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Trend analysis of Agro-climatic Determinants for Onion Yield Dynamics in Odisha, India

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Onion (*Allium cepa* L.) cultivation in Odisha is significantly affected by climatic variability, requiring a comprehensive study of stage-specific meteorological impacts. This study assesses the long-term trends of critical climatic variables, such as, maximum and minimum temperatures, relative humidity, precipitation, and photosynthetically active radiation (PAR) across six principal onion producing districts of Odisha - Balangir, Angul, Kalahandi, Sundargarh, Subarnapur, and Sambalpur.
The research employs a comprehensive statistical framework, utilizing a 28-year time-series dataset (1996–97 to 2023–24), which includes descriptive statistics and exponential growth models for Compound Annual Growth Rate (CAGR).
The trend analysis shows that rainfall increased during early growth stage, especially in Angul (2.88% in October) but decreased drastically during winter months particularly in Balangir (-7.54% in February).

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Maximum temperature also exhibited decreasing patterns during bulb growth stages in Kalahandi (-0.21% in January) and minimum temperature during peak winter with Balangir registering -1.14% in December. PAR showed favorable growth in the first growth period as Angul reported 0.85% in September and downward tendencies in the latter stages. Relative humidity showed increasing trends during mid-season months especially in Kalahandi (0.93% in December) indicating beneficial moisture conditions during crop growth. The results give us a number-based way to make climate adaptation plans at the district level that will help smallholder farmers in Odisha keep their yields stable.

Keywords: CAGR; agro-climatic; onion; PAR; trend; variation.

1. Introduction

In Odisha, farming is still the main source of income, supporting about 60% of the population (Directorate of Agriculture and Food Production, 2023). But the horticultural productivity of the state is often hurt by how easily it may be damaged by natural calamities and how unpredictable the monsoon season is. According to statistics, just 13 years out of a 52-year period have had regular rainfall patterns. This means that the state is quite likely to face weather disasters at any time. The onion is the most important horticultural commodity since it is valuable for business and important for daily meals, but its production is quite unstable.

Growing onions is a complicated biological process that needs certain weather conditions at different times of the year, such as when the plants are in the nursery, when they are growing, when the bulbs start to grow, and when they are ready to be harvested. Photosynthetically Active Radiation (PAR) is the main source of energy for biomass growth. The daily temperature changes, especially the difference between the highest and lowest temperatures, control the change from vegetative growth to bulb development. The plant's water potential and how likely it is to get fungal diseases like *Alternaria porri* (purple blotch) depend on the moisture levels, which are affected by the amount of rain and relative humidity (RH). This fungus does well in winter microclimates that are getting more humid.

Earlier research has shown that the amount of rain that falls during the bulb development stage is very important for the yield in western Odisha. Recently, changes in UV intensity and increasing "terminal heat" in March have become additional problems that could speed up bulb hardening and lower the biological yield potential (Singh et al., 2023).

Onion productivity is intrinsically linked to the environmental conditions that occur during its important phenological stages, making it extremely sensitive to the temporal variation of climate factors. As global climate patterns become more variable, understanding the relationship between climate variables (particularly rainfall, temperature, humidity, and solar radiation) and crop performance has become critical for good agricultural planning. Recent research shows that coordinating planting dates with favorable thermal and moisture windows is an important management strategy for reducing environmental stress and improving ultimate bulb quality. As a result, understanding the threshold-based responses of onion crops to these characteristics is critical for improving yield stability and building resilient production strategies in regional cropping systems. (Salari, 2024; Pujar et al., 2026).

Standard statistical techniques, such as descriptive statistics and trend analysis, are still necessary for understanding the basic patterns of these environmental changes (Prajneshu and Chandran, 2005). Recent literature has examined sophisticated computer models; nonetheless, there remains a want for a thorough linear framework to measure the stage-specific influence of environmental variables on onion yield (Kaur et al., 2024). This work fills this gap by looking at a 28-year longitudinal dataset to give an empirical basis for climate-resilient management strategies in the main onion-growing areas of Odisha.

Keeping in view the above perspectives, the long-term temporal patterns and Compound Annual Growth Rates (CAGR) of critical climatic variables and onion yield are assessed in the chosen areas.

1.1 Statement of the Problem

The main problem for onion farmers in Odisha is that they cannot accurately foresee how changes in the weather will affect their crops. Some districts have seen an improvement in the availability of moisture early in the season, but the big drop in rainfall during the off-season and the rise in nighttime temperatures during the harvest period pose a threat to the quality and shelf life of products. Without a way to measure and rank these climate factors across multiple districts, people in agriculture are still reacting to supply shocks, which is bad for the state's 93 per cent small and marginal farmers (Rout et al., 2024).

Objectives: To tackle the issues outlined above, this study has the following goals:

- **Spatio-Temporal Characterization of Agrometeorological Trajectories**: To evaluate and quantify the long-term temporal trajectories and Compound Annual Growth Rates (CAGR) of month-wise, stage-specific agrometeorological variables—specifically maximum temperature, minimum temperature, relative humidity (RH), total rainfall, and Photosynthetically Active Radiation (PAR) during the onion cultivation season (September to March) across the selected districts.
- **Quantifying Stage-Specific Precipitation Shifts**: To model and assess temporal shifts in precipitation distribution during critical phenological phases, specifically focusing on the growth rate (CAGR) of rainfall during the early nursery and seedling establishment phase (September-October) versus the sharp, off-season winter precipitation declines during the late-stage bulb maturation and curing phase (February-March).
- **Assessment of Diurnal Thermal Regimes:** Determine the temporal trends of diurnal thermal parameters, specifically evaluating the nighttime cooling trends of minimum temperature during peak winter bulb initiation (December-January) and the warming trends (terminal heat) during the late-season harvesting and curing phase.
- **Analysis of photosynthetically active radiation (PAR):** To analyze the annualized rate of change (CAGR) of Photosynthetically Active Radiation (PAR) during the crucial mid-to-late vegetative and bulb-filling stages (November to April), to evaluate potential light-harvesting limitations and biological yield bottlenecks.
- **Characterizing Microclimatic Relative Humidity (RH) Instability**: To monitor the trend and instability of atmospheric moisture (RH) during the mid-season winter months (November to January) to assess the development of cooler, more humid microclimates and their association with increased biological risk, specifically fungal disease pressure from “*Alternaria porri* ".

1.2 Research Questions

To guide the empirical investigations, this study addresses the following research questions:

- What are the long-term trend directions and compound annual growth rates (CAGR) of monthly rainfall, temperature, relative humidity, and PAR in Odisha's important onion farming areas from September to March?
- How do these monthly meteorological variables affect onion yields at different growth stages (establishment, vegetative growth, bulb initiation, and maturation)?
- Do the mean yield, variance, and proportion of onion area and output in Odisha deviate considerably from India's national average?

1.3 Research Gaps

- **Lack of Month-Wise, Stage-Specific Analysis:** Most prior agrometeorological research in Odisha have focused on broad seasonal (Kharif/Rabi) or annual weather indices. Because onions are very susceptible to microclimatic fluctuations during specific phenological stages (for example, bulb initiation in December and bulb filling in January-February), annual or seasonal averages mask the crucial monthly climatic shocks that influence final production.
- **Horticultural Crop Neglect:** While extensive research has been conducted to map the impact of climate change on staple crops such as rice, wheat, and maize in Eastern India, horticultural commodities, particularly high-value crops such as onions, have received little attention in terms of long-term quantitative trend modeling.

- **Lack of Rigorous Regional Baseline Modeling:** While some recent literature has investigated advanced machine learning or localized surveys for onion production, there is a need for a baseline, long-term (28-year) longitudinal study that applies uniform parametric and inferential testing across multiple agro-climatic districts in Odisha.

1.4 Review of Literature

Prajneshu and Chandran (2005) demonstrated the limits of this structure for trend analysis, pointing out that conventional exponential models presume infinite acceleration and misrepresent goodness-of-fit indicators during logarithmic transformation. Linear trends do not represent asymptotic static or mid-term growth decelerations in locations that have reached ecological or infrastructure thresholds. To overcome this, the authors suggest using non-linear trend models like the Logistic, Gompertz, and Monomolecular functions, which include internal deceleration mechanisms and upper asymptote limits. Adopting this nonlinear paradigm prevents growth trends from being overestimated and produces structurally reliable, mathematically sound long-term pathways.

Dash et al. (2017) critically assess this sector and give a "gloomy picture" of increasing agricultural instability over time, which is primarily due to climate variability and infrequent rainfall, rather than market developments. The instability is exacerbated by a paradoxical trend observed across various crop categories: despite a significant reduction in kharif cereals and oilseeds acreage due to a shift to non-food grain crops, total output has remained positive on account of significant yield improvements. Given these non-linear complexities, researchers are increasingly turning to machine learning frameworks such as Artificial Neural Networks (ANN) and Random Forest, which capture the erratic swings in Odisha's agricultural output better than typical ARIMA models.

Dash et al. (2020) predicted kharif cereal production in Odisha using the Autoregressive Integrated Moving Average (ARIMA) approach and historical data spanning 1970-71 to 2015-16. Rigorous testing using residual diagnostics and model cross-validation revealed ARIMA (1,1,0) and ARIMA (0,1,2) as the best fitted models for area and yield, respectively. The findings revealed that the area under kharif cereals is anticipated to decrease as non-food grain crops take precedence, while yields are expected to increase. The study concluded that, given the limited capacity for area extension, the food security of the state's growing population would be mostly dependent on agricultural productivity enhancement.

Dash and Hansdah (2020) investigated the district-specific growth and instability of kharif oilseed output in Odisha from 1993-94 to 2016-17. Area, yield, and production trends were analyzed using compound growth rates and Coppock's instability index. However, the data showed a robust and significant compound growth rate in yield of kharif oilseeds in Odisha, although overall production declined dramatically. The drop in production was mostly owing to a sharp decrease in the area under oilseed cultivation during the kharif season. These findings point to a serious challenge for the state's commercial agriculture sector, since productivity increases are being offset by a decline in oilseed acres.

Sripriya and Dash (2021) investigated kharif food grain output in Odisha, focusing on compound growth rates and instability across districts from 1993-94 to 2017-18. The analysis discovered a counterintuitive pattern: a positive gain in output is maintained by improving yields despite a negative growth rate of cultivated land. Using the Cuddy-Della Instability Index, the authors discovered that the state's production swings were mostly caused by yield volatility, while cultivation area remained rather consistent. The current study is a valuable tool for policymakers to visualize the progress of food grain cultivation and develop focused agricultural policies for the region.

Das et al. (2022) used convolutional neural networks using satellite data to evaluate onion crop health in Gujarat, detecting climate stress with 92% accuracy during the vegetative and bulbing stages. Temperature-humidity stress sensors offered 10-day advance warnings of yield loss, enhancing the statistical modeling method by allowing for real-time confirmation of model predictions in field.

Salari (2024). Apart from observational studies, research into optimal planting dates shows how farmers can regulate the crop's exposure to changing weather conditions to enhance yields. This study shows that planting date is an important management element that determines the degree of environmental stress faced by the crop by matching the planting window with favorable temperature, humidity, and rainfall patterns. The study concludes that timing specific growth stages with established "optimal" climatic windows is a strong predictor of bulb size, quality, and overall yield, offering a realistic technique for avoiding the hazards associated with unpredictable climate fluctuation.

Singh *et al*. (2023) utilized Random Forest (RF), XGBoost, and Support Vector Regression to evaluate onions, employing 18 years of data from several locations. The Random Forest model did quite well, with an RMSE of 0.38 t/ha. The study found that the highest temperature during the bulbing phase (October to November) was the most important element.

Mallick and Dash (2024) studied the trends and fluctuations in the growth of kharif rice agriculture in Odisha using the district-wise data for the period 1994-95 to 2017-18. The exponential model for growth and Cuddy-Della Valle instability index used in the study showed that rice area is generally more stable than production or yield across the state, but there are considerable regional variances. While districts such as Malkangiri and Subarnapur exhibited positive trends in area, yield was the key factor for production gains while most of the districts had decreasing area trends. The study indicated that the huge diversity in productivity among the districts calls for particular localised policies to promote sustainable and inclusive agricultural expansion.

Kaur *et al*. (2024) utilized detrending methodologies to separate climate signals from technological trends in 32 years of wheat data from Punjab. They generated composite weather indices with an R2 value of 0.92. The maximum temperature from October to November and the amount of rain in November made for 78% of the changes in production. This makes it easier to use the multi-variable climate integration strategy for rabi crops and gives methodological guidance for making the 28-year Odisha onion dataset.

Rout *et al*. (2024) evaluated the production, marketing, and storage challenges experienced by onion growers in Odisha's Western Undulating Agroclimatic Zone. The study used a multi-stage purposive sampling technique to examine a sample of 90 farmers from the Bhawanipatna and Golamunda blocks of Kalahandi district during the 2021-2022 crop year. The empirical data found that production was severely limited by manpower shortages for weeding, high input prices (seeds and weedicides), and a general lack of understanding of improved onion varieties. Growers faced significant marketing, climatic variability and post-harvest obstacles, including low harvest-month pricing, high price volatility, high transportation costs, and a crucial shortage of localized storage facilities and real-time market knowledge.

Gote (2026). The use of statistical modeling, particularly multiple regression, has been useful in measuring the complicated links between climate and onion performance. This study investigates a multi-factorial dataset that includes rainfall, diurnal temperature fluctuations (T_Max and T_Min), and humidity measures (morning and evening relative humidity) to determine their effects on area, production, and total productivity. The study found substantial positive and negative correlations between these individual weather inputs and harvest performance, suggesting that linear regression models are useful tools for separating onion crop susceptibility to localized climatic alterations in places such as Marathwada.

Pujar *et al*. (2026). Recent advances in agrometeorological research highlight the importance of studying crop-weather relationships for predicting onion yield changes. This paper summarizes how key climatic elements such as rainfall, temperature, relative humidity, and solar radiation influence crop phenological development and final productivity. By mapping these environmental variables to specific growth stages, the study gives a solid framework for understanding how seasonal weather patterns affect biomass accumulation and bulb formation, laying the groundwork for predictive productivity modeling.

2. Materials and Methods

The study concentrates on six principal onion-producing districts in Odisha: Balangir, Angul, Kalahandi, Sundargarh, Subarnapur, and Sambalpur. The research employs a 28-year time-series dataset on onion acreage, production, and yield spanning from 1996–97 to 2023–24 obtained from various volumes of Odisha Agricultural Statistics published by Directorate of Agriculture and Food Production. Data is taken as per the World Meteorological Organization (WMO) recommended standards. The monthly weather data for the onion growing season which usually runs from September to March has been examined.

Simultaneously, five critical climatic parameters which affect the onion crop yield are integrated into the analysis:

- Rainfall (in mm)
- Maximum Temperature (T_Max) (in ^{0}C)
- Minimum Temperature (T_Min) (in ºC)
- Relative Humidity (RH) (in %)
- Photosynthetically active radiation (PAR) (in MJ/m/day).

The current study uses statistical modeling to assess the effect of five essential environmental parameters such as rainfall, maximum and minimum temperature, relative humidity, and photosynthetically active radiation (PAR) on onion crop output. Following observed agrometeorological treatments, multiple regression analysis is used to separate crop productivity's sensitivity to each variable, allowing for a precise examination of their individual and cumulative associations. Data collection focuses on seasonal climatic changes, with a special emphasis on humidity tolerance and temperature dynamics, in order to determine how specific weather regimes influence growth trajectories during rainy seasons. Using these quantitative models, this study helps to determine the close connection between variables and clarifies the relative importance of each parameter on production outcomes (Gote 2026; World Vegetable Centre 2026).

2.1 Descriptive Statistical Analysis

To determine the baseline features and assess the variability of the data, basic descriptive statistics are calculated for all yield and climatic variables across the six districts. These measurements offer initial insights into the central tendency and level of instability within the agricultural and climatic profiles.

Here are the formulas written properly in standard statistical notation:

Mean $((\bar{x}))$

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

Standard Deviation $((\sigma_X))$

$$\sigma_X = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$$

Coefficient of Variation (CV)

$$CV = \frac{\sigma_X}{\bar{x}} \times 100$$ (Mallick and Dash, 2024)

Skewness (β₁)

$$\beta_1 = \frac{\mu_3^2}{\mu_2^3} \;;\; \gamma_1 = +(\beta_1)^{0.5}$$

where:

$\mu_2 =$ Second central moment
$\mu_3 =$ Third central moment

Kurtosis (β₂)

$$\beta_2 = \frac{\mu_4}{\mu_2^2}$$ (Dash et al., 2020)

where:

$\mu_4 = \frac{}{\text{Fourth central moment}}$; $\gamma_2 = \beta_1 - 3$

2.2 Trend Analysis and CAGR Modelling

An exponential growth model was used to look at the long-term behaviour and smoothed annualized changes in climate parameters and yield. This model is better for agricultural time series since it takes into account how environmental changes build up over decades (Dash et al., 2017; Prajneshu & Chandran, 2005).

While Compound Annual Growth Rate (CAGR) is a common metric, it should be considered a descriptive summary of historical performance rather than a predictive model because it simplifies a 28-year dataset by focusing solely on the initial and terminal values while ignoring all intermediate fluctuations. Unlike ARIMA, ETS, and regression techniques, which statistically analyze the entire time series to capture complex dependencies, weight recent observations, and define the functional relationship between time and crop productivity, CAGR assumes a constant, idealized growth rate that rarely reflects agricultural data volatility. As a result, in this study, CAGR is justified only as a high-level, standardized measure for assessing the overall historical pattern, whereas more robust analytical models are used to rigorously evaluate the underlying trend and correlation metrics, ensuring that the study accounts for the specific, non-linear temporal patterns inherent in the longitudinal data.

The exponential growth model is expressed as:

$Y_t = ae^{bt}e^{\epsilon}$ (Dash and Hansdah, 2020)

Where:

Y_t is the value of the climatic variable or yield at time.
a is the intercept representing the initial value.
b is the growth rate parameter.
t is the time in years (1, 2, n).
e is the multiplicative error term.

The Compound Annual Growth Rate (CAGR) is then calculated from the estimated parameter:

$CAGR(\%) = (e^b - 1) \times 100$ (Sripriya & Dash, 2021)

A positive CAGR indicates a steady upward trend, while a negative value signifies a decline, such as the observed drop in off-season precipitation

3. Results and Discussion

Fig. 1 shows that relative humidity dropped steadily from September to February in all areas, with the highest levels recorded in September. In March, the Subarnapur district had some stability and growth. Subarnapur has seen much greater humidity levels in recent months than Sundergarh and Balangir. The current pattern indicates that the amount of moisture in the air decreases gradually as the monsoon season ends and the winter season begins.

Fig. 2 indicates that the peak temperature decreases from September to December, with the lowest point being in December. From January to March, all areas had considerable increases. Temperatures in Angul and Balangir are much higher than in Subarnapur. The graph shows how temperatures drop in winter and rise as summer approaches.

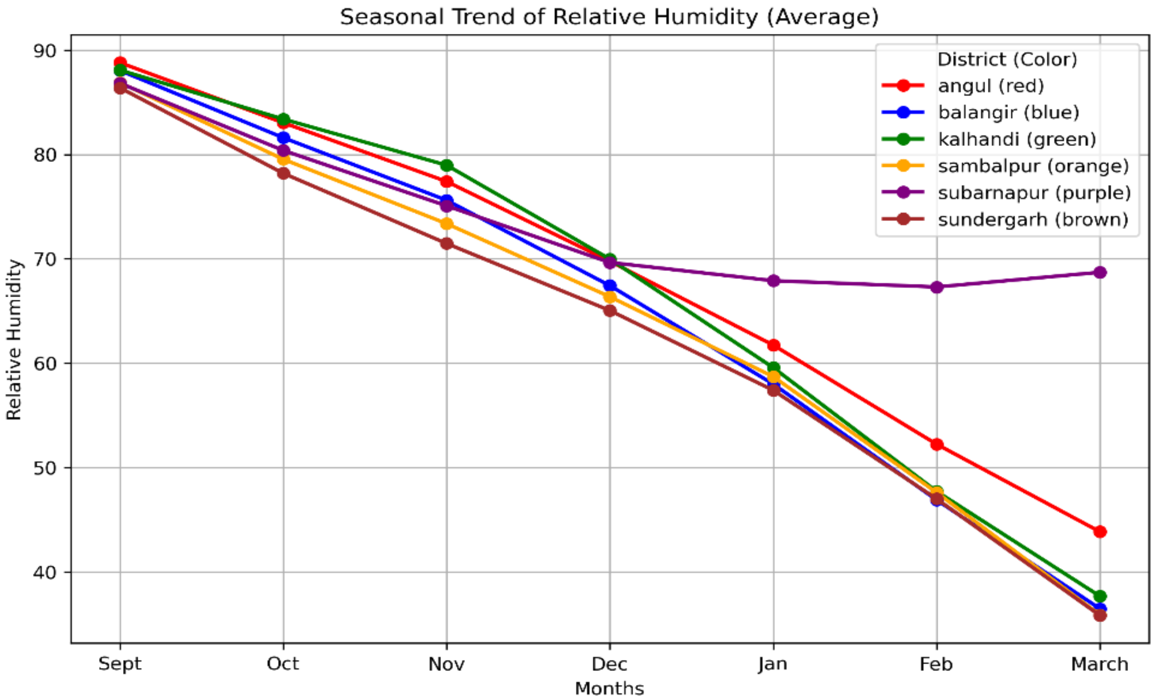

Fig. 1. Graph showing Monthwise variation of Relative Humidity (%) for growing period of onion averaged over the period 1996 to 2023

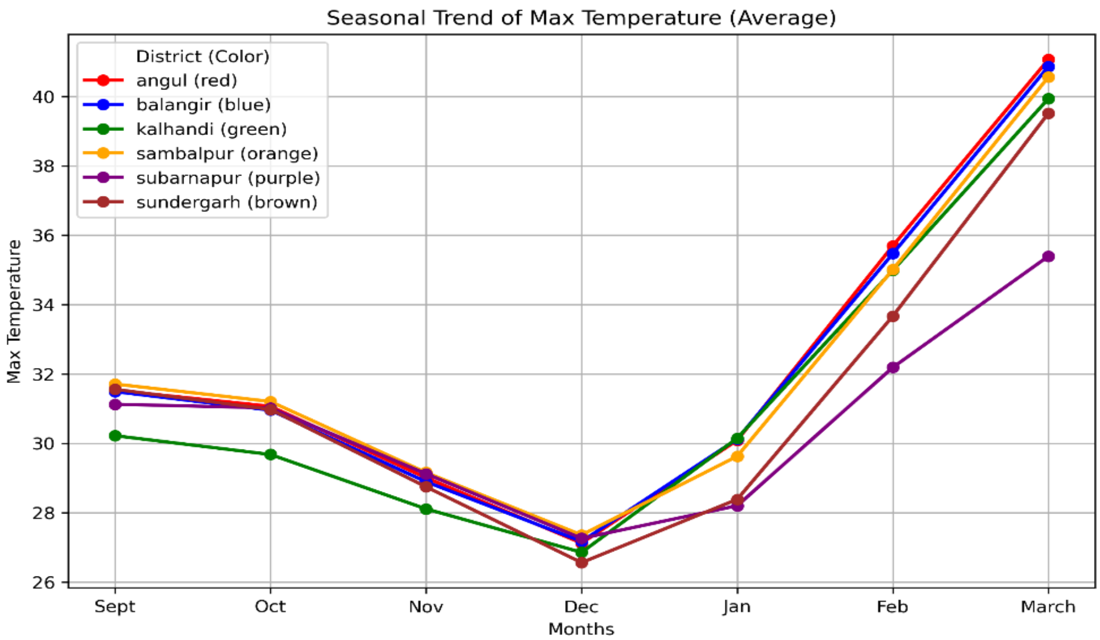

Fig. 2. Graph showing Monthwise variation of Maximum Temperature (^{0}C) for growing period of onion averaged over the period 1996 to 2023

Fig. 3 shows how the temperature drops gradually from September to January. Between January and March, the trend was upward. Subarnapur frequently experiences higher minimum temperatures than Sambalpur and Angul, which have lower temperatures. The graph depicts how temperatures decline in the winter and climb in the summer.

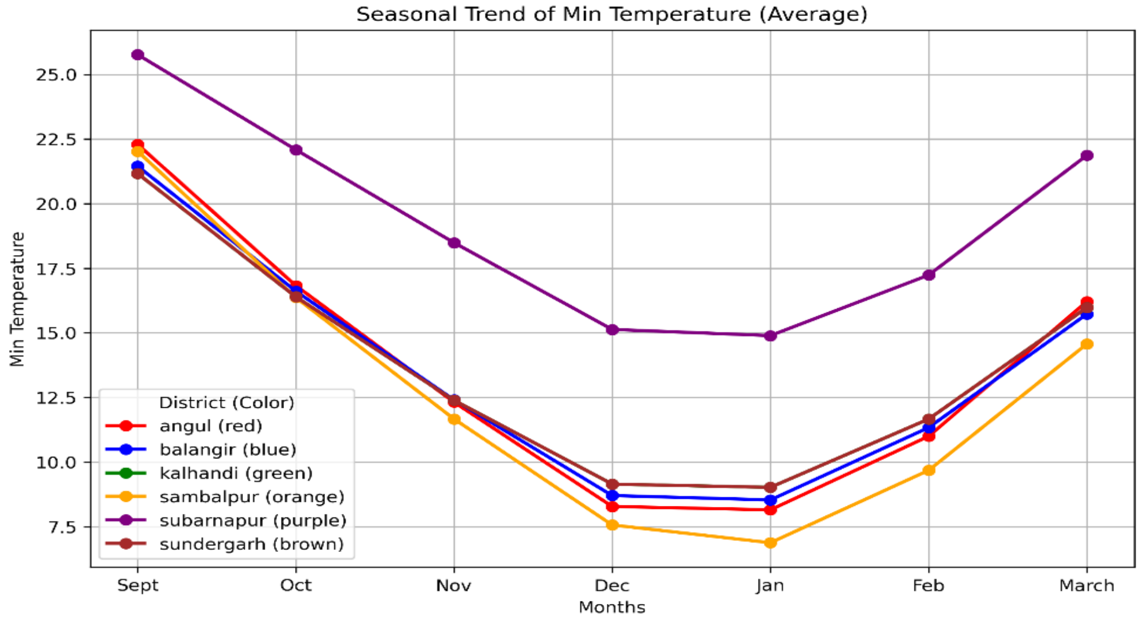

Fig. 3. Graph showing Monthwise variation of Minimum Temperature (^{0}C) for growing period of onion averaged over the period 1996 to 2023

Fig. 4 shows that photosynthetic active radiation drops from September to December, reaching its lowest point in December. From January to March, all districts saw a consistent growth. Kalahandi has slightly greater levels of PAR, while Subarnapur has lower values. The trend indicates that the amount of PAR varies with the season.

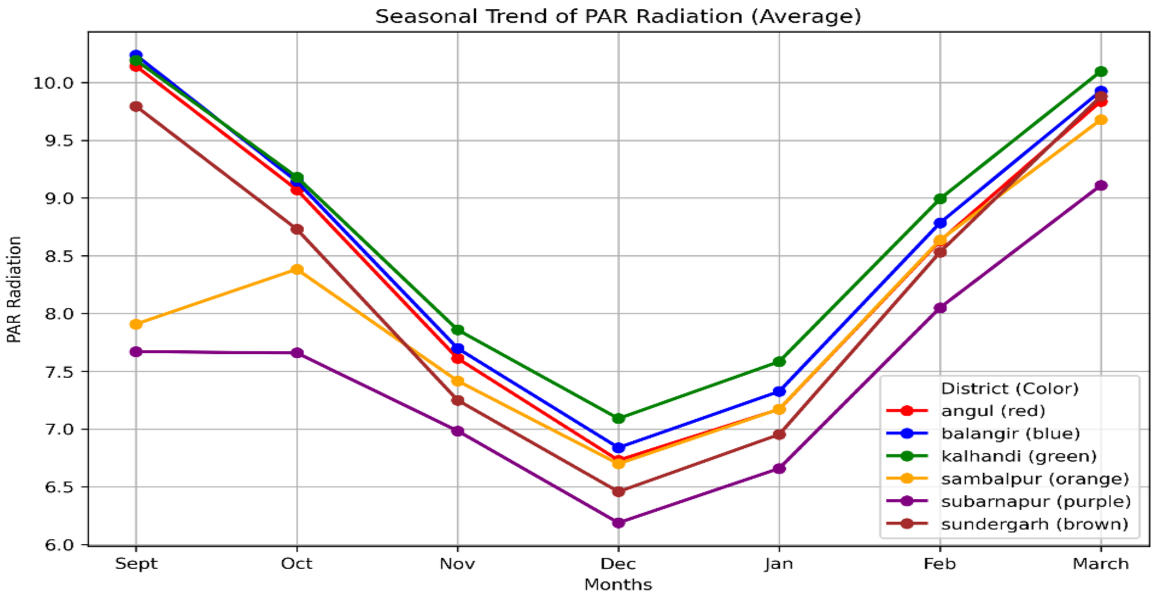

Fig. 4. Graph showing Monthwise variation of PAR (MJ/m^2/day) for growing period of onion averaged over the period 1996 to 2023

Fig. 5 demonstrates that precipitation peaks in September and begins to decline significantly in October across all districts. Between November and February, there is extremely little rainfall. March sees a small uptick. In September, Kalahandi gets the most rain, while Balangir gets the least. The graph shows how the monsoon is disappearing and how dry the winter is.

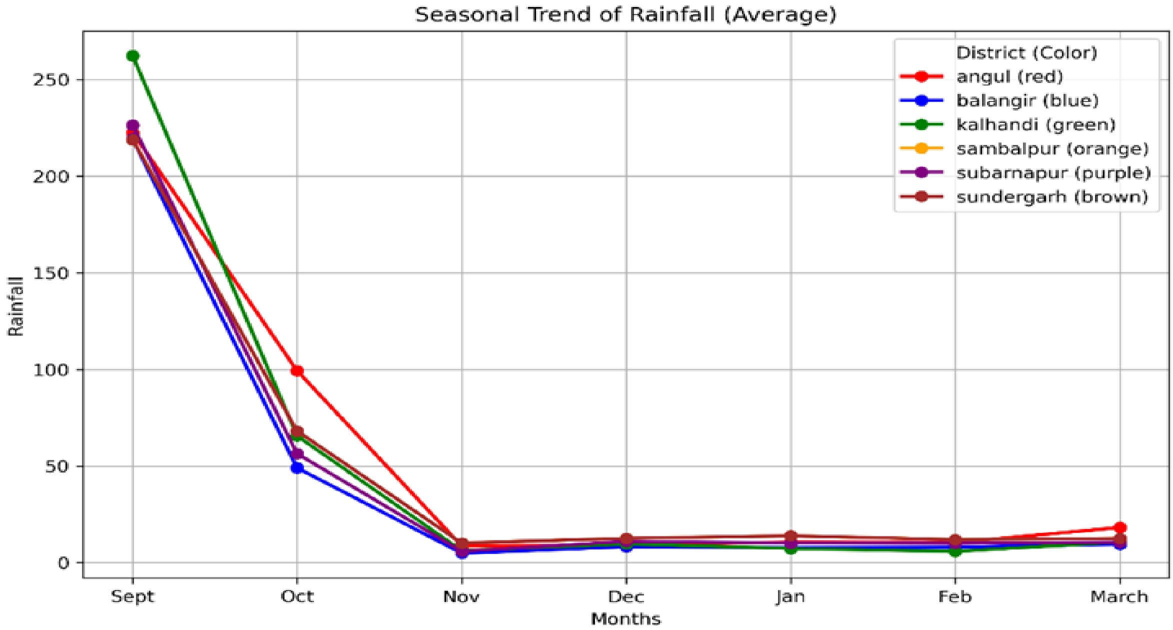

Fig. 5. Graph showing Monthwise variation of Rainfall(mm) for growing period of onion averaged over the period 1996 to 2023

Table 1 shows descriptive information for onion acreage, yield, and production in Odisha. The coefficient of variation for production was found to be the greatest, followed by yield and area, indicating that production varied more during the study period. The area had approximately symmetric distribution, whereas yield and production had a tiny negative skewness. All of the variables are platykurtic in character, with kurtosis values smaller than three, indicating a flatter distribution than the normal distribution.

Table 1. Descriptive statistics of area, yield and production of Onion

Variable	Area ('000 ha)	Yield (kg/ha)	Production ('000 MT)
Mean	35.03	8167.8	283.3
Standard Deviation	8.12	2537.31	95.95
Median	34.11	7904	296.53
Min	19.41	3376	73.96
Max	50.03	12066	432.1
Range	30.62	8690	358.14
Skewness	0.05	-0.13	-0.64
Kurtosis	-1.14	-0.81	-0.38
CV (%)	23.19	31.06	33.87

3.1 Trend for Various Climatic Variables for the Months of Growing Season of Kharif Onion in Important Onion Producing Districts of Odisha

In Table 2 the study of rainfall patterns during the Kharif onion growing season shows that the way rain falls throughout time has changed a lot in the main onion-producing areas of Odisha. In the beginning, especially in September and October, A lot of districts is seen with a positive compound growth rate. Angul had the highest rate at 2.88%, and Kalhandi was close behind at 2.56%. This rising tendency shows that moisture is becoming increasingly available during important times for transplanting and early growth. This could make crops stronger. But the analysis suggests a troubling trend in the winter months. For example, Balangir had a large drop in rainfall in February, with an annual rate of -7.54%. The slow decline in rainfall during the off-season suggests that climate change is becoming a bigger issue. This is why it is necessary to use irrigation systems to help the crops grow and reach their final bulb maturity. The facts and figures in Table 2 are represented in Fig. 2.

Table 2. Trend of Rainfall for the months of growing season of Kharif onion in important onion producing districts of Odisha

Districts	Growing season months of onion crop						
	September	October	November	December	January	February	March
Balangir	2.183	1.933	-1.020	-3.504	0.119	-7.544	-4.129
Angul	0.638	2.884	2.840	2.193	0.964	0.299	1.963
Kalahandi	1.890	2.555	-2.073	-4.234	0.982	0.612	3.563
Sundergarh	0.591	1.253	6.353	5.491	3.150	2.735	4.371
Subarnapur	1.337	1.871	-2.870	-1.014	0.850	4.334	-0.513
Sambalpur	0.591	1.252	6.482	5.376	3.066	2.725	4.340

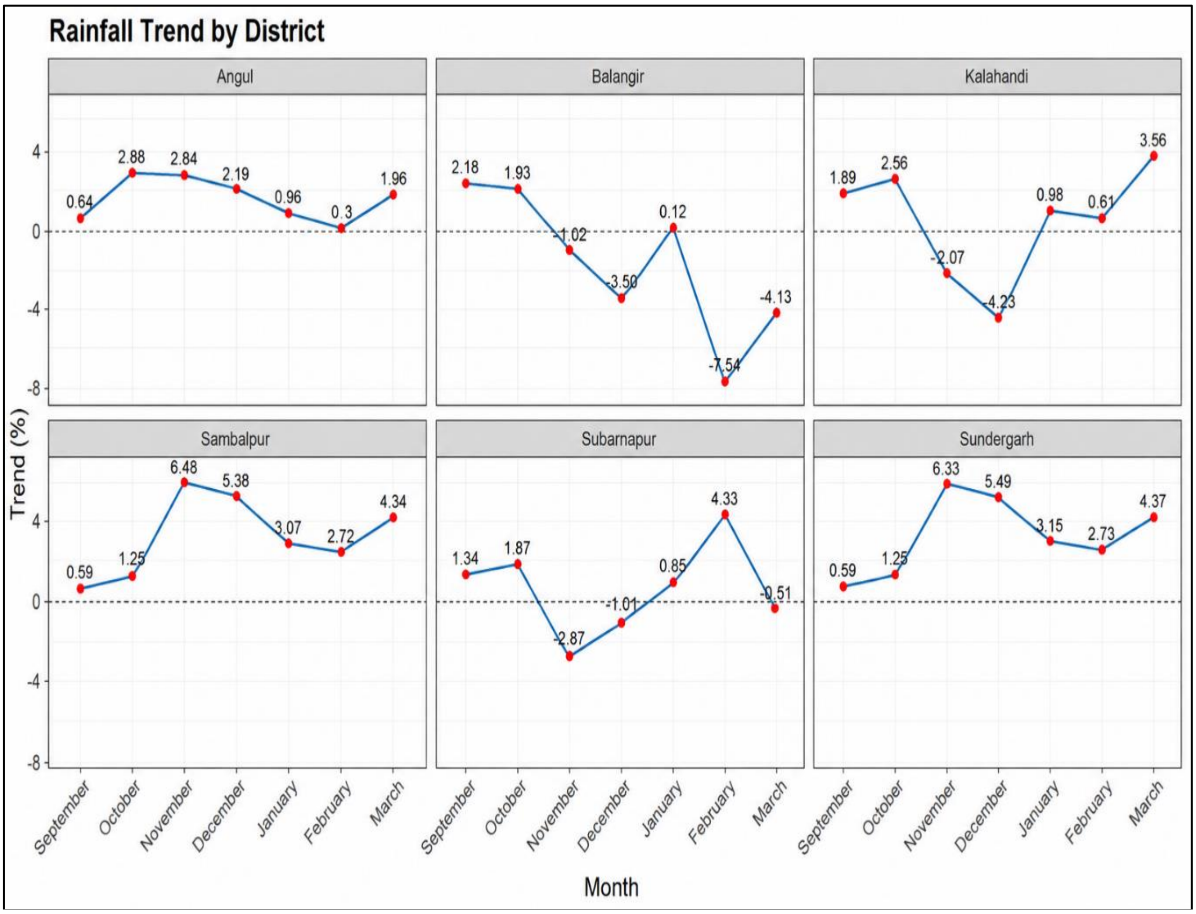

Fig. 6. Graph showing Graph showing Trend of Rainfall for the months of growing season of Kharif onion in important onion producing districts of Odisha

In Table 3, It is really important to look at the trends in minimum temperatures because they tell us what the weather is like at night, which affects how onions grow. The numbers show that the area analyzed has been increasing cooler during the coldest months of December and January. For instance, Sambalpur and Balangir have had yearly reductions of about -0.92% and -1.14%, respectively. The colder temperatures at night can help with vernalization and starting the bulbing process. But the changes in temperature could also make some locations more likely to feel stress from the cold. The good news is that the pattern in April, like the 0.46% rise in Balangir, suggests that evening temperatures will remain climbing over the harvest season. This change might speed up the curing process, but it could also impair the food's long-term quality and shelf life if the temperature limits are routinely broken. The facts and figures in Table 3 are represented in Fig. 6.

Table 3. Trend of Minimum Temperature for the months of growing season of Kharif onions in important onions producing districts of Odisha

Districts	Growing season months of onion crop						
	September	October	November	December	January	February	March
Balangir	0.088	-0.184	-0.047	-1.135	-0.534	-0.707	-0.012
Angul	0.009	-0.251	-0.060	-0.920	-0.529	-0.444	0.052
Kalahandi	0.094	-0.232	0.003	-0.901	-0.280	-0.678	0.044
Sundergarh	0.094	-0.232	0.003	-0.901	-0.280	-0.678	0.044
Subarnapur	0.060	-0.119	-0.177	-0.308	-0.202	-0.174	-0.142
Sambalpur	0.080	-0.089	0.143	-0.916	-0.728	-0.439	0.447

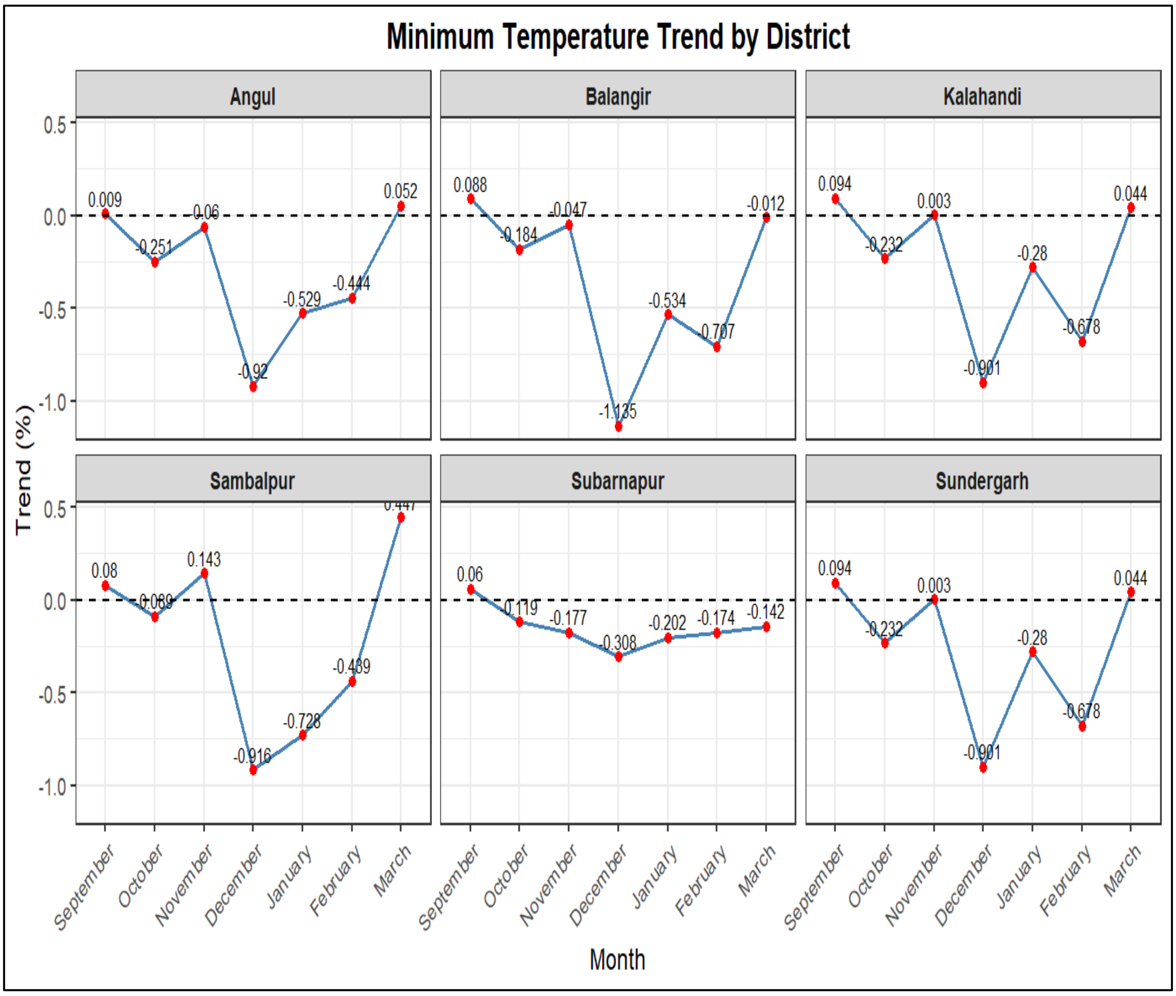

Fig. 7. Graph showing Trend of Minimum Temperature for the months of growing season of Kharif onions in important onions producing districts of Odisha

In Table 4, the main onion-growing areas, the maximum temperature profile stayed the same, but there are some little but major changes in how hot it got during the day. In January and February, daytime temperatures dropped somewhat, with Kalhandi reporting a minor drop of -0.21% in January. It would be very helpful to cool down during the day while the sensitive bulbs are growing. This would keep the soil moist and cut down on water loss. On the other hand, the minor uptick in daytime temperatures in September shows that the Kharif onion crop is having a harder struggle with heat during its nursery and transplanting stages. The results show how important it is to use heat-tolerant plant varieties and better nursery management practices to help seedlings grow robust and stay alive as temperatures rise earlier in the season. The facts and figures in Table 4 are represented in Fig. 7.

Table 4. Trend of Maximum temperature for the months of growing season of Kharif onion in important onion producing districts of Odisha

Districts	Growing season months of onion crop						
	September	October	November	December	January	February	March
Balangir	0.012	0.029	-0.102	0.019	-0.115	-0.092	-0.047
Angul	0.019	0.046	-0.046	0.030	-0.139	-0.083	-0.099
Kalahandi	0.004	-0.026	-0.155	-0.051	-0.207	-0.156	-0.089
Sundergarh	0.013	-0.023	-0.146	-0.025	-0.142	-0.111	-0.065
Subarnapur	0.020	0.035	-0.019	0.048	-0.110	-0.046	-0.030
Sambalpur	-0.007	-0.010	-0.133	0.007	-0.123	-0.105	-0.060

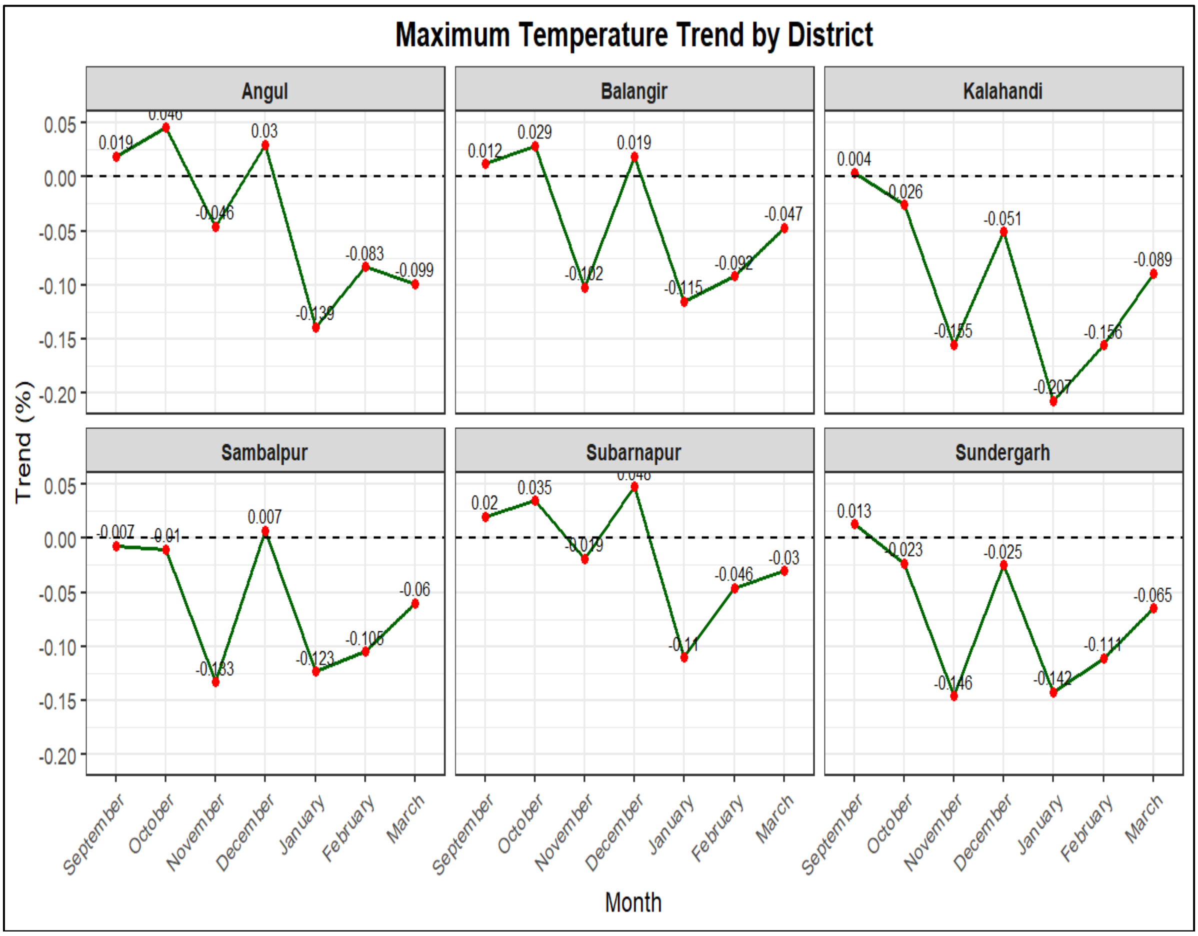

Fig. 8. Graph showing Trend of Maximum temperature for the months of growing season of Kharif onion in important onion producing districts of Odisha

In Table 5, Plants need a kind of light called Photosynthetically Active Radiation (PAR) to grow and manufacture their bulbs. Onions need this light a lot. The trend analysis shows that the level of radiation changed in two different ways. In August and September, the first months of growth, the growth rate was obviously favourable, with Kalahandi experiencing a 1.30% rise. This suggests that there is clearly more solar energy available when plants are just starting to grow. This is probably because there are fewer clouds or clearer skies. Most of the districts showed a steady reduction from November to April. The decrease in accessible PAR during the critical bulb-filling phase may significantly impede the crop's attainment of its full biological production capacity. This highlights how crucial it is to choose genotypes that can gather light well. The facts and figures in Table 5 are represented in Fig. 8.

Table 5. Trend of Photosynthetically active radiation (PAR) for the months of growing season of Kharif onion in important onions producing districts of Odisha

Districts	Growing season months of onion crop						
	September	October	November	December	January	February	March
Balangir	0.707	0.118	-0.295	-0.517	-0.560	-0.268	-0.407
Angul	0.848	0.223	-0.249	-0.501	-0.579	-0.291	-0.390
Kalahandi	0.766	0.214	-0.249	-0.481	-0.506	-0.247	-0.420
Sundergarh	0.669	0.103	-0.301	-0.495	-0.396	-0.233	-0.122
Subarnapur	-0.282	-0.294	-0.477	-0.816	-0.796	-0.519	-0.494
Sambalpur	-0.477	-0.228	-0.364	-0.561	-0.469	-0.265	-0.349

In Table 6, it shows that the relative humidity level is important for keeping the water in crops balanced and affects how good the environment is for fungal infections like purple blotch. The analysis demonstrates that the relative humidity always goes up during the middle of the year, in November, December, and January. Kalhandi and Sundergarh, on the other hand, are growing at rates of 0.93% and 0.83%, respectively. The rising humidity and falling minimum temperatures point to the formation of a cooler, more humid microclimate. These conditions make it less likely that the crop will need water from the air, but they also make it more likely that diseases will spread. Based on analysis, future farming efforts should focus on integrated pest and disease management systems that work well in the increasingly humid winter growing conditions. The facts and figures in Table 6 are represented in Fig. 9.

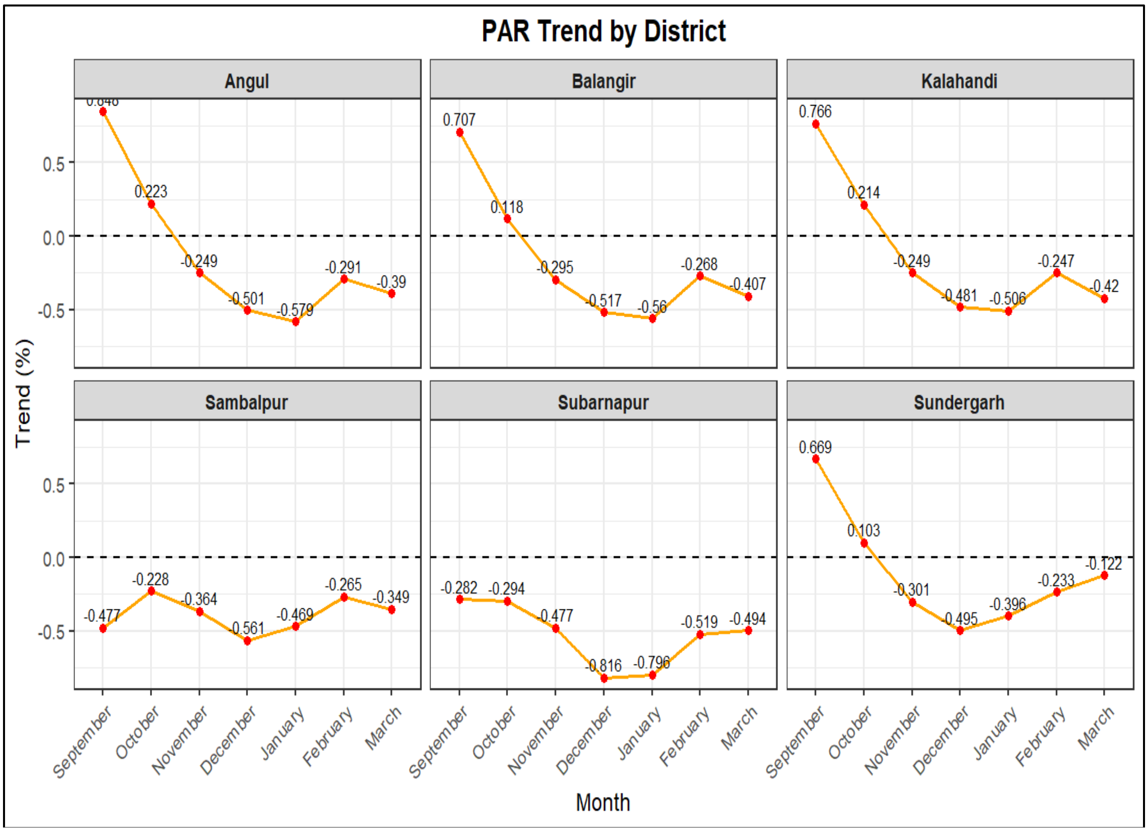

Fig. 9. Graph showing Trend of Photosynthetically active radiation (PAR) for the months of growing season of Kharif onion in important onions producing districts of Odisha

Table 6. Trend of Relative humidity for the months of growing season of Kharif onion in important onion producing districts of Odisha

Districts	Growing season months of onion crop						
	September	October	November	December	January	February	March
Balangir	-0.007	0.057	0.313	0.775	0.307	-0.157	0.430
Angul	-0.012	0.034	0.226	0.611	0.131	-0.290	0.235
Kalahandi	0.066	0.031	0.424	0.927	0.334	0.102	0.582
Sundergarh	-0.003	0.082	0.347	0.833	0.613	0.252	0.724
Subarnapur	-0.122	-0.027	0.185	0.373	0.176	-0.192	-0.035
Sambalpur	-0.008	0.075	0.337	0.789	0.549	0.065	0.578

Fig. 10 shows the comparative trend analysis of agro-climatic variables during the Kharif onion growing season indicated significant temporal trends during the research period. Rainfall showed the most positive trend throughout the season, going from 1.21% in September to a peak of 1.96% in October, then fluctuating and ending at 1.60% in March, showing better moisture availability for most growth stages. Relative humidity increased steadily, peaking at 0.72% in December before falling somewhat and climbing again in March, indicating more humid winter conditions suitable for crop growth but potentially raising disease risk. In contrast, PAR (Photosynthetically Active Radiation) showed a predominantly falling trend from September forward, reaching its lowest value (-0.56%) in December, indicating less sun radiation during the bulb growth phase. Minimum temperatures also decreased over the winter months, with the sharpest drop (-0.85%) in December, indicating cooler nighttime conditions that may influence bulb formation. The maximum temperature remained reasonably steady around 0 with mild negative tendencies for most months, showing very minor changes in daytime thermal conditions. Overall, the findings indicate that, while rainfall and relative humidity have increased over time, decreases in temperature and PAR during the winter months may have a significant impact on onion growth, development, and production in Odisha's major onion-producing districts.

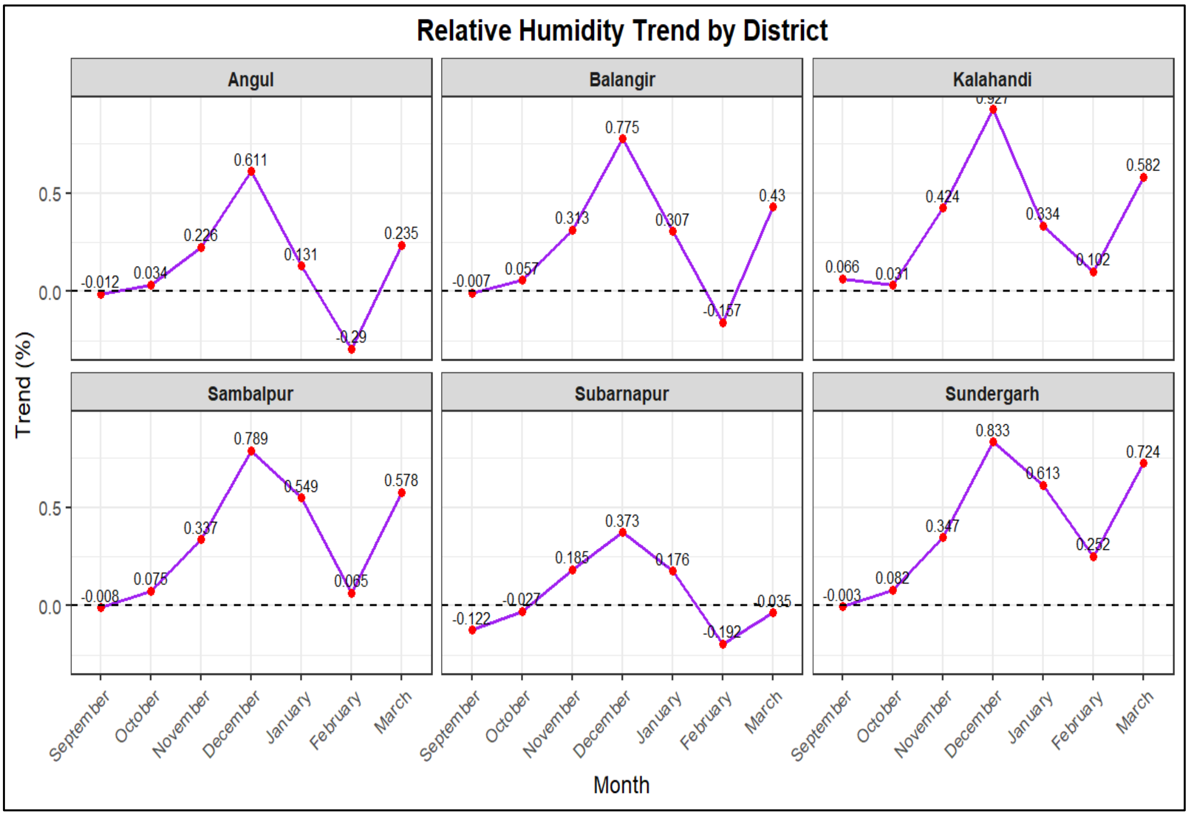

Fig. 10. Graph showing Trend of Relative humidity for the months of growing season of Kharif onion in important onion producing districts of Odisha

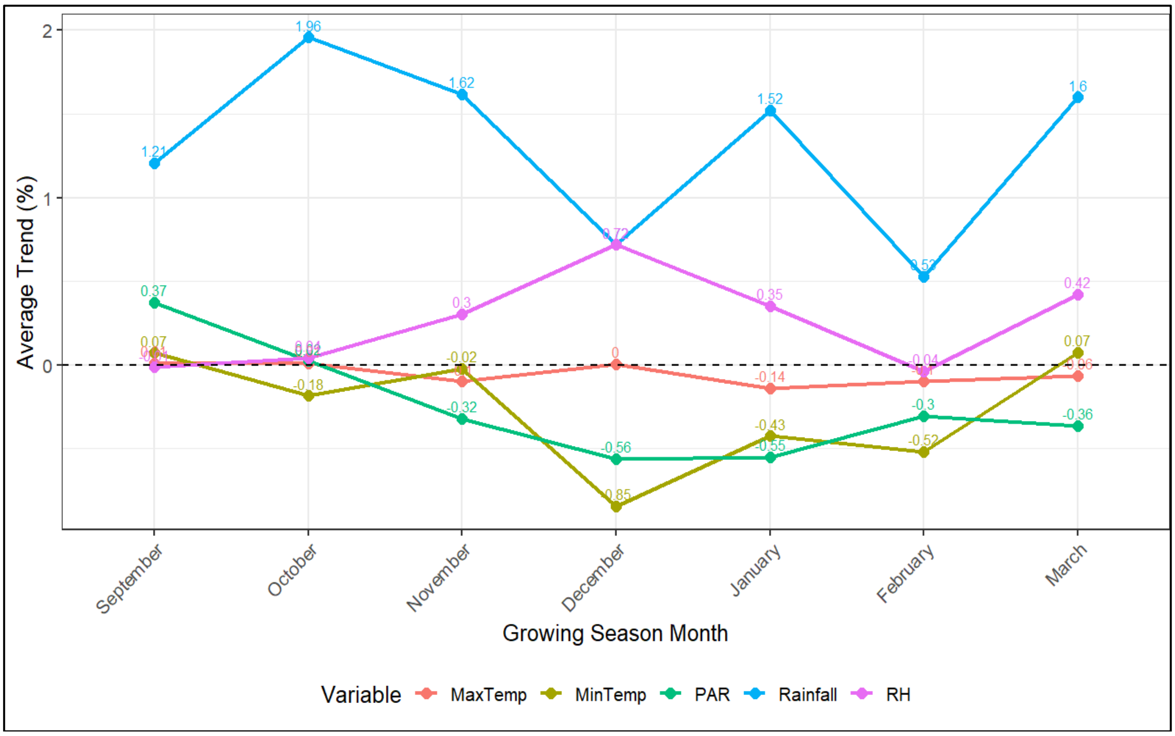

Fig. 11. Graph showing Comparison of Agro-climatic trends during kharif onion growing seasons

4. Limitations of Trend Analysis

1. Oversimplification and Linearity Assumption: Traditional trend analysis techniques, such as CAGR and basic linear regression (Y = a + bt), are based on the assumption of stable, continuous increases over time. However, the soil-plant-atmosphere continuum and onion physiological responses to weather are very nonlinear. Biological systems operate on critical environmental thresholds (such as excessive heat limits or waterlogging points) rather than smooth, linear gradients.
2. Predictive Limitations in a Non-Stationary Climate: Applying effective log-linear trend lines to a 28-year dataset does not guarantee future forecasting, particularly when dealing with fast and non-stationary climate shifts. Applying a historically averaged or smoothed growth rate may mask recent, accelerating changes in weather patterns, making future forecasts inaccurate.
3. Long-term temporal patterns based on monthly averages disguise short-term extremes and weather shocks by smoothing out severe, localized phenomena. Severe, short-duration agrometeorological shocks, such as unseasonal cyclonic rainfall, heatwaves, or flash droughts, have a substantial impact on onion crop establishment and bulb filling, but are frequently disregarded in monthly data aggregation.
4. Confounding Effects of Temporal Autocorrelation: Time-series weather data frequently exhibits substantial serial dependency, or autocorrelation, in which an observation in one month is influenced by the previous month. If not statistically adjusted, temporal autocorrelation can diminish effective degrees of freedom, exaggerate the statistical significance of monotonic trends and thus leading to incorrect conclusions.

5. Future Scope of the Study

- Transition to Non-Monotonic and Non-Linear Trend Models: Future research should use advanced non-parametric trend tests, such as the Mann-Kendall test combined with Sen's slope estimator. These methods can detect non-linear trajectories, shifting climatic "normals," and structural discontinuities in time series without relying on normal distribution assumptions.
- Phenophase-Specific and Daily-Level Resolution: Rather than depending on fixed calendar months, future study should synchronize climate information with actual crop phenophases (e.g., exact dates of 50% flowering, bulb commencement, and maturation) documented in the field. Evaluating daily

weather trends throughout these micro-stages will provide more biologically important information about yield vulnerability.

- Integration of advanced detrending techniques: To distinguish the pure impact of climate variability on onion yield from technological developments (such as improved seed types, fertilizers, and mechanization), future research should use advanced detrending indicators. Using the Cuddy-Della Valle Instability Index (CDVI) along with the standard coefficient of variation (CV) will be helpful in identifying actual climate-induced yield instability.
- High-Resolution Gridded Modeling: Onion productivity in Odisha varies significantly throughout its ten agro-climatic zones. Future study should use high-resolution gridded datasets (such as 12 km gridded products) or satellite-derived indices (such as MODIS phenology data) to assess trends at the block or sub-district level, rather than broad, district-level averages.
- Multi-Hazard Compounding Risk Profiling: Individual trends in maximum temperature or rainfall are not isolated. Developing an analytical framework to simulate compounding, multi-hazard risks, such as concurrent drought and heatwave occurrences during the late vegetative stage, can considerably improve risk management and aid in the formulation of resilient, district-level climate action plans.

6. Conclusion

From November to April, Photosynthetically Active Radiation (PAR) steadily decreases. This is important since it means that there is less "energy budget" available during the important bulb-filling stage. This environmental bottleneck, along with the fact that temperatures are rising at night during the April harvest period (0.46% CAGR in Balangir), threatens both the biological yield and the shelf life of the produce after it is harvested.

Growing onions in Odisha is a multi-faceted climate problem that requires a change from reactive to proactive management. The quantitative framework established by this research offers an empirical basis for formulating district-level climate adaptation plans, ultimately seeking to close the productivity gap between Odisha and national standards to secure the economic stability of smallholder horticultural systems in the state

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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