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Assessing multi-decadal climatic variability and its impact on cardamom cultivation in the Indian Cardamom Hills

Sivajothi Ramalingam[1,2,3], Kazuaki Tanaka[3], Nainaru Tarakaramu[4], Muthusamy Murugan[5], Ashokkumar Kaliyaperumal[6] & M. Ijaz Khan[7]✉

This study examines the multi-decadal variability and trends of surface air temperature and precipitation in the Indian Cardamom Hills (ICH), a degraded tropical rainforest area unique for cardamom cultivation. Utilizing observed long-term climatic data (1958–2017), statistical methods such as the Mann–Kendall test (MKT), Sen's Slope Estimator (SSE), and Incremental Trend Analysis (ITA) were applied to assess the impact of surface air temperature, rainfall, and the number of rainy days on cardamom yield. The analysis revealed a significant decline in annual rainfall by approximately 13.62 mm per year, with pronounced seasonal declines 0.87 mm for winter, 12.33 mm for pre-monsoon, 24.93 mm for southwest monsoon, and 18.10 mm for post-monsoon. Simultaneously, the number of rainy days dropped by nearly 19.75 days over the 40-year period. A noticeable increase in decadal minimum and average temperatures was observed, highlighting potential adverse effects on cardamom yield and irrigation water resources. The findings suggest that excessive rainfall during the southwest monsoon negatively correlates with cardamom yield, while slightly warmer temperatures show a weak positive correlation. The study also emphasizes the need for adaptive agricultural practices and climate-resilient policies to mitigate the effects of changing climatic conditions on cardamom production. This research contributes valuable insights for farmers and other stakeholders as well as policymakers aiming to ensure sustainable cardamom cultivation amidst climate change.

Keywords Climatic trends, Cardamom yield, Mann–Kendall test, Precipitation, Surface air temperature

Mountain ecosystems in tropical regions hold immense ecological significance due to their high biodiversity, unique habitats, and presence of endangered species. These areas, which include forested mountain regions, support a rich variety of ecological and climatic systems, making them crucial for global biodiversity conservation. Despite their critical role, particularly in regulating water resources and serving as biodiversity hotspots, tropical mountain ecosystems have received limited attention in global environmental policy and management. Mountain forests provide a wide range of products and services both locally and globally, yet they face increasing threats from unsustainable resource use, agricultural expansion, and inadequate management practices. Although the global importance of mountains has only recently gained recognition, many mountain nations have long understood the complex relationships between these ecosystems and the people who rely on them for their livelihoods. Mishra[1] highlighted the vital role mountain ecosystems play in providing essential services such as water, food, and energy. However, overexploitation and climate change continue to degrade these ecosystems, raising significant concerns.

[1]Department of Mathematics, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, Tamil Nadu 602105, India. [2]Department of Management Studies, A Unit of Subbalakshmi Lakshmipathy College of Science, Madurai, Tamil Nadu 625022, India. [3]Computer Science and Systems Engineering Department of Intelligent and Control Systems, Kyushu Institute of Technology, Kitakyushu, Japan. [4]Department of Mathematics, School of Liberal Arts and Sciences, Mohan Babu University, Sree Sainath Nagar, Tirupati 517102, India. [5]Cardamom Research Station, Kerala Agricultural University, Pampadumpara, Kerala 685553, India. [6]School of Agriculture and Animal Sciences, Ghandhigram Rural Institute Deemed University, Dindigul, Tamil Nadu 624302, India. [7]Department of Mechanical Engineering, College of Engineering, Prince Mohammad Bin Fahd University, Al-Khobar, Saudi Arabia. ✉email: 2106391391@pku.edu.cn

The Amazon rainforest, one of the largest and most diverse tropical ecosystems, is increasingly vulnerable to deforestation. Carvalho et al.[2] analyzed deforestation dynamics in the Amazon and projected heightened vulnerability under post-Paris climate scenarios. Similarly, mountain forests like those in the Eastern Himalayas face climate-induced challenges. Chanda et al.[3] found that rising temperatures have reduced forest growth in this region, emphasizing the need for adaptive management strategies. Climate change also heavily impacts agricultural productivity, especially in regions dependent on climate-sensitive crops like cardamom. Known as the "Queen of Spices," cardamom is highly sensitive to fluctuations in temperature, rainfall, and humidity. In the Indian Cardamom Hills (ICH) within the Western Ghats (WG), cardamom is particularly vulnerable to changing seasonal weather patterns. Murugan et al.[4] identified summer rainfall and the number of rainy days during monsoons as crucial for maintaining cardamom yields. Kuruvila et al.[5] observed that despite these vulnerabilities, global market demand for cardamom remains robust, reflecting its economic significance.

Key climatic factors such as temperature, rainfall, and humidity are fundamental to plant growth, and significant changes in these variables can greatly impact crop productivity. Rising temperatures may shorten the growing season, accelerate plant development, and increase the risk of pest and disease outbreaks, while extreme weather events like droughts or heavy rainfall can damage crops, leading to reduced yields. Gupta et al.[6] identified temperature surges and precipitation shortages as major contributors to forest fires in vulnerable ecosystems. Srivastav[7] further stressed the importance of forests for biodiversity conservation and the challenges posed by climate change in India. The interplay between climate change and agriculture has been widely studied. Lobell and Field[8] examined human-induced climate trends, suggesting that increased CO2 levels might offset some warming impacts on crops, though the overall effects remain uncertain. While much attention has been given to staple crops like wheat and corn, less is known about the impact of climate change on crops like cardamom. Rising CO2 levels, alongside temperature and precipitation changes, are expected to have broad implications for agriculture, particularly in tropical regions where communities rely on agriculture for their livelihoods.

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change[9] identified global warming trends, with an average temperature increase of approximately 0.74 °C over the past century. By 2100, global temperatures could rise by 1.1 to 6.4 °C, dramatically affecting agriculture. While some regions may benefit from longer growing seasons, others will experience increased water stress and reduced yields. For tropical regions, these impacts will be especially severe for crops like cardamom, which are sensitive to climatic fluctuations. In tropical mountain ecosystems, changing rainfall patterns due to global warming have significant implications for agriculture and water availability. The IPCC[10] stressed the importance of rainfall in determining agricultural productivity, particularly in mountainous regions where precipitation patterns are highly variable. Research shows that global warming has led to more frequent extreme weather events, such as floods and droughts[11,12]. These changes are particularly concerning for cardamom growers, as consistent rainfall is critical for the crop's growth.

Given the potential for climate change to significantly impact tropical agriculture, adaptive strategies are necessary to ensure the sustainability of crops like cardamom. Modak et al.[13] explored the role of tea plantations in the Northeast Himalayas as a means to achieve land degradation neutrality, highlighting their potential to mitigate climate change through sustainable land-use practices. Similarly, Nölte et al.[14] projected declines in tropical reforestation productivity if annual temperatures exceed 29 °C, demonstrating the vulnerability of reforestation efforts to future warming. As climate patterns shift, concerns about the sustainability of agricultural production intensify, particularly for perennial crops like cardamom that are sensitive to long-term climatic trends. Murugan et al.[15] conducted a comprehensive analysis of six decades of climate and yield data from the Indian Cardamom Hills, revealing significant trends in temperature, rainfall, and rainy days. Their findings provide valuable insights for farmers and policymakers to adapt cardamom cultivation to future climate conditions. sustainable agricultural practices, including improved irrigation, crop diversification, and the development of climate-resilient crop varieties, are essential to maintaining productivity in the face of climate change. Guntukula[16] advocated for adaptive strategies in Indian agriculture, such as improved irrigation systems and crop diversification, while Malhi et al.[17] promoted conservation agriculture and agroforestry as ways to enhance resilience.

Indian cardamom is a perennial crop having a lifespan of 10–12 years. The Indian Cardamom Hills (ICH) used to enjoy a typical rainforest climate until the last two and half decades. Also, the ICH used to record sufficient precipitation in every month which helped cardamom plants grow and yield successfully without soil moisture stress. But in the recent past couple of decades an erratic pattern of precipitation has been experienced in all seasons and months causing significant yield loss which motivated us to carry out this rigorous statistical analysis to understand any available variability of climatic elements on the decadal scale. In cardamom-growing regions, addressing challenges like irrigation water scarcity and pest management will be critical for long-term sustainability. Cardamom is the third costliest crop in the world, cultivated as a rain-fed crop across the mountain tropical rainforest regions. It is sensitive and its yield is drastically affected or reduced due to changing rainfall patterns coupled with elevated surface air temperature in the production areas. Historical and decadal analyses of primary climatic elements and their impact on cardamom yield have not been studied in detail so far. In 2024, due to severe drought due to 120 days rainless period from January to May resulted in a cardamom yield reduction of 60–70% which destroyed the livelihood of the cardamom community.

The tropical mountain ecosystems are at a critical juncture, facing significant threats from climate change and unsustainable practices. Agriculture, particularly in regions like the Indian Cardamom Hills, must adapt to these challenges by integrating scientific knowledge into planning and management. The sustainability of economically and culturally important crops like cardamom depends on developing adaptive strategies that enhance resilience and mitigate climate change effects. As global temperatures continue to rise, understanding and addressing the specific vulnerabilities of mountain ecosystems will be essential to safeguarding biodiversity and ensuring food security for the millions of people who rely on these regions.

Description of site, methods and statistical analyses

Long-term observed climate data (1958–2017) as well as yield data of cardamom were obtained from the meteorological observatory attached to the Cardamom Research Station (CRS), Kerala Agricultural University (KAU), Pampadumpara, Kerala. The observatory is the pioneering representative station for the entire Cardamom Hills (CH). The central portion between Munnar and Periyar Tiger Hills is called the Cardamom Hills (9°15′N-10°0′N Lat. 76°45′E-77°25′E Long). It is mostly a 700–1000 m high plateau. Both climate and yield data were thoroughly checked and verified before statistical analysis. A range of statistical tools, including Mann–Kendall Test (MKT), Sen's Slope Estimator (SSE), and Incremental Trend Analysis (ITA), to investigate the dynamic association between these climatic variables and cardamom productivity. Meticulous statistical analysis by employing the MKT, SSE, and ITA tests, we generate new insights into the dynamic interplay between climatic variables and cardamom productivity. Figures derived from actual data points and linear regression predictions illustrate the decadal trends in average temperature, total rainfall, and average rainy days, offering insights into their potential effects on cardamom yield. The Mann–Kendall test results, presented in a comprehensive manner, plus analyzed precipitation data across different time periods that highlights the presence of trends in the climatic parameters. The MKT is a nonparametric test used in climatological studies to identify trends in climate system. It is commonly used in climatology to analyze time series data for trends without requiring the data to follow any specific distribution. The MKT assesses whether there is a statistically significant trend (either increasing or decreasing) in dataset values over time. It does this by comparing the relative magnitudes of sample data points, rather than their actual values. The Sen's slope values provide a measure of the magnitude of the trend, whether it is increasing or decreasing. Positive values in months with an increasing trend and negative values in months with a decreasing trend are consistent with the direction of the trends identified by the Kendall ZMK values.

Significance of trends

Both increasing and decreasing trends are marked as "Not Significant" based on the MKT's *p*-value. The *p*-value provides the probability that the observed data could arise if the null hypothesis (that there is no trend) were true. *p*-values less than 0.05 are commonly considered significant, suggesting that the trend is statistically significant. A *p*-value greater or equal to 0.05 is considered not significant, indicating that any observed trend might be due to chance. A lower *p*-value (typically < 0.05) suggests that the observed trend is statistically significant, meaning it's unlikely to have occurred by chance.

The ZMK values are the indicator of the trend's direction and strength. Positive values indicate an increasing trend over time, while negative values indicate a decreasing trend. The magnitude (how far tahe value is from zero) indicates the strength of the trend. The *p*-values are all above the typical significance threshold of 0.05, implying that the observed trends could be due to random variation rather than a systematic change.

Kendall's Z (also referred to as Kendall's tau) is a statistic used in the MK test to measure the strength and direction of a trend. It can take any value between -1 to 1. A positive value indicates an increasing trend in the data series, where higher values suggest stronger trends. A negative value indicates a decreasing trend, with lower values (further from zero) indicating stronger decreasing trends. Values close to 0 suggest little to no trend. Increasing if Kendall's tau is positive, indicating that the precipitation is generally going up over time. Decreasing if Kendall's tau is negative, indicating that the precipitation is generally going down over time.

The MKT's statistic S

The MKT test is utilized to identify trends within precipitation time series data at a significance level of 5%. This non-parametric, rank-based statistical method is commonly applied for such analyses (Mann, 1945).

Mann–Kendall (MK) test

This is a non-parametric test used to identify trends in a time series without assuming that the data follow a particular distribution. The result of "No Significant Trend" indicates that, there's no statistically significant evidence of an upward or downward trend in the data for that season.

Sen slope (SS) estimator

The SS Estimator is used in conjunction with the MK test to quantify the magnitude of a trend. It provides a robust measure of the central tendency of the slope (trend) in a time series dataset. Terms like "Slight Decrease", "Minor Decrease," "Moderate Increase," and "Significant Increase," indicates the estimated rate and direction of the trend detected by the SS Estimator.

Innovative trend analysis (ITA) method

This relatively new method is used for detecting trends in hydro-meteorological time series. It splits the data into two equal parts and compares them to identify trends. Descriptors like Decreasing (Low), Increasing (Medium), and "Increasing (High) suggest the direction and relative strength of the trend.

Mann Kendall's Tau rank correlation coefficient

$$S = \sum_{k-1}^{n-1} \sum_{j-k+1}^{n} sign(x_j - x_k) \tag{1}$$

where:

n is the number of data points,

x_j and x_k are data values in time series at times j and k respectively ($j > k$),
$sign(x_j - x_k)$ is the sign function which equals 1 if $(x_j - x_k) > 0$, if $(x_j - x_k) = 0$, and -1 if $(x_j - x_k) < 0$,
The Variance of S is given by:

$$Var(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p-1}^{m} t_p(t_p-1)(2t_p+5)\right] \tag{2}$$

where:

m is the number of tied groups (a tied group is a set of sample data having the same value),
t_p is the number of data points in the pth group.
For a large sample size (n>10), the standard normal test statistic Z is computed by:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & if\ S < 0 \end{cases} \tag{3}$$

A positive (negative) value of Z (Eq. 3) indicates an upward (downward) trend. To determine the presence of a statistically significant trend, one would compare the absolute value of Z to a critical value from the standard normal distribution (typically 1.96 for a 95% confidence level). If the absolute value of Z is greater than the critical value, the trend is considered statistically significant. If the result of the MKT is statistically significant, it suggests a trend (either increasing or decreasing) in the time series data. The direction of the trend is indicated by the sign of the test statistic S (Eq. 1 and Eq. 2) and Z. If the test is not significant, no monotonic trend is suggested. The SSE[18] was employed to determine the slope of a linear trend within the precipitation data.

Results and discussions

Decadal trends of temperature, rainfall and rainy days

The (Fig. 1a) illustrated the decadal average temperature trend for the study period which is increasing (red line) and the blue line denoted the actual observed values. Trends of decadal average annual rainfall (Fig. 1b) as well as number of rainy days (Fig. 1c) found declining. Reduction in number of rainy days is profound and can hamper cardamom growth and development besides altering local soil hydrology and water balance in the cardamom hills. Earlier studies by Murugan et al.[15] detailed the ecophysiology of cardamom in relation to climate change and variability particularly the rainfall and rainy days.

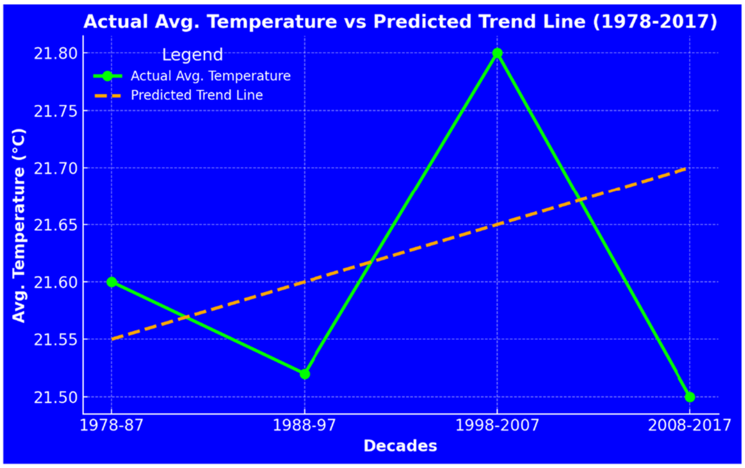
Surface air temperature

The change in the maximum temperature recorded from the decade 1978–1987 to the decade 2008–2017 showed a negative value (-2.1 °C) and this may be ascribed to intensive irrigation practiced in the entire cardamom growing areas during the recent past decades than the earlier decades. Minimum temperature calculated (T min in 2008–2017 minus T min in 1978–87) for the forty years (1978–2017) period showed an increase by + 1.9 °C. Unlike the maximum temperature, the minimum temperature has risen over the last 40 years. This could mean the warmer night temperatures in the more recent decades, which could have various negative implications on cardamom physiology and productivity. The change in average temperature over the 40 years period was calculated (T average in 2008–2017 minus T average in 1978–87). A small decrease of − 0.1 °C was observed in average temperature suggesting that the nights have become warmer. These changes are critical for overall function of the cardamom production system. This long-term trends in weather and climate patterns could be reflective of broader climate change phenomena in the perennial cardamom agro forestry system. The decrease in maximum temperatures could be due to various factors, including increased irrigation levels, cloud cover or precipitation rates, while the increase in minimum temperatures could be related to factors like degradation of forest and forest trees, land use change mainly to lesser shade loving crops like black pepper, coffee and tea. The slight decrease in average temperature, being a balance between the two, indicates a complex interplay of factors affecting the regional or local climate over the decades. Earlier studies showed how high value crops like cardamom, tea, coffee and black pepper would be impacted under present and future changing climatic condition in Indian cardamom hills[15]. The authors also explained implications of climatic change on the dynamics of pests and diseases affecting theses high value crops besides local hydrological change in the cardamom agroforestry system.

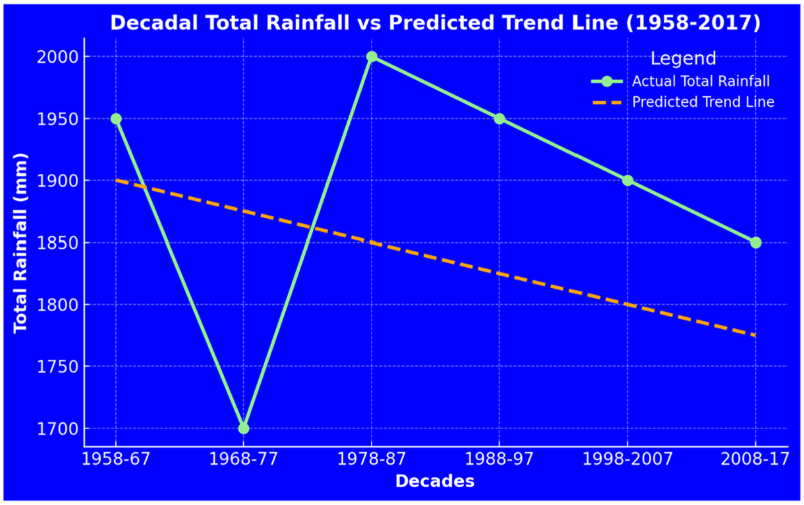
Projection of temperature trends

Model prediction of temperatures

Based on the observed data from previous decades (Fig. 2) the model predicted that the maximum temperature for the next decade (after 2017) will be around 26.0 °C. The negative slope and trend of approximately -0.51 indicates that, on average, the maximum temperature has been decreasing by about 0.51 °C per decade. However, the *p*-value (0.403) suggested that this decreasing trend is not statistically significant, meaning there isn't strong



(a)



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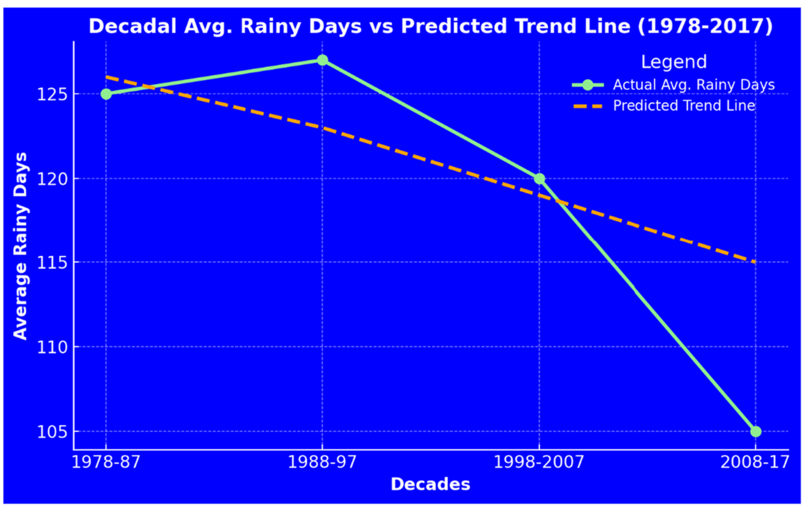

(c)

Fig. 1. (**a**) Decadal average temperature trend. (**b**) Decadal total rainfall trend. (**c**) Decadal average rainy days trend.

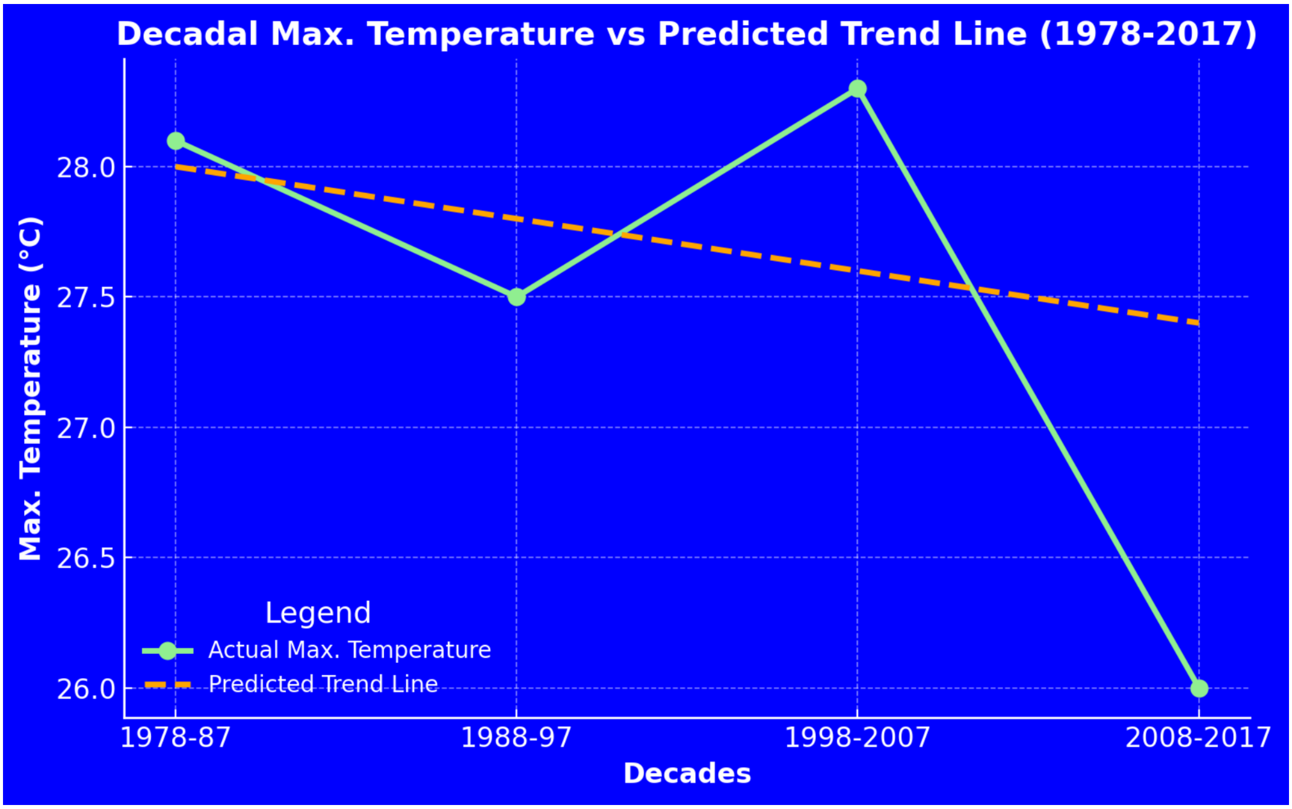

Fig. 2. Decadal trends in maximum temperature.

evidence to conclude that the maximum temperature has been decreasing systematically over the years studied. Instead, this trend could be due to random variation in the data.

The predictive model projects (Fig. 3) that the minimum temperature for the next decade will be around 17.3 °C. This projection is higher than the last observed decade. The positive slope of approximately 0.55 indicated that the minimum temperature has been increasing by about 0.55 °C per decade. This implied a warming trend at night or during the colder periods of the year. However, with a *p*-value of 0.136, the trend, while more pronounced than that of the maximum temperature, still does not reach conventional levels of statistical significance (typically $p < 0.05$). Thus, while there has been a pattern of increasing minimum temperatures, we are less confident in asserting this as a definitive long-term trend across decades based on statistical criteria.

The average temperature for the next decade is projected to be around 21.65 °C, indicating little change from the previous decade (Fig. 4). A small positive slope of approximately 0.01 showed an almost stable trend in average temperatures over the decades, with an increase of just 0.01 °C per decade. The *p*-value of 0.932 gave a slight upward trend was not statistically significant, suggesting the average temperature has been remaining relatively stable without clear evidence of systematic increases or decreases over the time period analyzed. The analysis brought that while the night-time (minimum) temperatures might be slightly increasing; the day-time (maximum) temperatures are slightly decreasing, leading to an overall stable average temperature. This implied a changing climate pattern, possibly with cooler days and warmer nights. However, lack of the statistical significance in these trends should be interpreted with caution. They highlight potential shifts but don't provide definitive evidence of long-term changes based on the periods analyzed. Amongst plantation crops, cardamom leaves and tillers are highly susceptible to elevated air temperature levels plus reduced root zone surface soil moisture that affect badly the normal growth and development of cardamom leaves and tillers leading to withering and death of leaves and tillers. To mitigate and off-set the ill effects of elevated surface air temperature during hot rainless summer months, provide adequate natural shade (≥ 60%) to cardamom plants by maintaining sufficient tree canopy so that normal growth and development of cardamom tillers can be maintained and yield can be realised the same season. If shade is not given, the yield will be delayed for at least 12 months[15].

The Mann–Kendall test exhibited increasing trends in most months, with exceptions during the summer months and on an annual basis. Despite the observable trends, the analysis emphasizes the non-significant nature of these trends, as determined by the MK test's *p*-values, suggesting that the observed variations might be attributed to random fluctuation rather than systematic changes. Furthermore, the research identifies strong negative correlations between cardamom yields and south west monsoon (SWM) rainfall indicating that the extreme and excessive soil moisture due to the SWM may adversely affect cardamom capsule yield. Conversely, a slight positive correlation with temperature suggested that marginal warmer condition could potentially benefit cardamom yield, albeit to a lesser extent than the negative impacts of extreme and excessive rainfall condition.

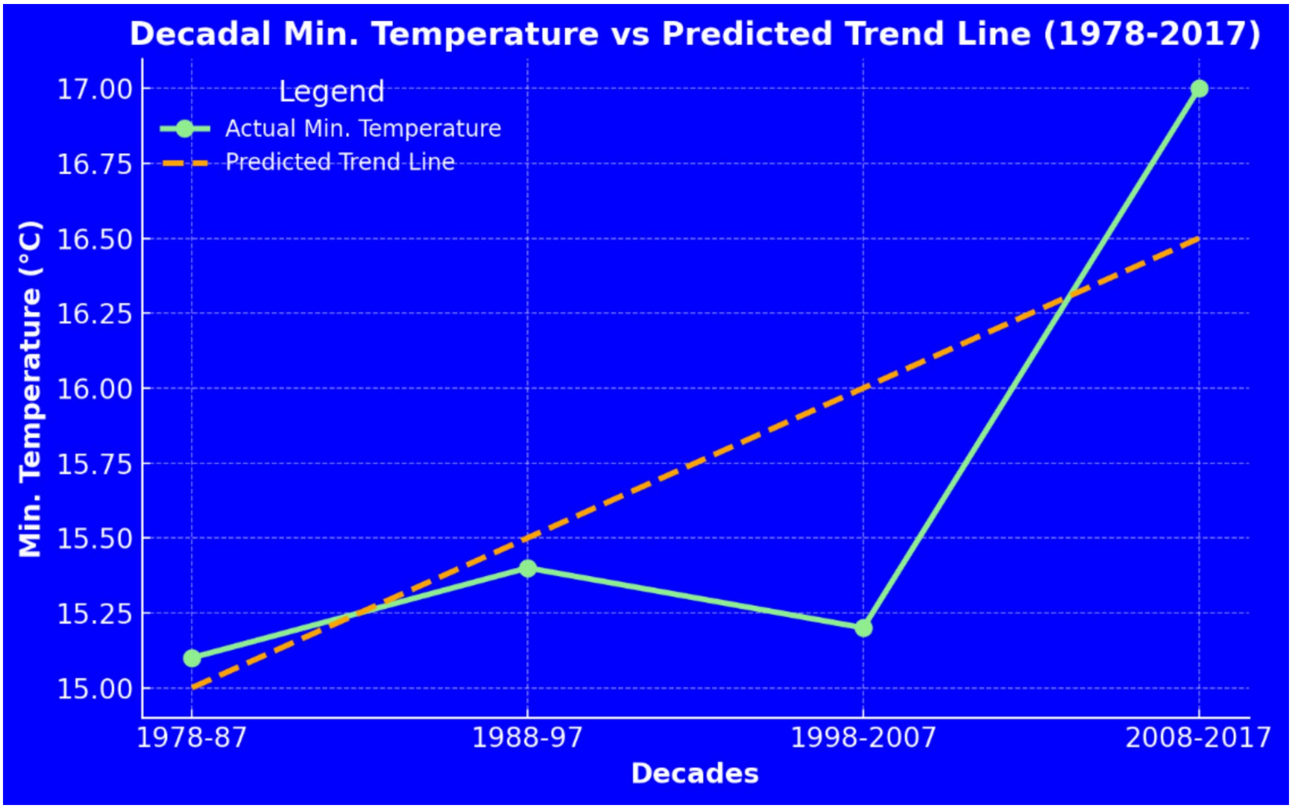

Fig. 3. Decadal trends in minimum temperature.

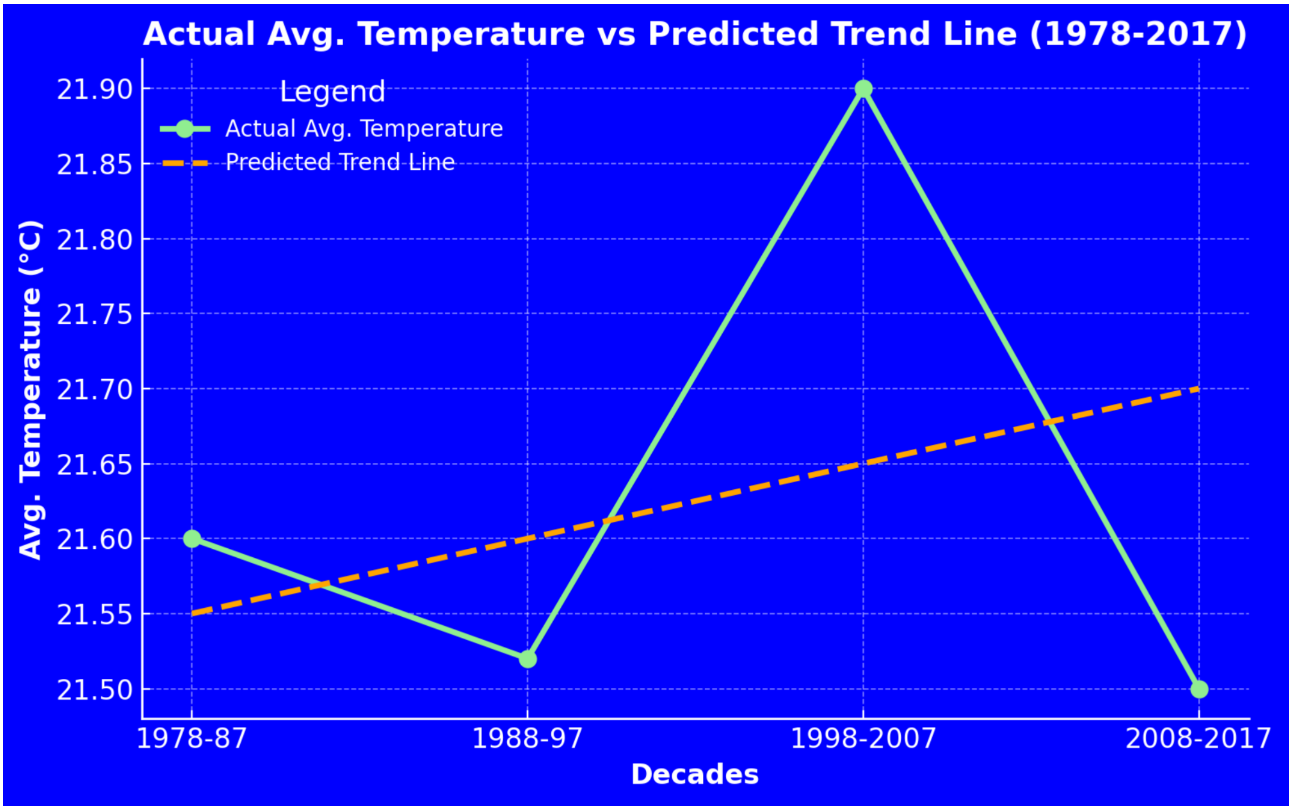

Fig. 4. Decadal trends in average temperature.

Precipitation duration	Kendall ZMK value	Trend result	MK Test p-value	Test result (SS)	Trend result (SS)
January	0.2	Increasing	0.719	Not Significant	Increasing
February	0.467	Increasing	0.272	Not Significant	Increasing
March	0.467	Increasing	0.272	Not Significant	Increasing
April	0.2	Increasing	0.719	Not Significant	Increasing
May	0.067	Increasing	1	Not Significant	Increasing
June	− 0.067	Decreasing	1	Not Significant	Decreasing
July	− 0.333	Decreasing	0.469	Not Significant	Decreasing
August	− 0.067	Decreasing	1	Not Significant	Decreasing
September	0.067	Increasing	1	Not Significant	Increasing
October	0.067	Increasing	1	Not Significant	Increasing
November	0.2	Increasing	0.719	Not Significant	Increasing
December	0.2	Increasing	0.719	Not Significant	Increasing
Yearly Avg	− 0.067	Decreasing	1	Not Significant	Decreasing

Table 1. MK test results for monthly and yearly precipitation time series.

Season	Average ZMK Value	General Trend	Significance
Winter	0.289	Increasing	Not Significant
Summer	0.245	Increasing	Not Significant
Monsoon	− 0.156	Decreasing	Not Significant
Post-Monsoon	0.111	Increasing	Not Significant

Table 2. Seasonal trend analysis.

Significant slopes are observed for certain months, such as April and July, indicating a relatively stronger rate of change in precipitation during these months. However, as the MK test results are not statistically significant, these trends should be interpreted with caution. The analysis suggests trends in precipitation changes across different months, with most months showing an increasing trend and the summer months (June, July, August) along with the yearly average showing a decreasing trend. Despite these observed trends, none are statistically significant according to the MK test results. This could indicate that while there might be changes in precipitation over the years, these changes are not consistent enough to be deemed statistically significant from a trend analysis perspective. Lack of significance suggests further investigation that might be necessary, possibly with a larger dataset, different time spans, to understand the dynamics of precipitation changes more comprehensively.

Results on the precipitation data, across different time periods (monthly and yearly averages) both increasing and decreasing trends .Rising trends were shown for months like January, February, March, April, May, September, October, November, and December while downward trend in precipitation was noticed in months such as June, July, and August, suggesting that precipitation has decreased during these months over the years (Table 1). The yearly average precipitation trend was observed to be declining signifying an overall decrease in precipitation when considering all months combined**.** Previous studies on precipitation trends also showed[15] such variability for the ICH. The researchers too pointed out that the change in precipitation levels noticed for the ICH area can impact the farming of plantations crops and its productivity. Among plantation crops, cardamom is highly susceptible to drought and shortage of rainfall because of superficial root system and continuous higher demand of surface soil moisture for normal growth and development of cardamom tillers[15].

From the (Table 2) the winter season (January, February, December) shows an increasing trend in precipitation, with an average ZMK value of 0.289, though it is not statistically significant, suggesting that the observed rise may be due to natural variability rather than a strong trend. Similarly, the summer season (March, April, and May) also exhibits an increasing trend with an average ZMK value of 0.245, though this weak trend is also not significant. The monsoon season (June, July, and August) presents a decreasing trend in precipitation, with an average ZMK value of -0.156. While this may raise concerns given the importance of monsoon rains, the trend is not significant and could be due to natural climate variations. Lastly, the post-monsoon season (September, October, and November) shows a slight increase in precipitation, with an average ZMK value of 0.111, but again, this trend is not statistically significant. In summary, while increasing trends are observed in the winter, summer, and post-monsoon periods, and a decreasing trend during the monsoon, none of these are significant based on the Kendall ZMK values and p-values. Further data and research are needed to confirm these patterns.

Precipitation intensity

Intensity of precipitation was analysed as low, medium, and high and shown in Table 3. The low intensity precipitation across seasons has been decreasing. Annually, the low intensity precipitation showed a downward trend and lighter precipitation events have become less frequent or less intense. Normally ICH used to get more of low intense thread like rainfall until 1970’s which is good for natural pollinators like honey bees as well

Season	Low	Medium	High
Winter	Decreasing	Decreasing	Decreasing
Pre-monsoon	Decreasing	No trend	Increasing
SW monsoon	Decreasing	No trend	Increasing
Post-monsoon	Decreasing	Decreasing	Decreasing
Annual	Decreasing	No trend	Increasing

Table 3. Trend analysis summary for seasonal and annual precipitation intensity.

Seasons	MK test result	SS estimator trend	ITA trend
Winter	No Significant Trend	Minor decrease	Decreasing (low)
Pre-monsoon	Increasing	Moderate increase	Increasing (medium)
South west monsoon	Increasing	Significant increase	Increasing (high)
Post-monsoon	No significant trend	Minor decrease	Decreasing (low)
Annual	No significant trend	Slight decrease	Decreasing (low)

Table 4. Comparative analysis of seasonal trends by the MK test, SS estimator, and the ITA method.

as protection of surface soil. Increased intensity of high annual, pre-monsoon and post-monsoon rainfall was observed. More intense rainfall events are becoming more frequent or more intense, suggesting a shift towards more extreme rainfall events during the pre-monsoon and south west monsoon season. High intensity rainfall of winter and post monsoon period found to be decreasing. Pre-monsoon and post-monsoon precipitation registered diminishing intensity while all others indicated no trend. Similar findings were reported in earlier studies for the ICH area[15].The uniform decrease across all intensities suggests a significant shift in winter precipitation pattern. A reduction in low intensity lighter rainfall during south west monsoon period indicated that the precipitation pattern has increased its erosivity level which can cause severe soil erosion and degradation in the ICH area[19]. No trend was shown for medium intensity signalling that the frequency or intensity of medium precipitation events remains stable during the south west monsoon. It has indicated that medium-intensity rainfall events have not changed over time on an annual scale. High intensity and increasing precipitation levels signified that heavier rainfall events have become common which would have significant implications for flooding and soil erosion, landslides and landslips on the slopes and direct crop damage and loss. Post-monsoon precipitation under all three intensity levels brought out a decreasing trend as that of winter season precipitation indicating a uniform reduction in the precipitation events. This could result in drying up of water sources at greater speed leading to water shortages during the successive months. On an annual basis, high intensity precipitation has increased which confirmed more extreme precipitation events with potential negative implications for the whole cardamom production system. Apparently the results pointed out a nuanced view of how precipitation intensity has been changed across seasons and intensities. Decreased low-intensity events indicated less frequent light rainfall which might affect groundwater recharge and water harvest. Lack of trend in the medium-intensity events showed stability in these occurrences, which often constituted the bulk of beneficial rainfall. Increased in high-intensity events highlighted a shift towards more extreme weather conditions, raising concerns about soil health and quality, flood risks and direct crop damage[15]. Understanding these trends is essential for adapting to changing climate conditions and managing water resources effectively in the ICH.

Precipitation trends

Trends of winter and post-monsoon precipitation by the MK test showed no significant trend with a small decrease (Table 4). The ITA method categorized these trends as low due to the small magnitude of change. The pre-monsoon and south west monsoon indicated an increasing trend with the MK test while the pre-monsoon precipitation gave a moderate increase and a significant increase for the south west monsoon. The ITA method aligns with these findings, categorizing pre-monsoon as medium and south west monsoon as high. Annually, no significant trend was obtained for the MK test but a slight decrease was quantified by the SS estimator. The ITA method measured this as a low decreasing trend due to the overall small variability.

Observed and extended prediction trends

The observed data showed variability in winter precipitation levels, some decades have experienced more rainfall than others (Fig. 5). The trend of observed data indicated a general increase in winter precipitation over time. The future predicted trend (magenta) also indicated an upping trend for winter precipitation which is expected to continue into the next two decades. The historical trend for the pre-monsoon precipitation data also registered significant fluctuations across the decades studied. However, the overall trend line produced a slight upward movement. The future prediction (orange line) reported as a continuation of the slight ascendant trend in pre-

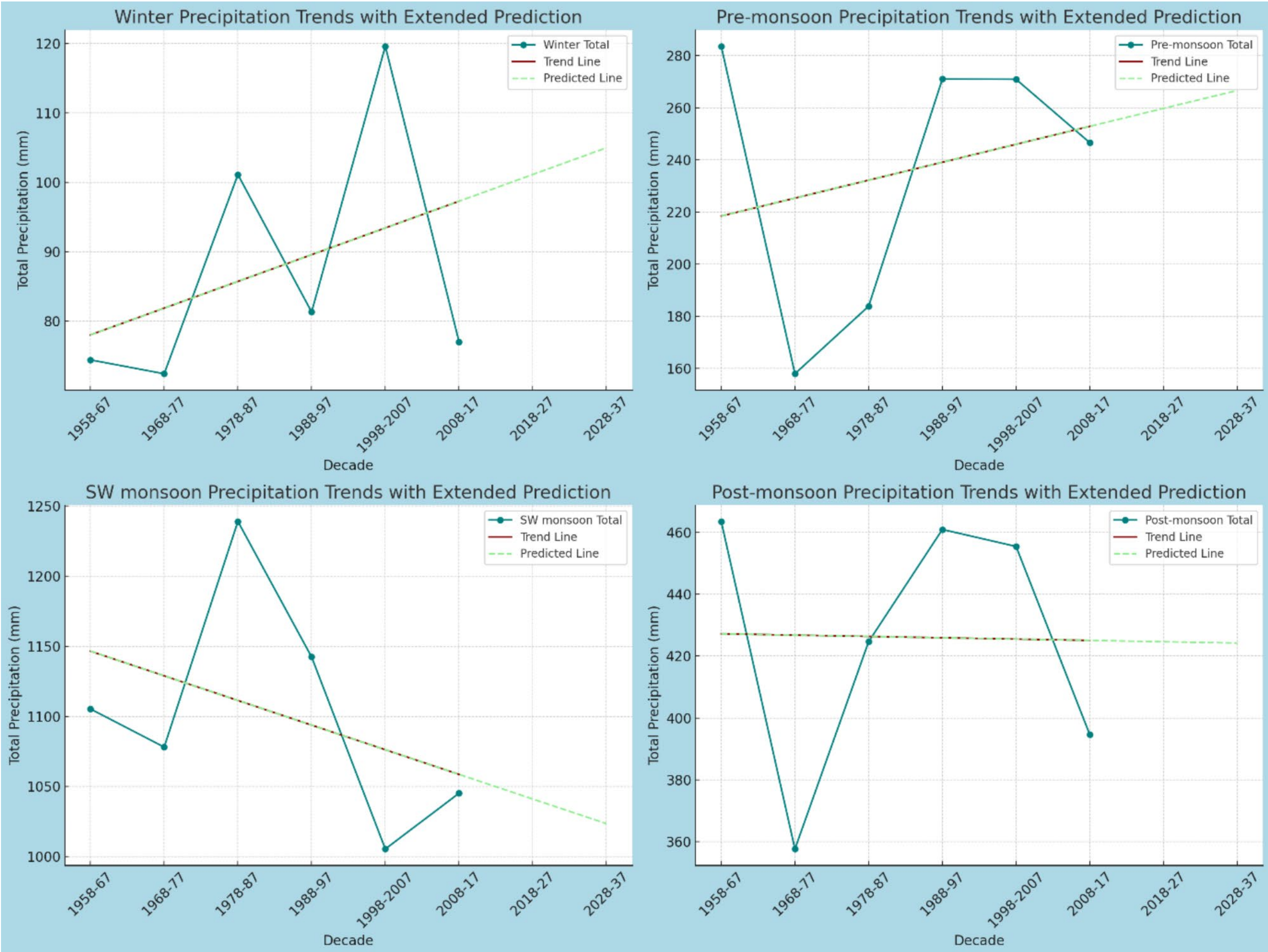

Fig. 5. Extended trend analysis of seasonal precipitation (1958–2037) by observed and future predictions.

monsoon precipitation. This is representing the evolution of climatic condition that could lead to more rainfall during the pre-monsoon season. Similar prediction has also been reported by earlier studies[15].

The south west monsoon season exhibited the most pronounced changes in precipitation, including a peak and subsequent decline (Fig. 5).However, the overall trend line pointed towards a gradual decrease. The extended trend line predicted a continued decrease in the SW monsoon rainfall. The result of this prediction would have significant implications for water resources and cardamom agriculture because the SW monsoon is long and if any reduction in its precipitation levels can cause long term repercussions in the ICH region which is heavily reliant on the SW monsoon rains.

The post-monsoon precipitation levels varied over the decades studied, with no clear directional trend observed from the historical data (Fig. 5). The future predicted trend indicated that the post-monsoon precipitation levels are expected to remain relatively stable. This stability suggests that post-monsoon rainfall patterns may not undergo significant changes in the near future. The decrease in rainfall over the 60 years for each defined season and annually, from the first decade (1958–67) to the last decade (2008–17), is as follows: Winter precipitation found decreased by 0.87 mm followed by a dipping of pre monsoon precipitation to the tune of 12.33 mm. South west and post monsoon precipitation respectively registered a fall of 24.93 mm and 18.10 mm. Annually, the precipitation levels plunged by 13.62 mm during the last 60 years. These statistics represented the change in average rainfall for each season and for the year as a whole, demonstrating how rainfall patterns have shifted over the six decades in the ICH area. The decrease in rainy days over the four decades (40 years) from the decade 1978–87 to 2008–17, is approximately 19.75 days. This showed a reduction in the number of rainy days meaning that the ICH area has lost at least 19.75 rainy days and its rainfall. From the table (4) it is evident that for each month a trend was noted (either increasing or decreasing)but none of these trends were statistically significant, as indicated by p values (greater than or equal to 0.05). This means that while there may appear to be a pattern of increase or decrease in precipitation over the period analysed, but these patterns could be due to random fluctuations in the data rather than a consistent, significant trend over time.

R-squared values and p-values

Maximum Temperature (T Max)

R-squared: 0.36 (Moderate fit)
p-value: 0.403 (Not significant at 5% level)

Minimum Temperature (T Min)

R-squared: 0.75 (Strong fit)
p-value: 0.136 (Not significant at 5% level)

Average Temperature (T Avg)

R-squared: 0.005 (Very weak fit).
p-value: 0.932 (Not significant at 5% level).

Rainfall

R-squared: 0.014 (Very weak fit)
p-value: 0.825 (Not significant at 5% level)

Analysis of significance

p-values
Since all *p*-values exceed 0.05, the observed trends in the data are not statistically significant. This implies that there is no strong evidence to support a meaningful trend in the decadal temperature or rainfall data.

R-squared values
The Maximum Temperature demonstrates a moderate correlation between the actual values and the trend line, though the trend is not statistically significant. The Minimum Temperature has a relatively strong correlation (0.75) between the actual and predicted values; however, the *p*-values suggests that this trend could be attributed to random variation rather than a meaningful pattern. Both Average Temperature and Rainfall exhibit very weak correlations with extremely low R-squared values, indicating that the trend lines do not provide a good fit for the data.

Comparative analysis

Winter and post-monsoon season both showed no significant trends according to the MK test, indicating stability or no clear pattern of change over time (Table 5). However, both the SS Estimator and ITA method registered a minor decrease, indicating a slight downward trend. Pre-monsoon precipitation reported an increasing trend across all methods, with the MK test representing a clear trend, and the SS estimator describing it as a moderate increase, and the ITA method categorizing it as increasing at a medium rate. All three methods described the south west monsoon as increasing trends, with the SS estimator highlighting a significant increase, signifying that this season is experiencing a notable upward trend in the variables studied. Annual precipitation produced no significant trend according to the MK test, a slight decrease was noted by the SS estimator, and a low decrease was obtained through the ITA method, demonstrating the overall stability with a minor downward tendency on a yearly basis.

Correlation between seasonal precipitation and cardamom yield

Results of the correlation analysis revealed a strong negative relationship as the precipitation increases greatly; the yield of cardamom tends to decrease significantly (Fig. 6). The coefficient value (-0.93) was very close to 1, indicating a strong inverse relationship. This might mean that excessive rainfall during monsoon months could be detrimental to cardamom production, possibly due to factors like physical damage to flowers and disruption of pollinators/pollination that can occur with intense rainfall events during peak flowering. It's important to note that correlation does not entail causation.

This weak correlation indicated that other factors, possibly including agronomical practices, soil fertility, or other climatic variables like sunshine levels, may have a more significant impact on cardamom yield than precipitation alone. Further analysis, potentially including more variables and a more detailed dataset, would be needed to draw any definitive conclusion about what influences the cardamom yield under natural forest

Seasons	MK test result	SS estimator trend	ITA trend
Winter	No significant trend	Minor decrease	Decreasing (low)
Pre-monsoon	Increasing	Moderate increase	Increasing (medium)
South west monsoon	Increasing	Significant increase	Increasing (high)
Post-monsoon	No significant trend	Minor decrease	Decreasing (low)
Annual	No significant trend	Slight decrease	Decreasing (low)

Table 5. Comparative analysis of seasonal trend results using MK test, SS estimator, and ITA method.

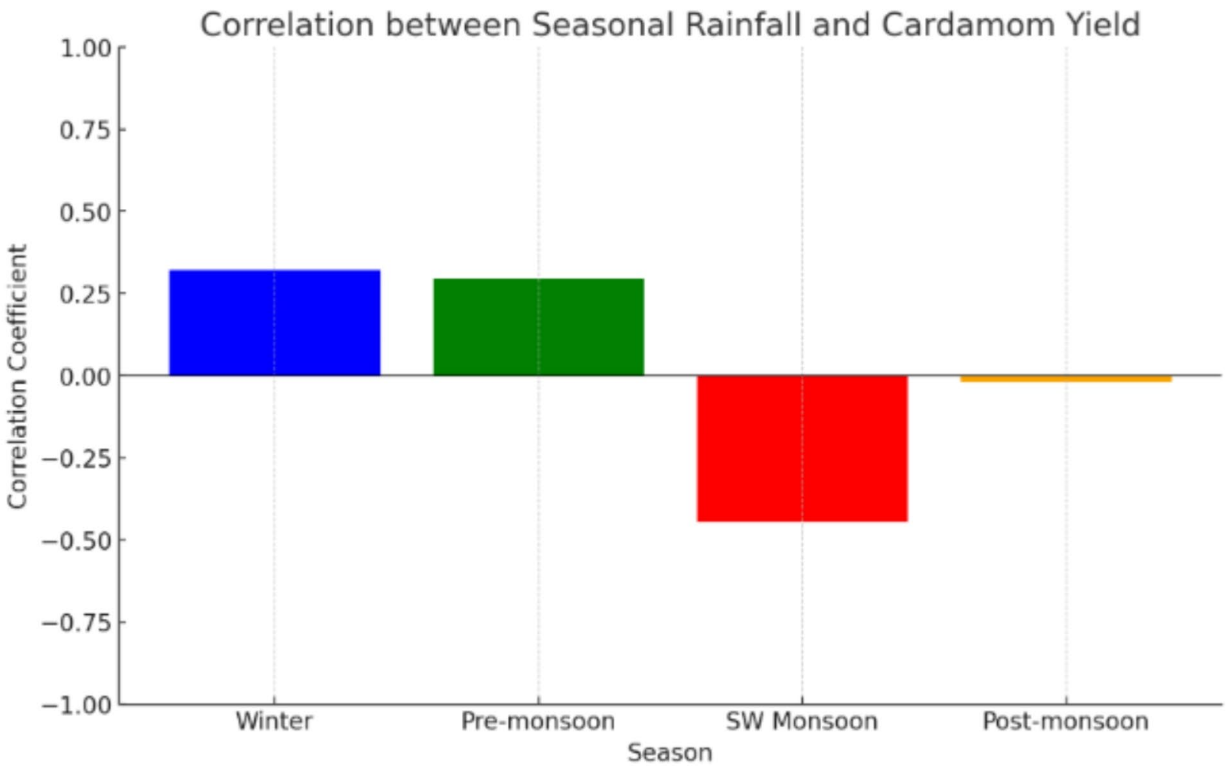

Fig. 6. Correlation between seasonal precipitation and cardamom yield.

ecosystem. Winter and pre-monsoon precipitation had a weak positive correlation with cardamom yield, signifying that higher rainfall in these seasons slightly tends to be associated with higher cardamom yields. Southwest monsoon reported a moderate negative correlation with cardamom yield, which is significant. This demonstrated that higher rainfall during the southwest monsoon season is associated with lower cardamom yields, potentially indicating that too much rain in this critical growing and flowering period could be detrimental to cardamom production. Precipitation during the post-monsoon had a very weak negative correlation with cardamom yield, representing almost no linear relationship between post-monsoon rainfall and cardamom yield. Earlier studies have shown similar results in relation to cardamom yield and climate[4].

The findings underscore the complex nature of agricultural dependency on climatic factors, revealing that while there are increasing trends in rainfall in most months, these changes are not statistically significant when evaluated through the Mann–Kendall test. This suggests that the observed variations could be attributed to random fluctuations rather than definitive systemic changes. Importantly, the study identifies a pronounced negative correlation between cardamom yields and both total rainfall and the number of rainy days, highlighting the adverse effects of excessive moisture on cardamom cultivation. Conversely, a slight positive correlation with temperature points to the potential benefits of marginally warmer conditions for cardamom yield, although these effects are notably less significant than the negative impacts of excessive rainfall.

Correlation between temperature and cardamom yield

The positive coefficient **(0.208)** reported in our analysis indicated a slight positive relationship between temperature and cardamom yield. Although the correlation between cardamom yield and temperature was much weaker than the coefficient related to rainfall; it indicates that higher temperatures may be somewhat beneficial to cardamom yield, or conversely, that lower temperatures are slightly less favourable. The environmental factors like heavy rainfall during monsoons and long wettest rainy days have strong negative correlations with cardamom yield, suggesting that less intense precipitation during monsoon months may be more conducive to higher yields of cardamom. On the other hand, surface air temperature showed a weak positive correlation, indicating its less pronounced effect than that of rainfall, but generally, slightly warmer conditions might be marginally beneficial for cardamom yield.

Regression model

A regression model (Y) (Eq. 4) is a statistical approach that analyzes the connection between a dependent variable (also referred to as the outcome or target variable) and one or more independent variables (also known as predictors or features). The primary objective of a regression model is to forecast the value of the dependent variable using the values of the independent variables, while also gaining insights into the relationships between them.

General regression model

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \varepsilon$$

where:

Y is the dependent variable, representing the cardamom yield (Kg/Ha).
β_0 is the intercept (Constant term).
X_1 is the average maximum temperature.
X_2 is average minimum temperature.
X_3 is the average temperature.
X_4 is the total rainfall.
$\beta_1,\ \beta_2,\ \beta_3,\ \beta_4$ are the regression coefficients for each of the independent variables representing the amount of change in Y for a unit change in the respective independent variable.
ε is the error term,
For the specific model development from the data:

$$\text{Cardamom Yield} = \left.\begin{matrix} -106.25 + 273.37(Max\ Temp) + 37.71\,(Min\ Temp) \\ -565.75\,(Avg\ Temp) - 0.0748(Ra\inf all) + \varepsilon \end{matrix}\right\}$$

The intercept − 106.25 indicated the expected cardamom yield when all weather parameters are set to zero. The coefficients 273.37, 337.71, and − 565.75 represented the influence of maximum temperature, minimum temperature, and average temperature, respectively, on cardamom yield. The coefficient − 0.0748 reflected the relationship between rainfall and cardamom yield, indicating a minimal negative effect of rainfall on the yield in this model.

Conclusion

The study employed various statistical methods to analyze the variability and trends in climatic variables, focusing on surface air temperature and rainfall data in the Indian Cardamom Hills. The results indicated no statistically significant increasing or decreasing trend for the entire study period. Precipitation distribution, in terms of rainy days, was found to be inconsistent across different decades. The reduction in both rainfall and rainy days poses a threat to the local agroforest ecosystem, as extended droughts and long rainless periods coupled with sparse tree cover could negatively affect cardamom growth and yield. Our findings showed that excessive rainfall between June and September reduced cardamom yields, while pre-monsoon and winter rainfall contributed to increased production. The study also revealed that the temporal variation of decadal monthly rainfall was greater than that of monthly temperature, indicating that rainfall patterns are more unpredictable and subject to change over time than temperature levels. Since the study area relies heavily on rain-fed cardamom agriculture, climate change-induced variability and irregular rainfall distribution could have significant negative impacts on cardamom-based livelihoods in the ICH agroforestry system. These results underscore the urgent need for appropriate and responsible measures to mitigate the effects of climatic variability by curbing the degradation of cardamom forests and maintaining canopy levels.

Data availability

The data will be made available on a reasonable request to the corresponding author.

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Additional information
Correspondence and requests for materials should be addressed to M.I.K.

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