NE monsoon), green (summer), blue (SW monsoon), and purple (winter) lines represent the average seasonal temperature, with the upper and lower SD indicated by their colors.

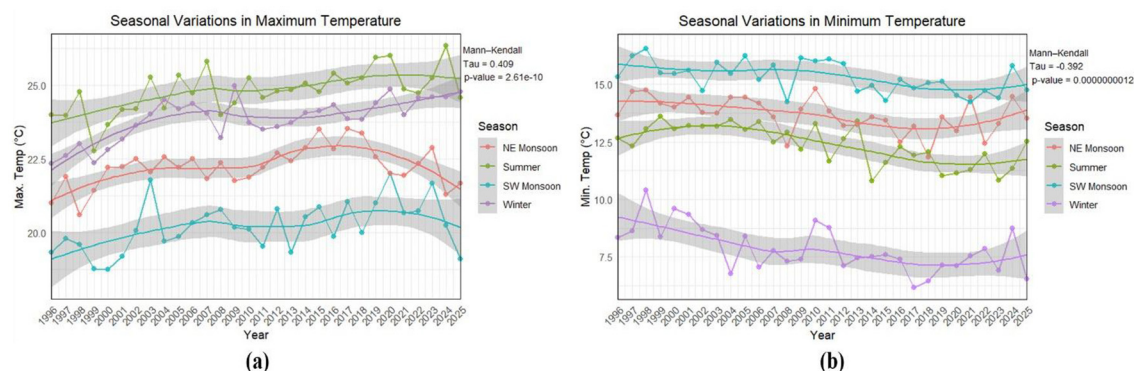


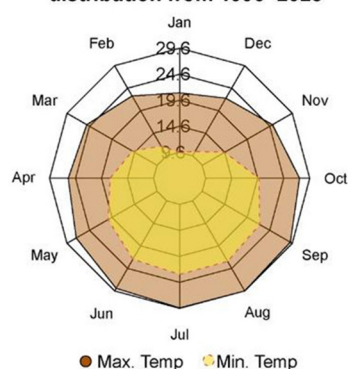
FIGURE 9

Seasonal variation of (a) Tmax and (b) Tmin in the High Ranges region of Kerala (1996–2025), where the x-axis shows the years, and the y-axis represents temperature (°C). The pink (NE Monsoon), green (summer), blue (SW monsoon), and purple (Winter) lines represent the average seasonal temperature, with the upper and lower SD indicated by their colors.

3.8% in yield was observed when the monthly temperatures were above 26.6 °C (Duncan et al., 2016). These climatic shifts are reported to have observable effects on tea cultivation, as they can significantly ($p < 0.001$) affect the overall tea production

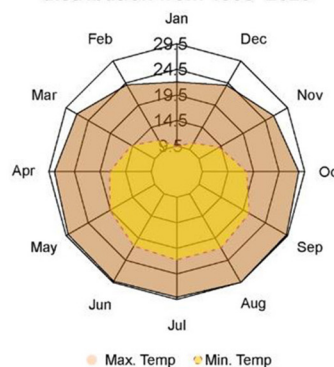
(Baruah and Handique, 2021; Boehm et al., 2016). In a study by Jayasinghe and Kumar (2020), it was predicted that changing annual mean temperatures and rainfall variations can decrease suitable habitats for tea cultivation by 26.2%, 14.0%, and 4.7% in

Average Maximum & Minimum Temperature distribution from 1996–2025



(a)

Average Maximum & Minimum Temperature distribution from 1996–2025



(b)

FIGURE 10

Shifts in average Tmax and Tmin distribution in (a) South Bank and (b) Nagrakata regions between 1996 and 2025.

Kenya, Sri Lanka, and China, respectively. Moreover, a reduction of 12%–15% in tea yield was recorded due to pest and disease occurrence (Roy et al., 2020; Varatharajan et al., 2019), caused by rising temperatures.

According to our findings, the South Bank region of Assam experienced a severe increase in June, July, August, and September, driven by changes in its average Tmax and Tmin during the recent decade (Figure 10a). This shift in temperature across the months was also prominent in the region of Nagrakata, where extreme temperatures occurred in May, June, July, August, and September (Figure 10b). Similarly, a study in Darjeeling's tea sector confirmed that approximately 0.51 °C of temperature increase over two decades (1991–2023), coupled with changing rainfall patterns, has shifted the timing of flushes in tea crops and their yields (Sahu et al., 2024). These extreme temperature fluctuations have led to water scarcity, resulting in oxidative stress and decreased concentrations of bioactive compounds, such as theanine and catechins, found in tea leaves (Wang et al., 2016; Cheruiyot et al., 2007; Singh et al., 2009). Similar studies have also reported a potential decrease in tea production due to rising Tmax in key tea-growing regions of Kenya (Okoth, 2011). A survey by Duncan et al. (2016) found that when monthly temperatures exceed 26.6 °C, tea yield in Assam declines gradually. In his study, he also noted that an additional 1 °C rise in temperature, at a monthly average of 28 °C, reduces yield by 3.8%. Similarly, Wijeratne et al. (2023) reported yield reductions in Sri Lanka at temperatures above 25 °C–26 °C, whereas Han et al. (2017) observed yield increases in cooler regions as temperatures rose.

3.2 Changing precipitation in tea-growing regions

Tea cultivation relies heavily on abundant and well-distributed rainfall for sustained commercial production (Aryal et al., 2014). Rainfall fluctuations can directly affect biotic stress and drastically influence crop growth and productivity (Guo et al.,

2017; Ahmed et al., 2018). The regional data of our study sites highlighted a clear divergence in how rainfall has shifted across India's tea belts during the last 30 years. Here, it was observed that the South Bank had experienced declining annual RF trends ($p > 0.05$; τ -coefficient of -0.22 , Sen's slope of -10.05) over the last three decades (Figure 11a). Earlier reports have documented that South Bank has experienced uneven rainfall, where during the period of 2014–2023, the rainfall decreased by 249 mm, leading to drought stress during the key flushing period of tea (Rahman et al., 2025). Interestingly, compared to the South Bank, the Nagrakata region showed an increasing trend in average annual RF ($p > 0.05$; τ -coefficient of 0.09 ; slope of 0.46 ; Figure 11b). Researchers had previously observed that long-term precipitation trends indicated a decline of over 200 mm in annual precipitation in Assam, exacerbating climate stress on tea cultivation (Bhagat et al., 2016). In our study, we observed that in Assam and Nagrakata, the total annual RF decreased by 364 and 88 mm, respectively, in 2025, which is consistent with their findings. Further, to observe variations, seasonal analyses were performed across the four tea-growing regions.

When compared across seasons, rainfall gradually decreased over the years, especially during the monsoon and pre-monsoon seasons. In South Bank, seasonal rainfall decreased significantly ($p > 0.05$; $\tau = -0.22$; Figure 12a). Farmers in China reported that changing monsoon patterns affect tea harvests, where data from 1980 to 2011 showed that a 1% delay in monsoon retreat reduces tea yields by 0.48%–0.53%, while a 1% increase in monsoon precipitation decreases yields by 0.18%–0.26% (Boehm et al., 2016). From our findings, in Nagrakata, the overall seasonal rainfall showed an increasing trend line ($p > 0.05$, $\tau = 0.09$; Figure 12b), but the monsoon season downpour showed a decrease. Interestingly, Anamallais and the High Range region have experienced steep deviations in their seasonal rainfall patterns. In the Anamallais region, the overall seasonal rainfall showed a significant increase ($p < 0.05$, with τ -coefficient of 0.13 ; Figure 13a). Notably, the High Range region of Kerala also showed an overall increase in seasonal rainfall ($p < 0.05$, with a τ -coefficient of 0.11); however, a declining trend in monsoon

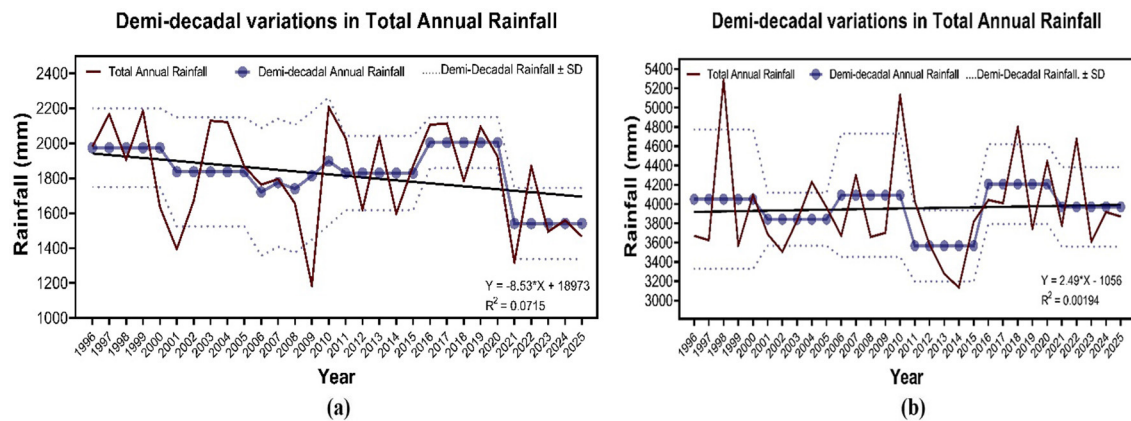


FIGURE 11

Demi-decadal total annual rainfall in (a) South Bank and (b) Nagrakata from 1996 to 2025, where the x-axis shows the years, and the y-axis represents rainfall (mm). The red line represents the annual total rainfall, while the blue line represents the demi-decadal annual rainfall, with upper and lower SD represented by dotted blue lines.

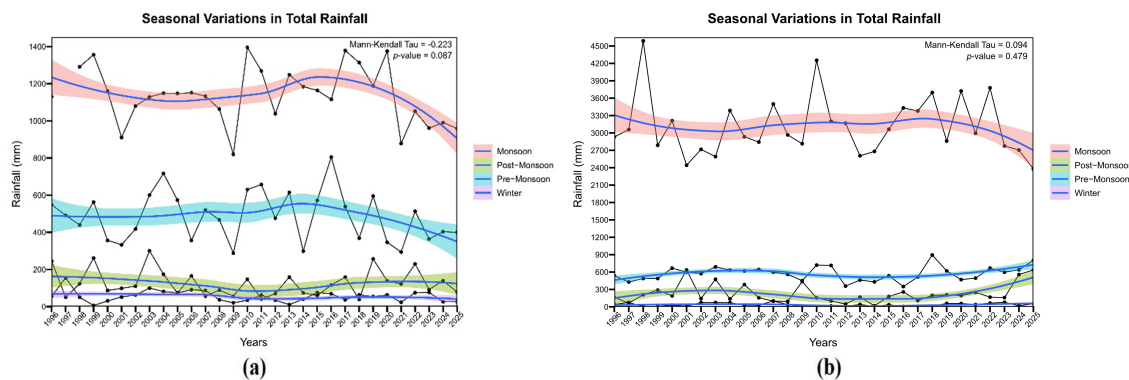


FIGURE 12

Seasonal analysis of rainfall in (a) South Bank and (b) Nagrakata from 1996 to 2025, where the x-axis shows the years, and the y-axis represents rainfall (mm). The lines pink (monsoon), green (post-monsoon), blue (pre-monsoon), and purple (winter) represent the average seasonal rainfall, with the upper and lower SD indicated by their colors.

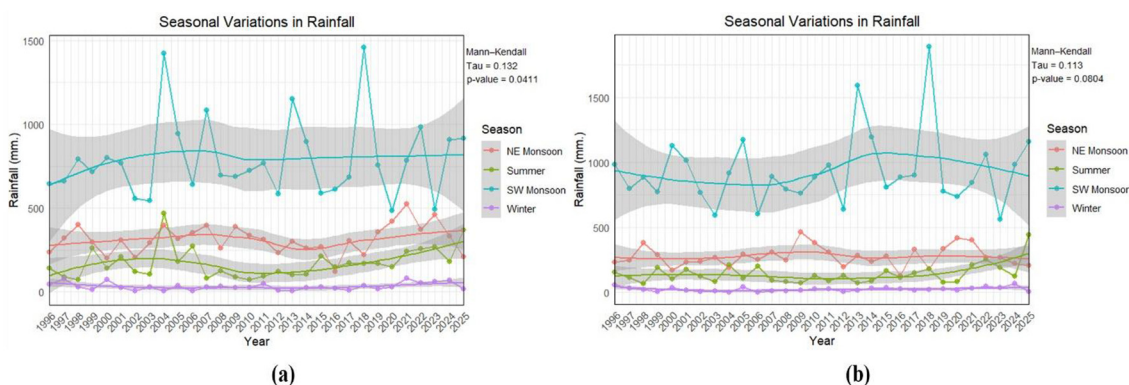


FIGURE 13

Seasonal analysis of rainfall in (a) Anamallais and (b) High Ranges from 1996 to 2025, where the x-axis shows the years, and the y-axis represents rainfall (mm). The pink (NE Monsoon), green (summer), blue (SW monsoon), and purple (Winter) lines represent the average seasonal temperature, with the upper and lower SD indicated by their colors.

rainfall was observed (Figure 13b). Previous studies have indicated that in tea cultivation, there is a relation between soil water and the carbon balance. This relationship may be disturbed by

drought, which reduces soil moisture, limiting water uptake and transpiration, thereby reducing CO₂ assimilation and carbohydrate production (Barman et al., 2012; Rahimi et al., 2019). Interestingly,

Ahmed et al. (2019) in their study have highlighted that reduced leaf flush and bud mortality during drought spells, which lowers tea yields by 53% (Rokhmah et al., 2022). This type of vulnerability may result in the mortality of planting stock and newly established bushes following prolonged floods or waterlogging episodes (Biggs et al., 2018; Lv et al., 2021); likely because excess water leads to hypoxic or anoxic soil conditions (Mukhopadhyay and Mondal, 2017). Rapid fluctuations between drought and intense rainfall can exacerbate these effects, causing greater harm than either condition alone (Bahadur and Dutta, 2023). Using time-series data from 2012 to 2017, Rahman et al. (2017) observed that drought and excessive rainfall negatively affected tea yield, resulting in a decline of 110.8 kg/ha/year. Thus, repeated cycles of such drought-flood stress render tea plants less able to withstand subsequent waterlogging and pathogen attack (Bhattacharyya and Sarmah, 2018).

Since tea is typically cultivated in Assam as a rain-fed crop, its optimal growth is heavily dependent on the weather. In our findings, it was recorded that the South Bank (Figure 14a) and Nagrakata (Figure 14b) showed prominent shifts in the monthly rainfall pattern, where it was seen that the distribution of

downpours in the recent decade (2015–2025) has narrowed down compared to the previous decade (1996–2005). Similar changes in the monthly rainfall pattern were also observed in the Anamallais and the High Range. In the case of Anamallais, the average rainfall received during June decreased, whereas it increased during May and September (Figure 15). Likewise, in High Ranges, the average rainfall received during June decreased, whereas it increased during May, August, and September (Figure 16). In an analogous event, over the previous 50 years, the sub-Himalayan tea-growing regions in North Bengal have recorded an increase in Tmax, along with changes in the rainfall pattern making this region vulnerable (Mukhopadhyay and Roy, 2009). Conversely, it was reported that insufficient rainfall lowers the amount of moisture available in the soil, which in turn suppresses stomatal conductance, photosynthetic efficiency, and new flush generation, which lowers shoot biomass and harvestable yield (Ahmed et al., 2018). Su et al. (2015) observed that a prolonged drought limits the uptake of water and nutrients by increasing oxidative stress and decreasing fine-root density. Similarly, other researchers had also noted that due to excessive or unseasonal rainfall, the tea

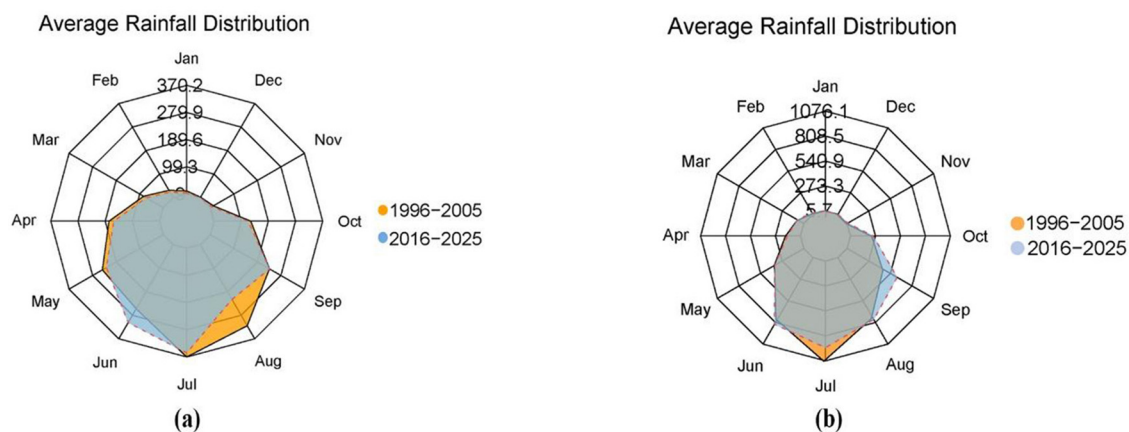


FIGURE 14 Decadal shift in mean distribution of monthly rainfall (mm) in (a) South Bank and (b) Nagrakata regions (1996–2005 vs. 2016–2025).

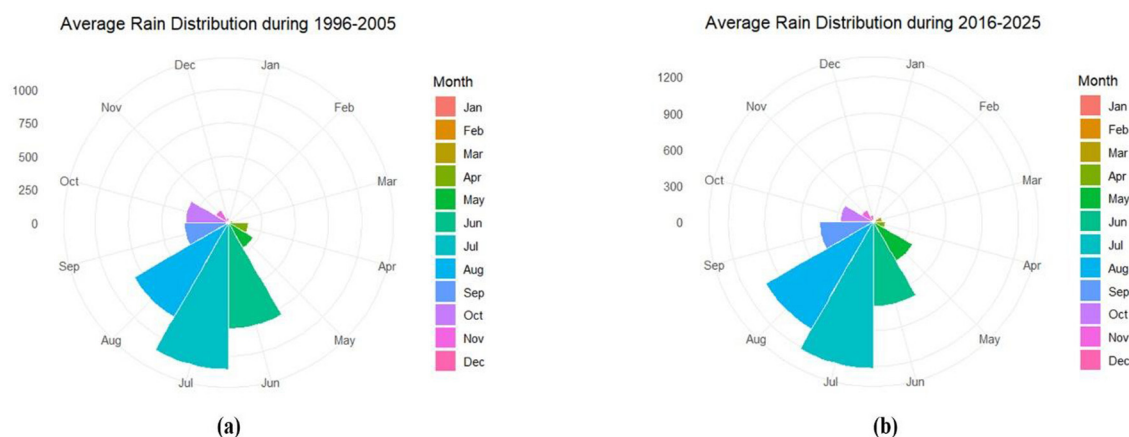
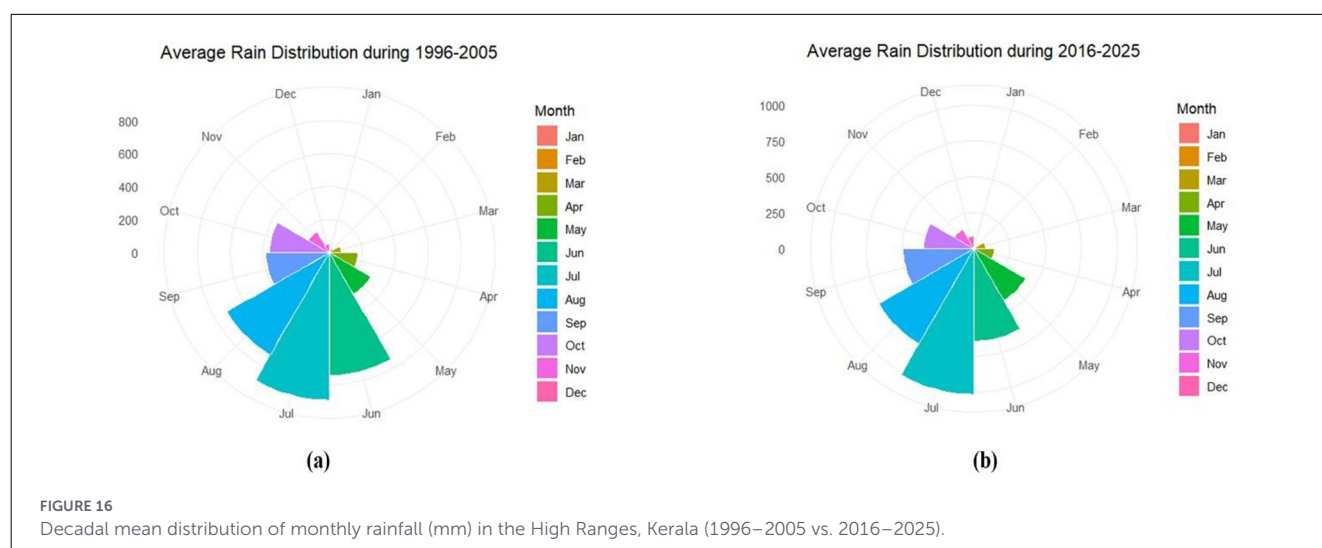


FIGURE 15 Decadal mean distribution of monthly rainfall (mm) in the Anamallais, Tamil Nadu (1996–2005 vs. 2016–2025).



crop undergoes waterlogging, root hypoxia, nutrient leaching, and increased susceptibility to root diseases (Karak et al., 2015; Owuor, 2018).

3.3 Changing relative humidity in tea-growing regions of India

As climate change brings severe droughts, maintaining humidity is crucial for tea growth because low RH hinders photosynthesis and the development of new shoots. In our study, we observed that RH in India's primary tea-growing regions has declined sharply from 1996 to 2025. Regional meteorological data indicate that the average RH during both the morning and afternoon hours has decreased noticeably in critical production belts such as the South Bank and Nagrakata. In South Bank, the decrease was significant in the morning ($p < 0.001$, τ -coefficient of -0.45 , and a Sen's slope of -0.9) and the afternoon ($p < 0.05$, τ -coefficient of -0.30 , and slope of -0.09 ; Figure 17). Likewise, in Nagrakata, the same decreasing trend in RH was observed in the morning ($p < 0.001$, τ -coefficient of -0.49 , and slope of -0.28) and the afternoon ($p < 0.001$, τ -coefficient of -0.45 , and Sen's slope of -0.11 ; Figure 18). This decreasing shift is considered critical because tea plants require high humidity for commercial production. Our study highlighted that, in the South Bank region of Assam, the average RH during the morning hours decreased by 1% in 2025, while the afternoon RH decreased by about 2% in both South Bank and Nagrakata in the same year. Previous studies reveal that these long-term changes in climatic variables cause tea to experience stress responses, leading to declining productivity (Ahmed et al., 2018).

In the South Bank, seasonal variations showed a downward trend in both the morning ($p < 0.001$) and afternoon ($p < 0.05$) hours, with τ -coefficients of -0.44 and -0.30 , respectively (Figure 19). Likewise, in Nagrakata, both morning ($p < 0.001$, τ -coefficient of -0.49) and afternoon ($p < 0.05$, τ -coefficient of -0.26) RH increased (Figure 20). In South India, the Anamallais

showed a consistent seasonal increase in RH levels ($p < 0.001$) during both the morning and afternoon hours (Figure 21). Meanwhile, the High Ranges of Kerala experienced a significant seasonal decline in morning RH ($p < 0.05$), but seasonal trends in evening RH increased with a τ -coefficient of 0.02 (Figure 22). Such fluctuations in humidity pattern change the microclimate by altering soil and air temperature, which in turn affects tea soil dynamics (Roy et al., 2020).

These climatic trends in increasing temperatures, shifting rainfall patterns, and extreme weather events are presenting challenges to tea cultivation, affecting yields and the socio-economic viability of tea estates (Hasan et al., 2023). Studies have also predicted a 12% decline in annual tea production by mid-century (Gunathilaka et al., 2017) under this changing climate. In Sri Lanka, a study highlighted that labor demand in the country's tea plantation sector is also expected to decline by over 1,175,000 person-days annually due to projected rainfall changes by 2050 (Gunathilaka et al., 2018). While these shifts in rainfall patterns influence tea cultivation and its labor dynamics, their most profound consequence lies in their direct impact on tea plant survival. Earlier studies also demonstrated that decreased leaf flush and shoot elongation are associated with rising temperatures, thereby reducing the number of pluckable leaves during peak seasons (Ahmed and Stepp, 2013; Wijeratne, 1996). Additionally, their studies also indicated how these climate stress factors, such as drought and heat, have altered the biochemical profile of tea plants, affecting key attributes like flavor and aroma, which are crucial for market competitiveness. Moreover, apart from these irregular climate extremes, which pose a significant threat to tea survivability (Lotha et al., 2024; Mohanty et al., 2024), regions like Assam have reported that for every 1 °C increase in temperature, tea yield drops by 0.087 tons/ha (Bordoloi and Dutta, 2025). Gupta et al. (2013) found that tea yield can be reduced by up to 40% if leaves wilt under drought stress caused by these shifts. Another study by Rao and his co-workers suggested that crop productivity was significantly affected by nighttime temperatures (< 5 °C) and humidity levels ($< 10\%$), while heatwaves in Himachal Pradesh may cause up to 50% damage in tea plants (Rao, 2016). Additionally, it

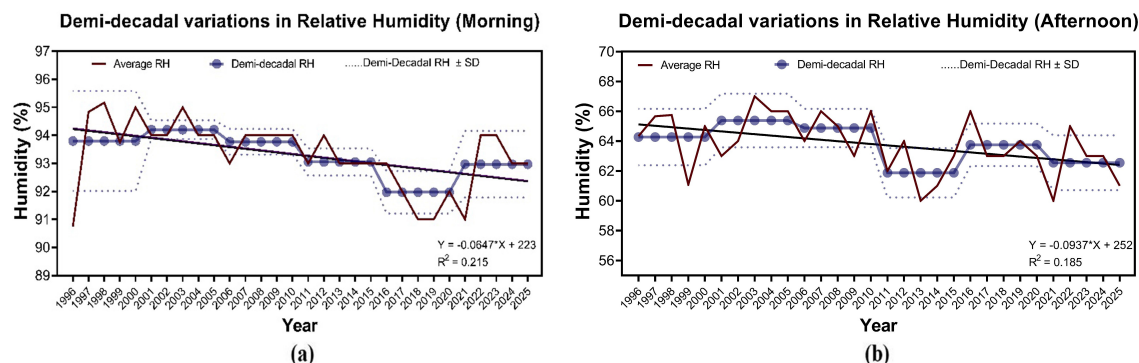


FIGURE 17

Demi-decadal analysis of RH (%) during (a) morning and (b) afternoon hours in South Bank, Assam (1996–2025), where the x-axis shows the years, and the y-axis represents humidity (%). The red line represents the average annual RH, while the blue line represents the demi-decadal RH, with the upper and lower SD represented by dotted blue lines.

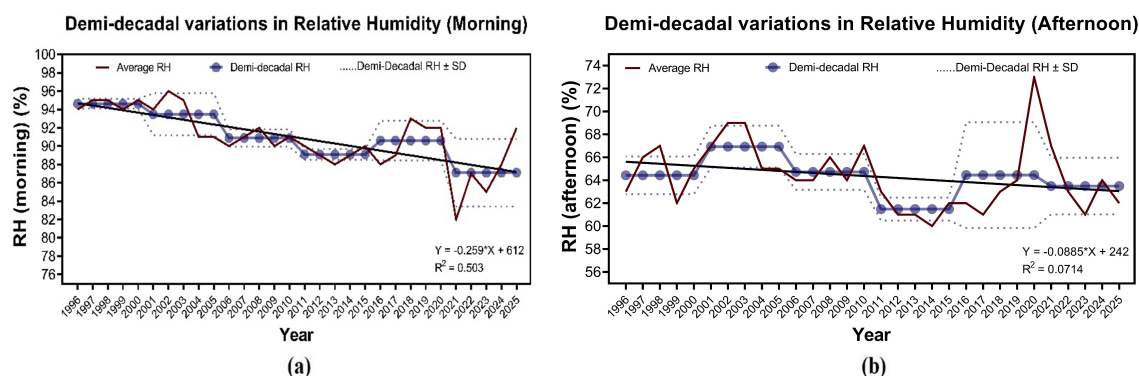


FIGURE 18

Demi-decadal analysis of RH (%) during (a) morning and (b) afternoon hours in Nagrakata, West Bengal (1996–2025), where the x-axis shows the years, and the y-axis represents humidity (%). The red line represents the average annual RH, while the blue line represents the demi-decadal RH, with the upper and lower SD represented by dotted blue lines.

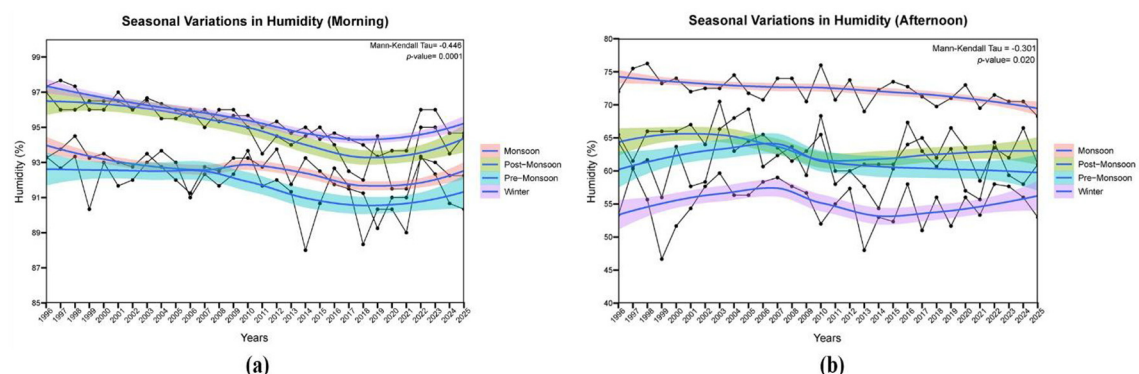


FIGURE 19

Seasonal variation of RH (%) during (a) morning and (b) afternoon hours in the South Bank region, Assam (1996–2025), where the x-axis shows the years, and the y-axis represents relative humidity (%). The lines pink (monsoon), green (post-monsoon), blue (pre-monsoon), and purple (winter) represent the average seasonal temperature, with the upper and lower SD indicated by their colors.

was reported that significant tea-growing regions, viz., North Bank, South Bank, and Cachar, are expected to remain barely suitable for tea by 2070, although Upper Assam's average suitability may rise (Bhagat et al., 2016). These results underline how susceptible the

tea sectors in Assam, Nagarakata, Kerala, and Tamil Nadu are to the adverse effects of climate change, and thus the necessity of adopting adaptive measures to lessen these negative consequences is crucial for the tea industry.

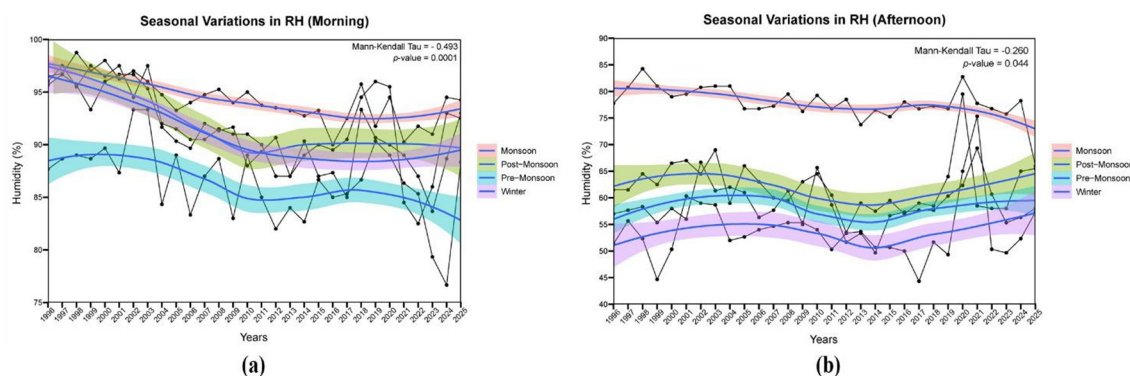


FIGURE 20

Seasonal variation of RH (%) during (a) morning and (b) afternoon hours in Nagrakata, West Bengal (1996–2025), where the x-axis shows the years, and the y-axis represents relative humidity (%). The lines pink (monsoon), green (post-monsoon), blue (pre-monsoon), and purple (winter) represent the average seasonal temperature, with the upper and lower SD indicated by their colors.

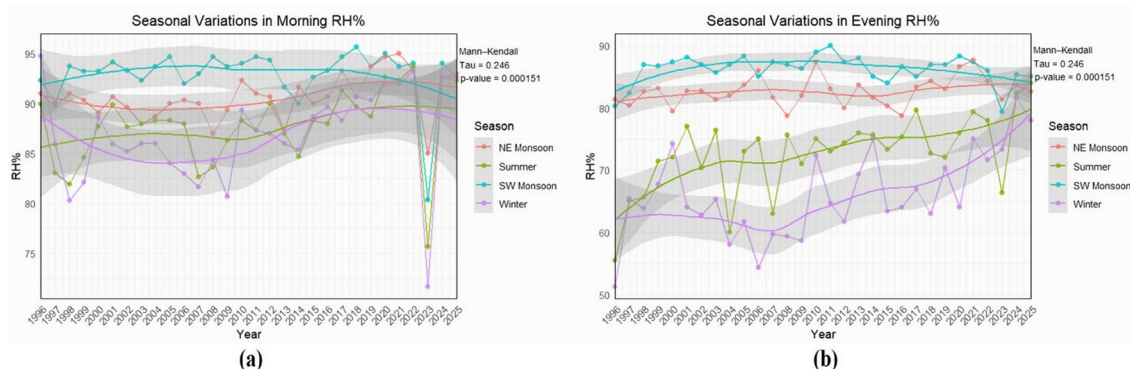


FIGURE 21

Seasonal variation of RH (%) during (a) morning and (b) afternoon hours, the Anamallais (1996–2025), where the x-axis shows the years, and the y-axis represents relative humidity (%). The pink (NE monsoon), green (summer), blue (SW monsoon), and purple (winter) lines represent the average seasonal temperature, with the upper and lower SD indicated by their colors.

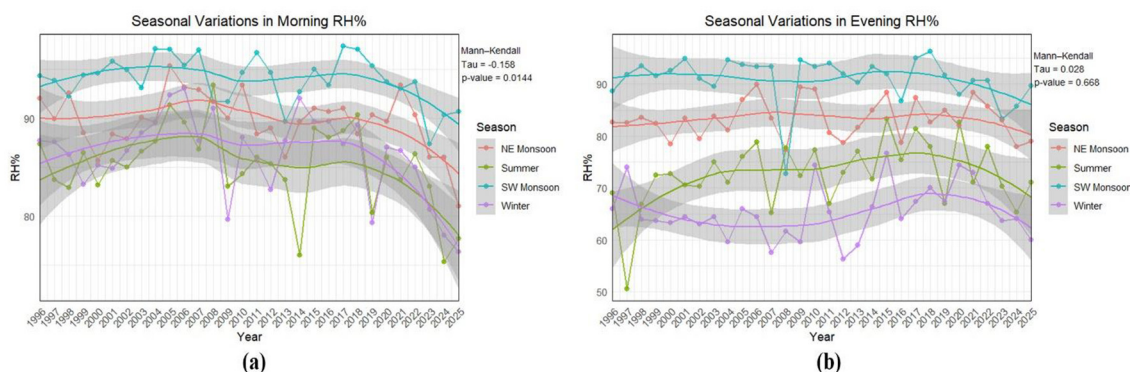


FIGURE 22

Seasonal variation of RH (%) during (a) morning and (b) afternoon hours in the High Ranges (1996–2025), where the x-axis shows the years, and the y-axis represents relative humidity (%). The pink (NE monsoon), green (summer), blue (SW monsoon), and purple (winter) lines represent the average seasonal temperature, with the upper and lower SD indicated by their colors.

3.4 Mitigation and adaptation management for tea cultivation

Projected future threats of climate change suggest a potential shift in plantation crops, especially tea, which is vulnerable to

climate stressors such as unpredictable rainfall patterns, prolonged droughts, unexpected hailstorms, and extreme temperatures (Han et al., 2017). Adaptation and mitigation strategies for the tea sector are critical (Thankappan, 2023; Jayasinghe and Kumar, 2019) and go hand in hand with its integrated management

practices (Tscharntke et al., 2005). In this regard, there is growing evidence that agroforestry systems can significantly lower soil erosion and degradation, increase above-ground and soil carbon stores, and mitigate greenhouse gas emissions (Mutuo et al., 2005; Albrecht and Kandji, 2003). Most researchers concur that traditional farmers' agricultural management techniques (Altieri, 2002; Baruah and Handique, 2021), such as applying more organic manure, using intercrops and green manures, and planting trees on farms, improve soil carbon sequestration (Stigter et al., 2005). Hereby, the International Panel on Climate Change (IPCC) has identified increasing soil organic carbon in agricultural systems as a key mitigation strategy (Niggli et al., 2009).

To mitigate the overall impacts of temperature and rainfall variations, several broad strategies are recommended. Planting specific drought-resistant clones such as PGL 6, PGL 10, PGL 16, and PGL 12, which showed only 1.07% yield reduction under stress (Rokhmah et al., 2022). Selection and deployment of drought-tolerant tea cultivars like TV1, TV18, TV19, TV20, TV22, TV23, TTRI1, TV34, and TV35 in North India and UPASI-9, UPASI-10, UPASI-15, UPASI-17, UPASI-19, UPASI-20, UPASI-24, UPASI-26, and UPASI-28 in South India can be beneficial (Saravanan, 2014). Additionally, the selection of drought-tolerant cultivars like TV9, SNT-10, MNPR/51/P2, GNGA/31/P3, can also be useful, as they have been reported to stand out as relatively tolerant genotypes, even under prolonged soil saturation conditions (Arefin et al., 2024, 2025).

As tea plants are shade-loving plants, selecting permanent shade tree species in tea gardens, like *Albizzia chinensis*, *Anadenanthera peregrine*, *Albizzia odoratissima*, *Acacia lenticularis*, and *Derris robusta*, will be beneficial for both shade management and temperature regulation (Rokhmah et al., 2022). Moreover, planting of temporary shade trees, such as *Albizzia lebbek*, *Leucaena leucocephala*, *Indigofera tesmanii*, *Melia azedarach*, and *Albizzia procera*, plays a dual role by sequestering carbon (Pramanik and Phukan, 2020) and buffering tea plants against heat stress, drought, and intense rainfall.

During moisture stress, meeting irrigation needs and maintaining the microclimate of the tea gardens through efficient rainwater harvesting (Rahman et al., 2025) plays a crucial role as an adaptation measure (Tocklai Special Bulletin, 2018). Further, it has been noted that using green manure, mulching materials like Guatemala, Napier grass, Water hyacinth, *Eupatorium*, *Ageratum*, as well as cover crops like *Crotalaria anagyroides*, *Pyrotripis cytisoides*, and *Sesbania rostrata*, enhances tea crop productivity. Application of cattle manure at 3–5 tons/ha/year, alternately, and decomposed oil cakes at 2–3 tons/ha/year, depending on soil texture, improves soil fertility (Sun et al., 2011). Additionally, the use of vermicompost, recycling of crop residues like pruning litter, pod dropping, shade tree leaves, and application of decomposed tea waste at a rate of 1–2 tons/ha/year are recommended by TTRI, TRA, which are also standardized for South India by UPASI TRE, as these add a large amount of organic matter to the tea soil.

Landscape-level, climate models (Panda et al., 2003) and policy measures (Banja et al., 2025) must also be integrated into adaptation strategies (Tesfay et al., 2024), along with building potential distribution maps for tea habitats to strengthen

the land use management (Zhao et al., 2021). Providing tea gardeners with timely weather forecasts, along with models for the current and future distribution of the tea plantation, can serve as useful scientific foresight for effective measures (İzmirli and Gül, 2023; Pham et al., 2023). Pest outbreak alerts in tea gardens can also significantly enhance the decisions for smart management (Deka and Goswami, 2021). Financial support mechanisms, such as insurance for climate-related losses and credits for resilient tea cultivation, are crucial for sustaining tea farming (Zhang et al., 2023). Thus, a coordinated approach combining policy frameworks, financial investments, and research efforts is essential to strengthen resilience in the tea sector amid ongoing climate change challenges.

4 Conclusion

Climate change has shifted from a distant threat to an immediate crisis for the Indian tea industry, particularly in the tea-growing belts of the North East and South India. Rising temperatures and uneven rainfall patterns are shifting the ideal conditions for tea cultivation, pushing regions like Assam, West Bengal, Tamil Nadu, and Kerala toward a critical climatic scenario. This changing climate risks India's status as a premium producer and threatens millions of livelihoods. However, the industry can secure its future by transitioning to climate-smart agriculture and adaptive ecosystem management. By adopting integrated practices such as utilizing drought-tolerant cultivars, implementing agroforestry with shade-providing *Albizzia* trees, and applying organic soil amendments, growers can build resilience against climate variability. Furthermore, a comprehensive policy framework incorporating real-time weather data, crop insurance, and capacity-building programs for smallholders is essential. Ultimately, safeguarding this historic crop requires a multi-stakeholder commitment to treating tea landscapes as resilient ecosystems, ensuring they remain drivers of economic and environmental stability for future generations.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AB: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. AR: Data curation, Formal analysis, Investigation, Software, Visualization, Writing – original draft, Writing – review & editing. RB: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Supervision, Validation, Writing – original draft, Writing –

review & editing. VS: Supervision, Project administration, Investigation, Resources, Writing – review & editing. HS: Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. RS: Formal analysis, Investigation, Writing – original draft, Writing – review & editing.

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Conflict of interest

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