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Climatic Variability and Rice Yield Instability in a Semi-Arid Region of India: Evidence from Banda District, Bundelkhand

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Abstract

Climate variability has emerged as a major challenge for agricultural sustainability in semi-arid regions where crop production is highly dependent on monsoon rainfall. The present study examines the impact of climatic variability on rice productivity and yield instability in Banda district, located in the drought-prone region of Bundelkhand, during 1990–2019. The study utilized district-level time-series data on rice yield, monsoon rainfall, monsoon temperature, water deficit, irrigation, and fertilizer consumption obtained from the International Crops Research Institute for the Semi-Arid Tropics database. Descriptive statistics, trend analysis, Mann–Kendall test, Sen's slope estimator, correlation analysis, multiple regression modelling, yield anomaly analysis, and the Cuddy–Della Valle instability index were employed to assess climate–agriculture relationships and productivity instability. The results revealed a significant increasing trend in rice yield despite substantial interannual variability in climatic conditions. Monsoon temperature exhibited a significant increasing trend, while rainfall and water deficit did not show significant long-term changes. Regression and anomaly models identified monsoon rainfall as the most important determinant of interannual rice yield variability. The instability analysis indicated moderate-to-high rice yield instability; however, the decline in trend-adjusted instability during the post-2005 period suggests partial stabilization of productivity through agricultural adaptation measures such as irrigation expansion and input intensification. The findings highlight that although technological improvements have enhanced agricultural resilience, rice cultivation in Banda district remains highly vulnerable to monsoon variability and hydro-climatic stress. The study emphasizes the need for climate-resilient agricultural strategies to strengthen food security and sustainable agricultural development in semi-arid regions of India.

Keywords: Climate variability; Monsoon rainfall; Cuddy–Della Valle Index; Semi-arid agriculture; Agricultural resilience

1. Introduction

Climate change has emerged as one of the most serious global environmental challenges of the twenty-first century, substantially altering temperature regimes, precipitation patterns, and the frequency of extreme weather events across the world (Ripple et al., 2023, 2024, 2025).

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Increasing greenhouse gas concentrations have intensified climatic instability, resulting in irregular rainfall distribution, recurrent droughts, heat waves, floods, and hydrological stress in many regions (Mora et al., 2018). These changes are particularly severe in developing countries where socioeconomic systems remain highly dependent on climate-sensitive sectors. Recent evidence suggests that monsoon systems across South Asia are becoming increasingly erratic, with rising uncertainty in rainfall timing, duration, and intensity (Bhatla et al., 2023; Borah et al., 2022). Such climatic irregularities have profound implications for natural ecosystems, water resources, and agricultural production systems (Rosenzweig et al., 2004). Semi-arid regions are considered especially vulnerable because of their fragile ecological conditions, high rainfall dependence, and limited adaptive capacity. Studies conducted in Bundelkhand have shown that changing rainfall behaviour, delayed monsoon onset, and recurrent drought conditions are increasingly affecting agricultural stability and rural livelihoods in the region (Ahmed et al., 2019).

Agriculture is one of the most climate-sensitive sectors because crop growth, soil moisture availability, evapotranspiration, and water resources are directly influenced by climatic conditions (Datta et al., 2022). Variability in rainfall and temperature affects sowing periods, crop growth stages, irrigation demand, and overall crop productivity. Several studies have demonstrated that increasing temperature and irregular precipitation patterns negatively affect agricultural output, particularly in rainfed farming systems (Ousayd et al., 2025; Yeleliere et al., 2023). In semi-arid agricultural regions, prolonged dry spells and moisture stress often lead to crop failure, declining productivity, and increasing production instability (Mohammed et al., 2025). Existing literature has further highlighted that warming temperature intensify evapotranspiration demand and water deficit conditions, thereby increasing agricultural vulnerability under climate change scenarios (Hakami-Kermani & Babazadeh, 2025; Hatfield & Prueger, 2015). Rainfall variability has therefore become a major concern for sustainable crop production and food security, particularly in monsoon-dependent agricultural economies such as India. Recent studies from India have reported that changing climatic conditions are increasingly affecting rice and wheat productivity, while long-term climate projections suggest further agricultural stress under future warming scenarios (Bowden et al., 2025; Kumari et al., 2026).

In India, agriculture continues to play a central role in food security, employment generation, and rural economic sustainability (Singh, 2026). Although the contribution of agriculture to national GDP has declined over time, a substantial proportion of the population still depends directly or indirectly on agriculture for livelihood and nutritional security. Rice is one of the most important staple crops in India and forms the backbone of national food security due to its extensive consumption and cultivation. However, rice cultivation is highly water-intensive and strongly dependent on monsoon rainfall, making it particularly vulnerable to climatic variability (Surendran et al., 2021). In drought-prone and semi-arid regions such as Bundelkhand, agricultural production is frequently affected by rainfall irregularity, increasing thermal stress, declining groundwater availability, and recurrent droughts (Ghosh & Siddiqui, 2026). Previous studies have indicated that the Bundelkhand region experiences high climatic uncertainty due to variable precipitation trends, fragile hydrological systems, and limited irrigation resilience. These conditions often result in unstable crop productivity and heightened agrarian distress (Naika & Jare, 2025). At the same time, technological advancement, irrigation expansion, fertilizer intensification, and improved agricultural practices have contributed to productivity enhancement in several parts of India, raising important questions regarding the extent to which agricultural adaptation has reduced climatic vulnerability in semi-arid farming systems (Gamage et al., 2024; Sharafi et al., 2025).

Despite growing research on climate change and agriculture in India, limited empirical studies have comprehensively examined the long-term relationship between climatic variability and rice productivity at the district level in drought-prone semi-arid regions. In particular, there remains inadequate understanding regarding how monsoon rainfall, temperature variability, hydrological stress, irrigation, and fertilizer use collectively influence rice productivity and yield instability over time in the Bundelkhand region. Moreover, most previous studies have primarily focused either on climatic trends or crop productivity, while relatively few studies have integrated trend analysis, yield anomaly modelling, and instability assessment to distinguish short-term climatic effects from long-term technological improvements in agriculture. Against this background, the present study investigates the impact of climatic variability on rice productivity in Banda district during 1990–2019. Specifically, the study aims to: (i) examine temporal trends in rice yield and climatic variables; (ii) assess the relationship between climatic variability and rice productivity; and (iii) evaluate rice yield instability using the Cuddy–Della Valle instability index. By integrating climatic, agricultural, and instability analyses, the study contributes to the growing literature on climate-sensitive agriculture and provides important insights for climate-resilient agricultural planning in semi-arid India.

2. Data and Methods

2.1 Study Area

The present study was conducted in Banda district, situated in the semi-arid region of Bundelkhand. Agriculture constitutes the primary livelihood source in the district, where crop production is highly dependent on monsoon rainfall. The region frequently experiences climatic irregularities such as rainfall variability, drought conditions, and moisture stress, making it highly vulnerable to climate-induced agricultural instability (Ahmed et al., 2019; Ghosh & Siddiqui, 2026). Rice is one of the major Kharif crops cultivated in the district and is particularly sensitive to monsoonal fluctuations and hydrological stress conditions.

2.2 Data Sources and Variable Construction

The study utilized annual time-series data for the period 1990–2019 obtained from the International Crops Research Institute for the Semi-Arid Tropics database. The dataset included information on rice production, rice yield, irrigation, fertilizer consumption, rainfall, temperature, and water deficit conditions for Banda district.

Rice yield was measured in kilograms per hectare (kg/ha), while rice production was expressed in thousand tons. Monsoon rainfall and water deficit were measured in millimetres (mm), monsoon temperature in degree centigrade (°C), irrigated area in thousand hectares, and fertilizer consumption in tons.

Considering the monsoon dependence of rice cultivation in Banda district, climatic variables were aggregated specifically for the Kharif season. Monsoon rainfall was calculated by summing monthly rainfall values from June to September. Monsoon temperature was estimated as the average maximum temperature recorded during June–September. Similarly, monsoon water deficit was derived by aggregating monthly water deficit values from June to August, depending on data availability.

The explanatory variables used in the study included:

- ✓ monsoon rainfall,
- ✓ monsoon temperature,
- ✓ monsoon water deficit,
- ✓ rice irrigated area, and
- ✓ kharif fertilizer consumption.

Rice yield was considered the principal outcome variable for the analysis.

2.3 Descriptive and Trend Analysis

Descriptive statistical measures including mean, standard deviation, minimum, maximum, and coefficient of variation (CV) were computed to examine the temporal variability and dispersion of climatic and agricultural variables. The coefficient of variation was estimated using the following expression:

$$CV = \frac{\sigma}{\mu} 100$$

where:

- ✓ σ represents the standard deviation, and
- ✓ μ denotes the mean of the variable.

Linear trend regression analysis was employed to assess temporal changes in rice yield during the study period. The linear trend model was specified as:

$$Y_t = \alpha + \beta t + \in_t$$

where:

- ✓ Y_t denotes rice yield in year (t),
- ✓ α represents the intercept,
- ✓ β indicates the annual rate of change, and
- ✓ $\in_t$ is the random error term.

To identify monotonic trends in climatic and agricultural variables, the non-parametric Mann–Kendall trend test was applied. The Mann–Kendall test is widely used in hydro-climatic studies because it does not require normal distribution assumptions and is comparatively less sensitive to extreme values and outliers. Sen's slope estimator was further employed to estimate the magnitude and direction of annual changes in the selected variables.

2.4 Correlation Analysis

Pearson's correlation analysis was performed to examine the direction and strength of association between rice yield and climatic variables. The correlation matrix was used to assess interrelationships among monsoon rainfall, temperature, water deficit, irrigation, fertilizer consumption, and rice productivity.

2.5 Regression Modelling

To evaluate the influence of climatic variability and agricultural inputs on rice productivity, multiple linear regression models were estimated.

The baseline regression model was specified as:

$$\begin{aligned} RiceYield_t \; = \; & \beta_0 + \beta_1 Rainfall_t + \beta_2\, Temperature_t + \beta_3\, WaterDeficit_t \\ & + \beta_4\, Irrigation_t + \epsilon_t \end{aligned}$$

where:

- ✓ $RiceYield_t$ denotes rice yield in year (t),
- ✓ $Rainfall_t$ represents monsoon rainfall,
- ✓ $Temperature_t$ denotes monsoon temperature,
- ✓ $WaterDeficit_t$ indicates monsoon water deficit,
- ✓ $Irrigation_t$ denotes irrigated area, and
- ✓ ϵ_t is the random error term.

To isolate the short-term effect of climatic variability from long-term technological improvements, a yield anomaly model was additionally estimated. Rice yield anomaly was derived from the residuals of the temporal trend regression model. This approach effectively removed long-term productivity trends associated with technological advancement, improved agricultural practices, and input intensification.

The climate–yield anomaly model was estimated as:

$$\begin{aligned} & YieldAnomaly_t \\ & \quad = \beta_0 + \beta_1 Rainfall_t + \beta_2\, Temperature_t + \beta_3\, WaterDeficit_t \\ & \quad + \beta_4\, Irrigation_t + \beta_5\, Fertilizer_t + \epsilon_t \end{aligned}$$

$\epsilon_t$where:

- ✓ $YieldAnomaly_t$ represents detrended rice yield anomaly, and

- ✓ $Fertilizer_t$ denotes Kharif fertilizer consumption.

Standardized regression coefficients were further estimated to compare the relative influence of climatic and agricultural variables on rice yield variability.

To examine the presence of multicollinearity among explanatory variables, the Variance Inflation Factor (VIF) was computed. Variables with VIF values below 5 were considered free from serious multicollinearity problems.

2.6 Instability Analysis

To examine temporal instability in rice productivity, the study employed both the Coefficient of Variation (CV) and the Cuddy–Della Valle Instability Index (CDVI). Although the coefficient of variation measures overall variability, it may overestimate instability when long-term trends are present (Sindhuja & Malik, 2025; Zwan et al., 2022). Therefore, the Cuddy–Della Valle Index was used to estimate trend-adjusted instability in rice yield.

The Cuddy–Della Valle instability index was calculated using the following expression:

$$CDVI = CV * \sqrt{1 - R^2}$$

where:

- ✓ CV denotes the coefficient of variation, and
- ✓ R^2 represents the coefficient of determination obtained from the trend regression model.

The instability analysis was carried out for:

- ✓ the overall study period (1990–2019),
- ✓ Period I (1990–2004), and
- ✓ Period II (2005–2019),

in order to assess temporal changes in rice yield instability under varying climatic and agricultural conditions.

2.7 Statistical Software

All statistical analyses, graphical visualization, trend estimation, and regression modelling were performed using R statistical software environment.

3. Results

3.1 Descriptive Statistics of Rice Yield and Climatic Variables

The descriptive statistics of rice production, rice yield, climatic variables, irrigation, and fertilizer consumption are presented in Table 1. Rice yield in Banda district exhibited substantial temporal variability during 1990–2019, with an average productivity of 1296 kg/ha and a coefficient of variation (CV) of 35.57%, indicating considerable interannual fluctuations in rice productivity. Rice production also demonstrated relatively high variability

(CV = 29.80%), reflecting the sensitivity of agricultural output to changing climatic and environmental conditions.

Among climatic variables, monsoon rainfall recorded an average of 739.7 mm with moderate variability (CV = 28.51%), whereas monsoon temperature remained relatively stable across the study period (CV = 1.73%). In contrast, monsoon water deficit exhibited substantial variability (CV = 45.16%), indicating pronounced fluctuations in hydrological stress conditions within the region.

Agricultural input variables also demonstrated considerable variation. Kharif fertilizer consumption showed the highest variability among all variables (CV = 74.48%), suggesting substantial changes in fertilizer use over time. Rice irrigated area exhibited comparatively lower variability (CV = 14.99%), indicating relatively stable irrigation expansion during the study period.

Table 1. Descriptive statistics

Variables	**Mean**	**Standard Deviation**	**Minimum**	**Maximum**	**CV**
Rice Production (1000 tons)	74.91	22.32	35.24	123.73	29.8
Rice Yield (Kg/ha)	1296	461.01	639	2635	35.57
Monsoon Rainfall (mm)	739.7	210.85	263.2	1126.9	28.51
Monsoon Temperature (°C)	34.9	0.6	33.74	36.04	1.73
Monsoon Water Deficit (mm)	138.64	62.62	16.78	227.44	45.16
Rice Irrigation (1000 ha)	59.53	8.92	43.41	85.1	14.99
Kharif Fertilizer Consumption (tons)	4958	3692.87	-1	13213	74.48

Note: CV = coefficient of variation, Source. ICRISAT

3.2 Trend Analysis of Rice Yield and Climatic Variables

Figure 1 illustrates the temporal trend of rice yield in Banda district during 1990–2019. Rice yield demonstrated a clear increasing trend over the study period despite noticeable interannual fluctuations. The upward trajectory indicates gradual improvement in agricultural productivity over time, likely associated with technological advancement, irrigation expansion, and improved agricultural management practices.

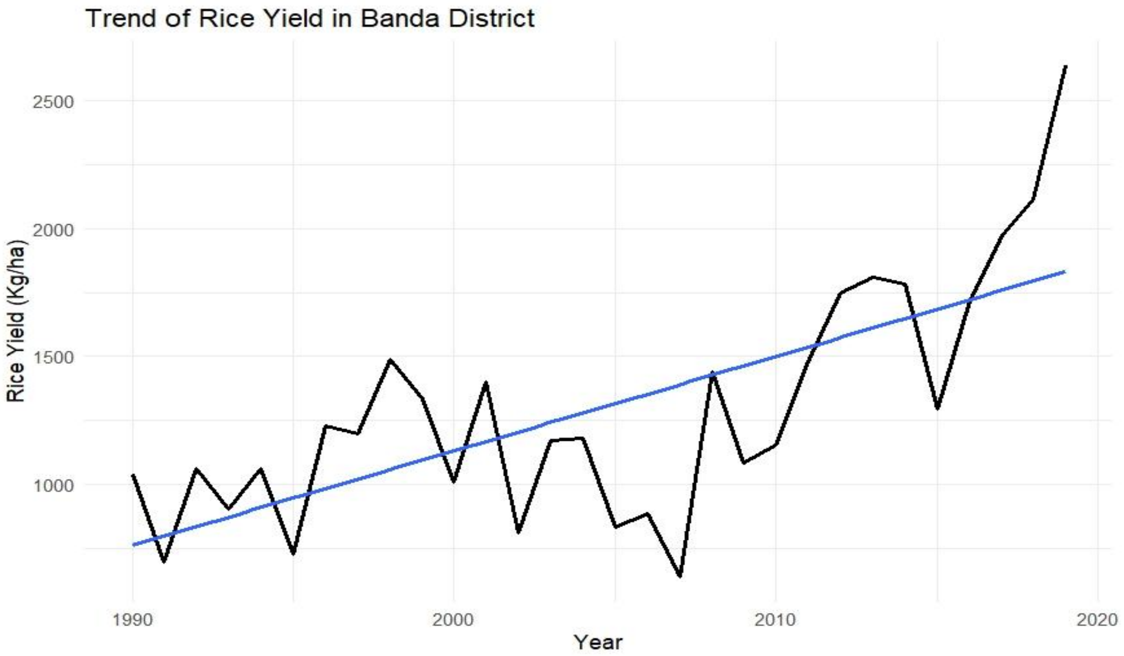

Figure 1. Trend of rice yield

The linear trend regression analysis presented in Table 2 confirmed a statistically significant increasing trend in rice yield. The regression coefficient indicated that rice productivity increased by approximately: 36.92 kg ha^{-1} $year^{-1}$, during the study period. The model explained nearly 50% of the temporal variation in rice yield ($R^2 = 0.497$; $p < 0.001$), indicating substantial long-term improvements in rice productivity.

Table 2: Linear Trend Regression Analysis of Rice Yield in Banda district (1990–2019)

Variables	Coefficient Estimate	Standard Error	t-value	p-value	Significance
Intercept	-72717.8	14067.06	-5.17	<0.001	***
Year	36.92	7.02	5.26	<0.001	***

Table 3. Model statistics

Statistics	Value
Residual Standard Error	332.7
R^2	0.497
Adjusted R^2	0.479
F-statistic	27.68
Model p-value	<0.001

The Mann–Kendall trend test and Sen's slope estimator further supported these findings (Table 4). Rice yield exhibited a statistically significant increasing trend ($Z = 3.854$; $p < 0.001$) with a Sen's slope of 35.75 kg ha^{-1} $year^{-1}$. Monsoon rainfall did not show any statistically significant trend (p = 0.775), suggesting that rainfall variability in Banda district is dominated by interannual fluctuations rather than systematic long-term change.

In contrast, monsoon temperature demonstrated a marginally significant increasing trend (Z = 1.963; p = 0.050), indicating gradual warming conditions during the monsoon season. The estimated Sen's slope suggested an annual increase of approximately: 0.031 ∘C $year^{-1}$. Monsoon water deficit did not exhibit any statistically significant trend (p = 1.000), indicating the absence of persistent long-term drying conditions despite considerable year-to-year variability.

Table 4. Mann–Kendall Trend Test and Sen's Slope Estimator for Rice Yield and Climatic Variables in Banda district (1990–2019)

Variables	**Sample Size (n)**	**Z-value**	**Sen's Slope**	**95% CI [LL–UL]**	**p-value**
Rice Yield	30	3.854	35.75	[21.44 – 52.52]	<0.001
Monsoon Rainfall	30	-0.285	-1.45	[-12.73 – 8.02]	0.775
Monsoon Temperature	30	1.963	0.031	[0.001 – 0.056]	0.05
Monsoon Water Deficit	30	0	-0.144	[-3.33 – 3.63]	1

3.3 Correlation Analysis

The correlation matrix among rice yield, climatic variables, irrigation, and fertilizer consumption is presented in Table 5. Rice yield showed a moderate positive correlation with monsoon rainfall (r = 0.402) and Kharif fertilizer consumption (r = 0.557), indicating the beneficial role of rainfall availability and agricultural input intensification in enhancing rice productivity.

A moderate negative association was observed between rice yield and monsoon water deficit (r = −0.396), suggesting that hydrological stress adversely affects rice cultivation in the district. Rice yield exhibited only a weak association with monsoon temperature (r = 0.010) and rice irrigation (r = 0.097).

Among climatic variables, monsoon rainfall demonstrated a strong negative relationship with monsoon temperature (r = −0.644) and monsoon water deficit (r = −0.688), indicating that lower rainfall years are generally associated with warmer and drier monsoon conditions. Furthermore, monsoon temperature showed a strong positive correlation with monsoon water deficit (r = 0.700), highlighting the role of increasing thermal conditions in intensifying moisture stress within the semi-arid agricultural environment of Bundelkhand.

Table 5: Correlation matrix

Variables	**Rice**	**Monsoon**	**Monsoon**	**Monsoon**	**Rice Irrigatio**	**Kharif**

	Yield	Rainfall	Temperature	Water Deficit	n	Fertilizer
Rice Yield	1	0.402	0.01	-0.396	0.097	0.557
Monsoon Rainfall	0.402	1	-0.644	-0.688	0.549	0.138
Monsoon Temperature	0.01	-0.644	1	0.7	-0.577	0.379
Monsoon Water Deficit	-0.396	-0.688	0.7	1	-0.54	-0.108
Rice Irrigation	0.097	0.549	-0.577	-0.54	1	-0.16
Kharif Fertilizer	0.557	0.138	0.379	-0.108	-0.16	1

3.4 Regression Modelling of Rice Yield and Yield Variability

The regression results examining the influence of climatic and agricultural variables on rice productivity are presented in Table 6. The baseline regression model (Model 1) explained approximately 42.7% of the variation in rice yield ($R^2 = 0.427$; $p < 0.05$). Among the explanatory variables, monsoon temperature exhibited a significant positive effect on rice yield ($p < 0.05$), while monsoon water deficit showed a statistically significant negative association with rice productivity. Monsoon rainfall demonstrated marginal significance ($p < 0.10$), suggesting that favorable rainfall conditions contribute positively to rice yield.

The variance inflation factor (VIF) values remained below the critical threshold of 5, indicating the absence of serious multicollinearity among the explanatory variables.

To isolate the short-term influence of climatic variability from long-term technological improvements, a climate–yield anomaly model was estimated (Model 2). The anomaly model explained approximately 48.7% of the variation in rice yield anomaly ($R^2 = 0.487$; $p < 0.05$). In contrast to the baseline model, monsoon rainfall emerged as the only statistically significant predictor of rice yield anomaly ($\beta = 0.898$; $p < 0.05$), indicating that rainfall variability is the dominant determinant of interannual fluctuations in rice productivity.

Table 6. Comparative Regression Models Explaining Rice Yield and Yield Variability in Banda district

Variables	**Model 1: Rice Yield**	**Model 2: Yield Anomaly**	**Model 3: Standardized Model (β)**
Intercept	-11040.00*	-3460	0.01
Monsoon Rainfall	0.738†	0.898*	0.579*
Monsoon	356.00*	49.18	0.091

Temperature			
Monsoon Water Deficit	-3.067*	0.797	0.153
Rice Irrigation	-5.477	17.02	0.465
Kharif Fertilizer	—	-0.008	-0.093

Table 7. Model summary

Statistics	**Model 1**	**Model 2**	**Model 3**
Observations	30	30	30
Residual Standard Error	269.7	239.7	0.733
Multiple R^2	0.427*	0.487*	0.487*
Adjusted R^2	0.318*	0.358*	0.358*
F-statistic	3.911*	3.792*	3.792*
Model p-value	0.016*	0.014*	0.014*

Monsoon temperature, monsoon water deficit, irrigation, and fertilizer consumption did not show statistically significant effects in the anomaly model. This finding suggests that although agricultural intensification and technological improvements have contributed to long-term productivity growth, short-term rice yield variability remains strongly governed by monsoon rainfall fluctuations.

The standardized regression model (Model 3) further demonstrated that monsoon rainfall exerted the strongest positive influence on rice yield anomaly ($\beta = 0.579$), followed by rice irrigation ($\beta = 0.465$). These findings indicate that irrigation may partially buffer climatic stress; however, rice cultivation in Banda district continues to remain highly sensitive to monsoon rainfall variability.

3.5 Instability Analysis of Rice Yield

The instability analysis of rice yield is presented in Table 8. The coefficient of variation (CV) for the overall study period (1990–2019) was 35.57%, indicating high variability in rice productivity. However, after adjusting for long-term trend effects using the Cuddy–Della Valle Index (CDVI), the instability level declined to 25.22%, suggesting moderate-to-high instability in rice yield.

Period-wise analysis revealed important temporal differences in rice yield instability. During Period I (1990–2004), the coefficient of variation was 21.61%, while the CDVI was 19.81%, indicating moderate instability in rice productivity. In contrast, Period II (2005–2019) exhibited substantially higher observable variability (CV = 35.82%), although the trend-adjusted instability index declined to 16.53%.

Table 8. Instability Analysis of Rice Yield in Banda district

Period	**Coefficient of Variation (CV %)**	**Cuddy–Della Valle Index (CDVI %)**	**Instability Interpretation**
Overall Period (1990–2019)	35.57	25.22	Moderate-to-high instability
Period I (1990–2004)	21.61	19.81	Moderate instability
Period II (2005–2019)	35.82	16.53	Moderate instability

4. Discussion

The present study investigated the relationship between climatic variability and rice productivity in Banda district using district-level time-series data from 1990–2019. The findings reveal that rice cultivation in the semi-arid region of Bundelkhand remains highly sensitive to climatic variability despite substantial improvements in agricultural productivity over time. Descriptive statistics demonstrated considerable variability in rice yield, monsoon rainfall, and water deficit conditions, while trend analysis indicated a statistically significant increase in rice productivity over the study period. In contrast, monsoon rainfall and water deficit did not exhibit significant long-term trends, although monsoon temperature showed gradual warming tendencies. The regression and yield anomaly models further identified monsoon rainfall as the most important determinant of interannual rice yield fluctuations. Importantly, the instability analysis revealed moderate-to-high yield instability, suggesting that agricultural productivity in Banda district continues to experience substantial climatic uncertainty despite technological and infrastructural advancements.

The major contribution of the study is that it demonstrates monsoon rainfall variability remains the dominant climatic driver of rice productivity in the district. The positive association between rainfall and rice yield observed in both correlation and regression analyses indicates the persistent dependence of rice cultivation on monsoonal water availability. Similar findings have been reported across rainfed agricultural systems in India, where monsoon variability significantly influences crop productivity, agricultural income, and food security outcomes (Chakraborty et al., 2025). Studies conducted in drought-prone regions of central and peninsular India have consistently shown that delayed monsoon onset, rainfall irregularity, and prolonged dry spells negatively affect crop growth and yield performance (Amale et al., 2023; Kapa et al., 2026). The present findings are particularly important because rainfall emerged as the only statistically significant predictor in the yield anomaly model after removing long-term productivity trends. This suggests that short-term climatic fluctuations continue to exert substantial influence on annual agricultural performance despite improvements in irrigation and agricultural intensification (Bouteska et al., 2024). Such findings align with broader global evidence indicating that climate-sensitive agricultural systems in semi-arid environments remain highly vulnerable to rainfall irregularity under changing climatic conditions(Asefa Bogale, 2023; Shah et al., 2026).

Another important finding of the study relates to the instability characteristics of rice productivity under changing climatic conditions. The coefficient of variation indicated substantial observable fluctuations in rice yield during 1990–2019; however, the Cuddy–Della Valle Index (CDVI) provided deeper insight into the underlying instability structure after accounting for long-term technological trends. Although the overall rice yield variability remained relatively high (CDVI = 25.22%), the period-wise analysis revealed a decline in trend-adjusted instability from 19.81% during 1990–2004 to 16.53% during 2005–2019, despite a substantial increase in observed variability during the latter period. This finding is scientifically important because it suggests that agricultural adaptation measures such as irrigation expansion, improved crop management, technological advancement, and increased fertilizer application may have partially stabilized underlying productivity even under increasingly variable climatic conditions (Li et al., 2024). Similar patterns have been documented in several semi-arid agricultural regions where technological progress reduces long-term production instability while climatic extremes continue to generate substantial year-to-year fluctuations (Moulim et al., 2026). At the same time, the significant warming trend observed in monsoon temperature and the strong positive relationship between temperature and water deficit indicate increasing hydro-climatic stress within the agricultural system (Ullah et al., 2026). Rising temperatures may intensify evapotranspiration demand, soil moisture depletion, and crop water stress, thereby increasing the vulnerability of rainfed agriculture in Bundelkhand (Olawoyin et al., 2026; Torkaman Pary et al., 2026). These findings are consistent with global literature suggesting that semi-arid agricultural systems are likely to experience increasing climatic stress due to the combined effects of warming temperatures and rainfall irregularity (Abebaw, 2025; Al-Bakri et al., 2011).

The study possesses several methodological and analytical strengths. First, the use of long-term district-level time-series data enabled a comprehensive assessment of climatic variability, productivity trends, and agricultural instability over nearly three decades. Second, the integration of multiple analytical approaches—including trend regression, Mann–Kendall testing, Sen's slope estimation, correlation analysis, regression modelling, yield anomaly assessment, and instability analysis—provided a robust framework for examining climate–agriculture interactions. Third, the incorporation of the Cuddy–Della Valle instability index strengthened the analysis by distinguishing observable variability from trend-adjusted instability, thereby offering deeper insights into the role of agricultural adaptation under changing climatic conditions. Nevertheless, certain limitations should also be acknowledged. The analysis was conducted at the district level and therefore may not fully capture intra-district heterogeneity in climatic exposure, irrigation access, and agricultural practices. In addition, the study primarily focused on climatic and selected agricultural input variables, while other important determinants such as groundwater availability, soil characteristics, crop varieties, pest incidence, institutional support, and socioeconomic factors could not be incorporated due to data limitations. Furthermore, the relatively small sample size associated with annual time-series analysis may limit statistical generalization. Despite these limitations, the study contributes important empirical evidence on climatic vulnerability, agricultural adaptation, and yield instability in semi-arid India and provides useful insights for climate-resilient agricultural planning in drought-prone regions.

5. Conclusion

The present study demonstrates that rice cultivation in Banda district remains highly sensitive to climatic variability despite significant improvements in agricultural productivity during 1990–2019. Rice yield exhibited a strong increasing trend, reflecting the contribution of irrigation expansion, fertilizer use, and technological advancement in agriculture. However, the findings clearly indicate that monsoon rainfall variability continues to be the dominant driver of interannual rice yield fluctuations. The anomaly regression model confirmed that rainfall variability significantly affects yield instability even after removing long-term productivity trends, while increasing monsoon temperature highlights emerging hydro-climatic stress in the semi-arid region of Bundelkhand.

The instability analysis further revealed that although observable fluctuations in rice productivity increased over time, the decline in the Cuddy–Della Valle instability index during the post-2005 period suggests partial stabilization of underlying productivity through agricultural adaptation measures. This indicates that technological and infrastructural improvements have improved resilience to some extent, but they remain insufficient to fully offset climatic uncertainty and rainfall irregularity. The study therefore emphasizes the urgent need for climate-resilient agricultural strategies, particularly improved irrigation management, drought-resilient crop varieties, water conservation practices, and weather-based agricultural support systems to ensure sustainable rice production and food security in drought-prone semi-arid regions.

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