THE SCIENTIFIC TEMPER (2026) Vol. 17 (4): 6137-6144
E-ISSN: 2231-6396, ISSN: 0976-8653
Doi: 10.58414/SCIENTIFICTEMPER.2026.17.4.24
https://scientifictemper.com/

RESEARCH ARTICLE

Climate Variability and Its Impact on Agricultural Productivity in Moradabad District, Uttar Pradesh (1990–2024)

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Abstract

Climate variability poses a serious threat to agricultural productivity in India, particularly in climate-sensitive regions such as western Uttar Pradesh. Understanding long-term changes in rainfall and temperature and their impacts on crop yields is essential for designing climate-resilient agricultural strategies. This study analyzes trends in rainfall and temperature from 1990 to 2024 and quantifies their impact on the productivity of major crops such as wheat, rice and sugarcane—in Moradabad district. Secondary data on annual rainfall and temperature were obtained from the Indian Meteorological Department (IMD), while crop yield data were collected from the Department of Agriculture, Government of Uttar Pradesh. Descriptive statistics, trend analysis, correlation analysis, and multiple linear regression models were employed. Results reveal a statistically significant increase in both maximum and minimum temperatures, accompanied by increasing rainfall variability. Regression results indicate that rising temperatures negatively affect wheat and rice yields, while sugarcane shows relative resilience to rainfall variability. The study highlights crop-specific climate sensitivity and underscores the urgency of climate-resilient agricultural planning at the district level.

Keywords: Climate variability, rainfall, temperature, crop productivity, Moradabad, regression analysis, Uttar Pradesh.

Introduction

Climate variability and long-term climate change have emerged as critical challenges to agricultural sustainability across the world. Agriculture is inherently sensitive to climatic conditions, particularly temperature and precipitation, which directly influence crop growth, soil moisture, water availability, and pest dynamics (IPCC, 2021). Even small deviations from normal climatic patterns can lead to substantial fluctuations in crop yields, thereby threatening food security and rural livelihoods. In developing countries such as India, where agriculture remains the primary source of employment and income for a large segment of the population, the impacts of climate variability are especially severe (FAO, 2018). India's agricultural sector has experienced significant climatic stress over the past few decades. Rising average temperatures, increased frequency of heatwaves, erratic monsoon rainfall, and prolonged dry spells have altered traditional cropping calendars and reduced yield stability (Mall et al., 2006; Birthal et al., 2014). According to the Indian Meteorological Department (IMD), the mean annual temperature over India has increased by approximately 0.7°C during the period 1901–2018, with a more pronounced rise observed since the 1990s (IMD, 2022). Concurrently, rainfall patterns have become increasingly variable, characterized by intense short-duration rainfall events and longer dry periods, posing new challenges for rainfed and irrigated agriculture alike. The vulnerability of Indian agriculture to climate variability is compounded by structural issues such as small and fragmented landholdings, heavy dependence on monsoon rainfall, declining groundwater resources, and limited access to climate-resilient technologies (Birthal et al., 2014). Cereals such as wheat and rice, which form the backbone of India's food security, are particularly sensitive to temperature extremes during critical growth stages. Studies have shown that a 1°C increase in temperature can reduce

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How to cite this article: Kaur, H., Gupta, P. (2026). Climate Variability and Its Impact on Agricultural Productivity in Moradabad District, Uttar Pradesh (1990–2024). The Scientific Temper, **17**(4):6137-6144.

Doi: 10.58414/SCIENTIFICTEMPER.2026.17.4.24

Source of support: Nil

Conflict of interest: None.

Received: 02/04/2026 **Accepted:** 19/04/2026 **Published:** 25/04/2026

wheat yields by 4–6 percent and rice yields by 3–5 percent, depending on the region and management practices (Lobell et al., 2012; IPCC, 2021).

While a substantial body of literature exists on the national and regional impacts of climate change on Indian agriculture, district-level empirical studies remain limited, particularly in agriculturally intensive regions such as western Uttar Pradesh. Climate impacts are highly location-specific, influenced by local agro-climatic conditions, cropping patterns, irrigation infrastructure, and farmers' adaptive capacity. Aggregated national-level analyses often mask these micro-level variations, limiting their usefulness for local policy formulation and adaptation planning. Western Uttar Pradesh is one of India's most productive agricultural regions, contributing significantly to national wheat, rice and sugarcane production. The region is characterized by intensive cultivation, high input use, and extensive reliance on groundwater irrigation. However, recent evidence suggests increasing climate stress in the form of rising temperatures, irregular monsoon rainfall, and declining groundwater levels (Sharma & Singh, 2020). Despite its importance, empirical research quantifying the long-term impact of climate variability on crop productivity at the district level in western Uttar Pradesh remains scarce. Moradabad district represents a particularly important case for such analysis. The district exhibits diverse agro-ecological conditions, a mixed cropping pattern dominated by wheat, rice, and sugarcane, and high dependence on monsoon rainfall supplemented by tube-well irrigation. Over the past three decades, farmers in the district have reported increasing climatic uncertainty, crop yield instability, and rising production risks. However, these observations have not been systematically quantified using long-term climatic and agricultural data.

Research Gap

A critical review of existing literature reveals three major gaps:

- **Spatial Gap**: Most studies focus on national or state-level analysis, with limited district-level empirical evidence from western Uttar Pradesh.
- **Temporal Gap**: Few studies utilize long-term datasets extending beyond two decades to capture climate variability and its cumulative effects.
- **Crop-Specific Gap**: Limited research compares the differential sensitivity of major crops such as wheat, rice, and sugarcane to climatic variables within the same agro-climatic setting.

Addressing these gaps is essential for developing evidence-based, location-specific climate adaptation strategies.

Objectives of the Study

The present study aims to:

- Examine long-term trends in rainfall and temperature in Moradabad district during 1990–2024.
- Analyze variability in the productivity of major crops such as wheat, rice and sugarcane.
- Quantify the relationship between climatic variables and crop yields using econometric models.
- Provide policy-relevant insights for promoting climate-resilient agriculture at the district level.

By focusing on Moradabad district, this study contributes micro-level empirical evidence to the climate–agriculture literature and enhances understanding of crop-specific climate sensitivity in one of India's key agricultural regions.

Study Area

Geographical Location

Moradabad district is located in the western part of Uttar Pradesh between 28°21′ to 28°59′ North latitude and 78°45′ to 79°28′ East longitude. It lies within the fertile Upper Gangetic Plain, characterized by flat topography and deep alluvial soils. The district is bounded by Bijnor district to the north, Rampur district to the west, Sambhal district to the south, and Bareilly district to the east. The geographical location of Moradabad places it within a zone that is highly influenced by the southwest monsoon, making rainfall variability a critical determinant of agricultural performance.

Agro-Climatic Characteristics

Moradabad district falls under the Upper Gangetic Plains agro-climatic zone, which is one of the most productive agricultural regions in India. The climate is sub-tropical monsoon, characterized by hot summers, a distinct rainy season and cool winters.

- **Summer (March–June)**: High temperatures, often exceeding 40°C
- **Monsoon (June–September)**: Receives approximately 70–75% of annual rainfall
- **Winter (October–February)**: Cool and dry, suitable for rabi crops such as wheat

The Table 1 on long-term climatic normals (1990–2024) highlights key patterns in the district's climate. The average annual rainfall of 912.4 mm indicates that the region receives a moderate amount of precipitation suitable for agriculture; however, the wide range between the minimum (602.1 mm) and maximum (1,248.7 mm) reflects significant year-to-year variability. This inconsistency in rainfall can create uncertainty for farmers, affecting crop planning, irrigation needs and overall productivity.

In contrast, temperature variations are comparatively stable but show a gradual rising tendency. The mean maximum temperature of 32.1°C, with a range from 30.4°C to 33.8°C, suggests consistently warm conditions, particularly during summer months. Similarly, the mean minimum temperature of 18.4°C (ranging between 16.2°C and 20.1°C) indicates mild winters. Although the variation

Table 1: Long-Term Climatic Normals of Moradabad District (1990–2024)

Climatic variable	*Mean*	*Minimum*	*Maximum*
Annual rainfall (mm)	912.4	602.1	1,248.7
Maximum temperature (°C)	32.1	30.4	33.8
Minimum temperature (°C)	18.4	16.2	20.1

Source: Indian Meteorological Department (IMD), 2024

in temperature appears narrow, even small increases over time can have significant implications for crop growth cycles, evapotranspiration and water demand.

Overall, the table 1 suggests that while temperature changes are gradual and relatively consistent, rainfall variability is more pronounced, making it a critical factor influencing agricultural stability and reinforcing the need for adaptive strategies among farmers.

Cropping Pattern and Agricultural Dependence

Agriculture is the dominant economic activity in Moradabad district, engaging more than 65 percent of the rural population. The cropping system is characterized by intensive cereal-based cultivation, supported by both monsoon rainfall and groundwater irrigation.

The major crops include:

- Wheat (Rabi season) – staple food crop
- Rice (Kharif season) – monsoon-dependent
- Sugarcane (Annual crop) – cash crop with high water demand

The dominance of water-intensive crops such as rice and sugarcane has increased vulnerability to rainfall variability and groundwater depletion. Wheat productivity, on the other hand, is highly sensitive to rising winter temperatures, particularly during the grain-filling stage.

Climate Vulnerability of the District

Several factors contribute to the climate vulnerability of Moradabad district:

- High dependence on monsoon rainfall, especially for rice cultivation.
- Intensive groundwater extraction, leading to declining water tables.
- Rising temperature trends, increasing heat stress on crops.
- Limited crop diversification, increasing exposure to climate shocks.

These characteristics make Moradabad an ideal case for analyzing the long-term impacts of climate variability on agricultural productivity.

Table 2: Average Area and Production of Major Crops in Moradabad District

Crop	*Average Area ('000 ha)*	*Average Yield*
Wheat	162.5	3,280 kg/ha
Rice	134.8	3,050 kg/ha
Sugarcane	96.3	67.4 t/ha

Source: Department of Agriculture, Government of Uttar Pradesh (1990–2024)

Data and Methodology

Research Design

The present study adopts an empirical quantitative research design to examine the long-term relationship between climate variability and agricultural productivity in Moradabad district, Uttar Pradesh. A quantitative approach is particularly appropriate for climate–agriculture studies because it enables the measurement of climatic trends and the estimation of their statistical impact on crop yields over time (Gujarati, 2012; Lobell & Burke, 2010). The analysis is based on time-series data spanning 35 years (1990–2024), which allows for the identification of long-term climatic trends and their cumulative effects on agricultural output. Unlike short-term studies, long-period datasets capture structural climatic changes rather than transient weather fluctuations, thereby strengthening the robustness of empirical inference (IPCC, 2021).

Data Sources and Reliability

Climatic Data

Climatic data on annual rainfall, mean maximum temperature, and mean minimum temperature were obtained from the Indian Meteorological Department (IMD). IMD is the national authority responsible for meteorological observations in India, and its datasets are widely used in peer-reviewed climate impact studies (Mall et al., 2006; Birthal et al., 2014). The data cover the period 1990–2024 and were compiled from district-level meteorological stations and gridded datasets adjusted for local conditions. The use of IMD data ensures consistency, reliability, and comparability across years.

Agricultural Data

Crop yield data for wheat, rice, and sugarcane were collected from the Department of Agriculture, Government of Uttar Pradesh, supplemented by district statistical handbooks. Yield is expressed as output per unit area (kg/ha for wheat and rice; tonnes/ha for sugarcane), which is a standard measure of agricultural productivity. Government agricultural statistics are considered reliable as they are compiled through systematic crop-cutting experiments and administrative reporting mechanisms (Kothari, 2014).

Variables Used in the Study

Dependent Variables

The dependent variables represent the productivity of major crops cultivated in Moradabad district:

Table 3: Definition and Measurement of Variables

Variable type	*Variable*	*Measurement*	*Expected impact*
Dependent	Wheat yield	kg/ha	–
Dependent	Rice yield	kg/ha	–
Dependent	Sugarcane yield	t/ha	–
Independent	Annual rainfall	mm/year	Positive
Independent	Max temperature	°C	Negative
Independent	Min temperature	°C	Negative

Represents no impact

- Wheat yield (kg/ha)
- Rice yield (kg/ha)
- Sugarcane yield (tonnes/ha)

These crops were selected due to their economic importance, contrasting water requirements, and differing sensitivity to climatic conditions.

Independent Variables

The independent variables capture key dimensions of climate variability:

- Annual rainfall (mm) – proxy for water availability
- Mean maximum temperature (°C) – indicator of heat stress
- Mean minimum temperature (°C) – relevant for crop growth during winter and night-time respiration

Rainfall is expected to positively influence yields, particularly for rice, while higher temperatures are expected to exert a negative effect, especially on wheat during the grain-filling stage (Lobell et al., 2012).

Analytical Framework

The analytical framework integrates trend analysis, correlation analysis, and multiple linear regression models to systematically assess climate crop relationships.

Descriptive Statistics

Descriptive statistics such as mean, standard deviation (SD), and coefficient of variation (CV) were used to summarize climatic variables and crop yields. The CV is particularly useful for comparing variability across variables with different units of measurement.

Trend Analysis

Linear trend models were employed to examine long-term changes in rainfall and temperature:

Table 4: Variance Inflation Factor (VIF) Values

Variable	*VIF*
Rainfall	1.84
Max temperature	2.31
Min temperature	2.09

The results indicate acceptable levels of multicollinearity.

$X_t = \alpha + \beta t + \varepsilon_t$ Where:

- X_t = climatic variable at time t
- t = time (year)
- β = trend coefficient

A statistically significant positive β indicates an increasing trend over time.

Correlation Analysis

Pearson's correlation coefficient was used to examine the direction and strength of association between climatic variables and crop yields. Correlation analysis provides preliminary insights but does not establish causality (Gujarati, 2012).

Multiple Linear Regression Analysis

To quantify the magnitude of climatic impacts on crop productivity, crop-specific multiple linear regression models were estimated.

Model Specification

$Y_t = \alpha + \beta_1 R_t + \beta_2 T_{max,t} + \beta_3 T_{min,t} + \varepsilon_t$ Where:

- Y_t = crop yield
- R_t = annual rainfall
- $T_{max,t}$ = mean maximum temperature
- $T_{min,t}$ = mean minimum temperature
- ε_t = error term

Separate regressions were estimated for wheat, rice, and sugarcane to capture crop-specific sensitivity.

Econometric Assumptions and Diagnostics

To ensure the validity of regression results, standard econometric assumptions were tested and represent in results section.

Multicollinearity

Variance Inflation Factor (VIF) values were computed to assess multicollinearity among independent variables. VIF values below 5 indicate the absence of serious multicollinearity (Hair et al., 2010).

Autocorrelation

Durbin–Watson statistics were examined to detect autocorrelation in residuals. Values close to 2 suggest no serious autocorrelation problem.

Heteroscedasticity

Visual inspection of residual plots and Breusch–Pagan tests were used to assess heteroscedasticity. The results indicated homoscedastic residuals, supporting the reliability of coefficient estimates.

Software Used

All statistical analyses were conducted using:

- Statistical Package for the Social Sciences (SPSS, Version 26).
- Microsoft Excel for data cleaning, preliminary analysis, and graphical representation.

These software tools are widely accepted in climate and agricultural economics research and ensure transparency and reproducibility.

Results

This section presents the empirical findings of the study, focusing on long-term climatic variability in Moradabad district and its quantified impact on agricultural productivity. The results are organized into four sub-sections: (i) trends in rainfall and temperature, (ii) variability in crop yields, (iii) correlation between climatic variables and crop productivity, and (iv) multiple regression results estimating the magnitude of climatic impacts on major crops.

Trends in Rainfall and Temperature (1990–2024)

Rainfall Variability

Annual rainfall in Moradabad district exhibits substantial inter-annual variability over the 35-year study period. The long-term average annual rainfall is estimated at 893.6 mm, with a standard deviation of 142.8 mm, indicating high variability in monsoon performance. A linear trend analysis reveals a statistically significant declining trend in annual rainfall.

The coefficient of variation close to 16% reflects increasing rainfall instability, which is critical for a region heavily dependent on monsoon-fed agriculture. Trend estimation using ordinary least squares indicates a decline of approximately 3.2 mm per year, statistically significant at the 5% level.

Temperature Trends

Both maximum and minimum temperatures show a consistent upward trend over the study period.

The results indicate a cumulative increase of approximately 1.0°C in maximum temperature and 0.9°C in minimum temperature over 35 years, consistent with broader warming trends observed across northern India (IMD, 2023).

Crop Yield Variability in Moradabad District

Crop productivity in the district shows notable temporal fluctuations, particularly for climate-sensitive crops such as rice and wheat.

Table 4.1: Descriptive Statistics of Annual Rainfall (1990–2024)

Statistic	*Value*
Mean (mm)	893.6
Median (mm)	875.2
Maximum (mm)	1,182.4 (1996)
Minimum (mm)	612.7 (2014)
Standard Deviation	142.8
Coefficient of Variation (%)	15.98

Table 4.2: Trend in Annual Temperature in Moradabad (1990–2024)

Variable	*Mean (°C)*	*Trend (°C/ year)*	*t-value*	*Significance*
Maximum Temperature	30.8	+0.031	3.84	$p < 0.01$
Minimum Temperature	18.2	+0.026	3.12	$p < 0.01$

Descriptive Statistics of Crop Yields

Rice exhibits the highest yield variability, reflecting its sensitivity to rainfall timing and temperature stress during the flowering stage. Sugarcane, owing to irrigation support and longer growing period, shows relatively lower variability.

Temporal Yield Trends

Trend analysis reveals moderate yield improvements over time, largely driven by technological interventions; however, yield growth is uneven and punctuated by climate-induced downturns.

Despite positive trends, yield stagnation is evident in years characterized by rainfall deficits or extreme temperature events, particularly post-2010.

Correlation between Climatic Variables and Crop Yields

Pearson correlation analysis was conducted to assess the strength and direction of relationships between climatic variables and crop yields.

The results indicate:

- Positive and statistically significant correlations between rainfall and all crop yields.

Table 4.3: Descriptive Statistics of Major Crop Yields (kg/ha)

Crop	*Mean*	*Minimum*	*Maximum*	*Std. Deviation*	*CV (%)*
Wheat	3,124	2,218	3,892	412	13.2
Rice	2,846	1,902	3,611	468	16.4
Sugarcane	67,820	54,300	79,600	6,210	9.2

Table 4.4: Yield Trend Estimates (1990–2024)

Crop	*Trend (kg/ha/year)*	*t-value*	*Significance*
Wheat	+21.4	2.76	$p < 0.01$
Rice	+18.9	2.12	$p < 0.05$
Sugarcane	+184.6	3.04	$p < 0.01$

Table 4.5: Correlation Matrix between Climate Variables and Crop Yields

Variable	*Rainfall*	*Max Temp*	*Min Temp*
Wheat Yield	0.48*	–0.42*	–0.21
Rice Yield	0.56*	–0.51*	–0.29
Sugarcane Yield	0.31**	–0.28**	–0.19

Notes: *** $p < 0.01$, ** $p < 0.05$

- Negative correlations between maximum temperature and crop productivity, particularly strong for rice.
- Minimum temperature effects are weaker and statistically insignificant for most crops.

Multiple Regression Results: Climatic Impact on Crop Productivity

Multiple linear regression models were estimated separately for wheat, rice, and sugarcane to quantify the marginal impact of climatic variables on yields.

Wheat Yield Model

Table 4.6: Regression Results – Wheat Yield

Variable	*Coefficient*	*Std. Error*	*t-value*	*Significance*
Rainfall (mm)	1.82	0.54	3.37	p < 0.01
Max Temperature (°C)	–96.4	28.7	–3.36	p < 0.01
Min Temperature (°C)	–24.8	19.3	–1.28	NS
Constant	4,312	—	—	—
R^2	0.52			
F-statistic	11.6			p < 0.01

Rice Yield Model

Table 4.7: Regression Results – Rice Yield

Variable	*Coefficient*	*Std. Error*	*t-value*	*Significance*
Rainfall (mm)	2.36	0.61	3.87	p < 0.01
Max Temperature (°C)	–124.7	31.4	–3.97	p < 0.01
Min Temperature (°C)	–41.6	22.9	–1.82	*p < 0.10
Constant	3,998	—	—	—
R^2	0.58			
F-statistic	14.9			p < 0.01

Sugarcane Yield Model

Table 4.8: Regression Results – Sugarcane Yield

Variable	*Coefficient*	*Std. Error*	*t-value*	*Significance*
Rainfall (mm)	15.4	6.3	2.44	p < 0.05
Max Temperature (°C)	–612.3	241.6	–2.53	p < 0.05
Min Temperature (°C)	–188.5	162.8	–1.16	NS
Constant	78,942	—	—	—
R^2	0.46			
F-statistic	8.4			p < 0.01

Summary of Key Empirical Findings

- Rainfall has a positive and statistically significant impact on all three crops.
- Maximum temperature exerts a strong negative effect, especially on rice and wheat.
- Rice emerges as the most climate-sensitive crop, followed by wheat.
- Sugarcane shows relatively lower sensitivity, reflecting irrigation buffering.

These results provide a robust empirical foundation for the interpretative discussion and policy analysis presented in the subsequent section.

Discussion

This study provides robust empirical evidence on the nature of climate variability and its differential impacts on agricultural productivity in Moradabad district of western Uttar Pradesh. The discussion situates the key findings within the broader national and international literature, highlighting crop-specific sensitivities, regional implications, and structural factors shaping climate–agriculture linkages.

Climate Variability and Agricultural Sensitivity

The observed decline in annual rainfall and consistent rise in both maximum and minimum temperatures over the period 1990–2024 reflect broader climatic shifts documented across the Indo-Gangetic Plains (IPCC, 2021; IMD, 2023). The statistically significant negative impact of rising maximum temperatures on crop yields particularly rice and wheat underscores the vulnerability of temperature-sensitive growth stages such as flowering and grain filling. The magnitude of yield loss associated with a one-degree Celsius increase in maximum temperature is substantial, especially for rice. This aligns with earlier studies which report yield declines of 3–10% per °C increase in temperature for major cereals in India (Lobell et al., 2012; Guntukula, 2020). The results reinforce the argument that warming poses a more severe threat to crop productivity than rainfall variability alone.

Crop-wise Sensitivity to Climate Variables

Rice

Rice emerged as the most climate-sensitive crop in the study. The strong positive elasticity with respect to rainfall and the significant negative coefficient for maximum temperature highlight rice's dependence on adequate monsoon rainfall and vulnerability to heat stress. These findings are consistent with district-level studies from eastern Uttar Pradesh and Punjab, where temperature-induced sterility during flowering has been identified as a key yield-reducing factor (Pathak et al., 2018).

Wheat

Wheat productivity exhibited moderate sensitivity to climatic variables. The negative impact of maximum temperature is particularly relevant during the terminal grain-filling stage, when heat stress accelerates crop maturity and reduces yield potential. Similar effects have been reported for wheat-growing regions across northern India (Asseng et al., 2015).

Sugarcane

Sugarcane showed relatively lower climate sensitivity compared to cereals. This can be attributed to greater irrigation coverage, longer crop duration, and adaptive management practices. However, the significant negative coefficient of maximum temperature indicates that prolonged heat stress may still adversely affect sucrose accumulation and yield quality, as observed in previous studies (Singh et al., 2019).

Comparison with National and Global Evidence

The findings are broadly consistent with empirical studies conducted in other parts of India and comparable agro-climatic regions globally. For instance, studies from China and Southeast Asia report similar negative impacts of rising temperatures on rice and wheat yields (Peng et al., 2004; Zhao et al., 2017). At the national level, the results align with evidence from the Indian Council of Agricultural Research (ICAR), which highlights western Uttar Pradesh as a climate hotspot due to increasing heatwaves and erratic monsoons. Notably, the district-level focus of this study addresses a critical research gap, as most existing studies rely on state or national aggregates, which often mask local heterogeneity in climate impacts.

Implications for Food Security and Regional Planning

Given Moradabad's contribution to regional food supply, declining and unstable crop yields have significant implications for food security, farm incomes, and rural livelihoods. The pronounced sensitivity of rice and wheat to climatic stress suggests that existing production systems may become increasingly unsustainable under future climate scenarios. The results emphasize the urgency of integrating climate risk assessments into district-level agricultural planning. Without targeted interventions, climate-induced yield losses may offset technological gains achieved through improved seeds and fertilizers.

Conclusion

This study analyzed long-term climate variability and its impact on agricultural productivity in Moradabad district over the period 1990–2024. The key conclusions are:

- Annual rainfall exhibits a declining and increasingly variable trend, while both maximum and minimum temperatures show a statistically significant upward trend.
- Crop yields display considerable inter-annual variability, with rice being the most climate-sensitive crop.
- Rainfall positively influences crop productivity, whereas rising maximum temperatures exert a significant negative impact on all major crops.
- Technological progress has partially offset climate stress; however, its effectiveness is diminishing under increasing temperature extremes.

Overall, the findings confirm that climate variability poses a serious threat to agricultural sustainability in western Uttar Pradesh.

Policy Implications

Based on the empirical evidence, the following policy recommendations are proposed:

Strengthening Climate-Resilient Agriculture

- Promotion of heat- and drought-tolerant crop varieties, particularly for rice and wheat.
- Expansion of climate-smart agricultural practices such as alternate wetting and drying (AWD) in rice cultivation.

Water Resource Management

- Enhancing irrigation efficiency through micro-irrigation and improved canal management.
- Promoting rainwater harvesting and groundwater recharge to buffer rainfall variability.

Institutional and Extension Support

- Strengthening agricultural extension services to disseminate climate advisories and adaptive technologies.
- Integrating climate information services with local farming decisions.

District-Level Climate Planning

- Incorporating climate risk assessments into district agricultural plans.
- Targeting small and marginal farmers who are disproportionately vulnerable to climate shocks.

Limitations and Scope for Future Research

Despite its contributions, the study has certain limitations. The analysis does not account for non-climatic factors such as input use intensity, pest incidence, or policy changes, which may also influence yields. Future research could adopt panel data techniques incorporating farm-level observations and explore the role of adaptation strategies in mitigating climate impacts.

Acknowledgement

The authors are thankful to the IFTM university for the support.

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