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Impact of Rainfall Variability on Agricultural Productivity in India

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ABSTRACT

This study investigates the trends and patterns of rainfall variability and its impact on agricultural productivity in India, using time series data with 34 observations. The study reveals that, based on descriptive statistics, there is significant variability in food grain production, but rainfall is relatively stable, reflecting the rising importance of non-climatic factors like irrigation and fertilisers in agricultural productivity. Correlation analysis reveals a strong positive relationship between food grain production and gross irrigated area (GIA), as well as fertilisers, but a weak relationship with rainfall, reflecting the rising importance of controlled inputs in agricultural productivity. The study also reveals that, based on the Augmented Dickey-Fuller (ADF) test, the order of integration of the variables is mixed, where rainfall is found to be stationary at the level, and other variables are found to be stationary after first differencing, which is a prerequisite for applying the ARDL model. The bounds test provided evidence of the long-run cointegrating relations between food grain production, rainfall, fertilisers, and irrigation. The estimates of the long-run model show that, indeed, rainfall and GIA have a significant and positive impact on agricultural output, while fertilisers are statistically insignificant in this context. Further, in the short-run estimates, it is evident that rainfall and irrigation have a significant and positive impact on food grain production, while there is a negative and significant error correction term, suggesting a stable error correction response to equilibrium, thus providing evidence of a stable model. From a policy perspective, the estimates of this study underscore the significance of irrigation, in addition to rainfall, in explaining *agricultural productivity in India, and this is a pointer to the importance of efficient management of water resources in this context.*

Keywords: Rainfall Variability; Agricultural Productivity, Gross Irrigated Area (GIA), ARDL Model, Climate Variability

1. Introduction

The agricultural sector in India is highly vulnerable to climatic factors, especially rainfall, as nearly half of the total cultivated areas are under rain-fed systems. Rainfall is one of the most significant climatic factors, and its variability is crucial in regulating the growth and productivity of crops and the agricultural sector as a whole. In recent years, the increasing variability in rainfall patterns, as reflected in irregular monsoon onset, distribution, and weather events, has posed one of the major challenges to the agricultural sector. The variability in rainfall patterns is closely linked to climate change, and it has led to increased uncertainties in agricultural production. The Intergovernmental Panel on Climate Change (IPCC) has defined climate change as "a change in the state of the climate that can be identified (and therefore separated) by changes in the mean and/or the variability, and lasts for an extended period, typically decades or longer." (IPCC, 2014). Climatic variability in rainfall and temperature plays an important role in determining agricultural productivity, especially in rice production, as rainfall and temperature are major contributors to the variability in rice yields and are key contributors to increasing risks in agriculture (Rahman et al., 2017). Indian agriculture is highly dependent on rainfall as a significant portion of Indian agriculture is rainfed. The Indian Summer Monsoon is the primary source of annual rainfall and plays a vital role in agriculture. Rainfall is considered the most important climatic factor in determining agricultural productivity in monsoon-dependent economies such as India (Parry et al., 1988). According to the Food and Agriculture Organisation (FAO), rainfall variability has significant impacts on agricultural productivity and food security, especially in developing countries where agriculture is mostly rain-fed. In this context, it is important to look into the relationship between rainfall variability and agricultural productivity in India. This is because understanding this relationship would be critical in formulating effective measures to mitigate the impacts of climate change. Therefore, the primary objective of the present study is to examine the impact of rainfall variability on agricultural productivity in India. More specifically, the objectives of the present study are two-fold. First, it would examine the trends and patterns of rainfall variability in different regions of India. Secondly, it would examine the impact of rainfall variability on agricultural productivity in India. In this respect, the study would also focus on understanding the impact of rainfall variability in terms of its implications for crop yields.

2. Literature Review

Rainfall variability and climate change have a considerable influence on agricultural productivity and food security in India. According to research findings, rainfall variability impacts crop yields in different ways; some crops show higher vulnerability to rainfall variability, while some crops show resilience to such variability by practising adaptation (Thimmegowda et al., 2025). Although rainfall trends do not show significant results in the long term, irrigation has emerged as an important adaptation that increases agricultural productivity (Thomas et al., 2024). Climate change and rainfall variability have affected agricultural productivity by increasing temperature and reducing rainfall patterns (Bhanumurthy & Kumar, 2018). Climate change variability still affects agricultural productivity and food security in India, especially for small and marginal farmers (Kumar & Sharma, 2022). Changes in temperature and rainfall patterns also impact water resources and their sustainability, though this effect is reduced by adaptive farming (Kumar & Gautam, 2014). Fluctuations in rainfall patterns have negative effects on crop production, thus highlighting the need to improve irrigation and crops (Singh et al., 2014). Rainfall shocks reduce crop production, wages, and increase prices, depending on regional patterns (Brey & Hertweck, 2019). Even in regions with high rainfall, variability plays a significant role in affecting productivity depending upon the seasonal pattern (Dkhar et al., 2017). Climatic factors like ENSO and IOD events increase rainfall variability, resulting in reduced crop productivity and area due to drought conditions in some regions (Todmal, 2022). Rainfall decline also results in groundwater depletion, affecting the sustainability of agriculture (Dey et al., 2020). Rainfall variability in the future may also become a challenge to rain-fed agriculture (Chakraborty et al., 2025). Climate change has severe impacts on food crops like rice, affecting food security in many regions (Vyankatrao, 2017). Rainfall variability also has severe impacts on livelihoods and often results in migration as a coping mechanism in many regions (Murali & Afifi, 2013). In regions like Odisha, rainfall during the monsoon season plays a significant role in affecting agricultural productivity in the region (Panda et al., 2019).

3. Data and Materials

3.1 Data Sources and Variable Description

This study uses annual data from the All-India Time Series over a period of 34 years, from 1991 to 2024. The proxy for agricultural productivity is foodgrain production (Y_t) measured in million tonnes. The proxy for climatic variability is the summer monsoon rainfall (R_t) measured in millimetres. Fertiliser consumption (F_t) and gross irrigated area (G_t) are the proxies for non-climatic factors affecting the agriculture sector. The data on foodgrain production, fertilisers, and irrigation is obtained from the Handbook of Statistics on the Indian Economy (RBI) and Ministry of Agriculture reports. The rainfall data is obtained from the Indian Institute of Tropical

Meteorology (IITM) in Pune. The rainfall during the monsoon season (June to September) is matched with the corresponding agricultural years.

3.2 Model Specification

The relationship between agricultural productivity and its determinants over the long run is given by a linear functional relationship as follows:

$$Y_t = \alpha + \beta_1 R_t + \beta_2 F_t + \beta_3 G_t + \mu_t$$

Here, Y_t stands for foodgrain production, R_t stands for monsoon rainfall, F_t stands for fertiliser consumption, and G_t stands for gross irrigated area. The white noise error term is denoted by μ_t. The coefficients β_1, β_2, and β_3 represent the marginal values of the variables.

3.3. Econometric Strategy

In most instances, macroeconomic variables are found to be non-stationary in nature, which might lead to spurious regression results. In order to analyse the long-run equilibrium as well as the short-run dynamic relationship between the variables, this paper makes use of the Autoregressive Distributed Lag (ARDL) bounds testing approach, as proposed by Pesaran et al. (2001). The ARDL approach for this analysis seems appropriate for two specific reasons. First, this approach can be used for variables of order I(0) as well as order I(1) in nature, whereas other cointegration tests, such as the Johansen approach, can be applied for variables of order I(1) in nature only. Second, this approach can be used for obtaining consistent results for the estimation of long-run as well as short-run coefficients, considering the endogeneity issues as well.

Step 1: Unit Root Testing

The Augmented Dickey–Fuller (ADF) test was conducted to determine the stationarity properties of each variable and to ensure that none are integrated of order two (I(2)), which would invalidate the ARDL bounds testing procedure. Variables exhibiting a deterministic trend, namely, foodgrain production, fertiliser consumption, and irrigation, were tested accordingly.

Step 2: ARDL Bounds Testing for Cointegration

To verify the presence of a long-run relationship, an Unrestricted Error Correction Model (UECM) was employed. The null hypothesis of no cointegration, i.e., $H_0: \lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = 0$, was tested using an F-statistic. The calculated F-statistic was compared with the critical bounds proposed by Pesaran et al. (2001). The rejection of the null hypothesis confirms the presence of a long-run relationship among the variables.

Step 3: Error Correction Model (ECM)

After establishing cointegration, the short-run dynamics and the speed of adjustment to long-run equilibrium were estimated using an Error Correction Model (ECM). The coefficient on the error correcting term (ECTt-1) captures the speed of adjustment to long-run equilibrium and represents the proportion of deviations from long-run equilibrium that are corrected each period. This coefficient should be negative and statistically significant. The lag specification for the ARDL model chosen on the basis of AIC is employed for estimation. Estimation is done using the Stata software.

3.4 Diagnostic and Stability Tests

To ensure the reliability and robustness of the estimated model, a number of diagnostic tests were conducted. First, the Breusch-Godfrey LM test was used for testing the presence of serial correlation in the model, and the Breusch-Pagan/Cook-Weisberg test was conducted for testing the presence of heteroscedasticity in the model. Further, the normality of the residuals was checked through the skewness and kurtosis tests. In addition, for testing the stability of the model parameters over the sample period, the Cumulative Sum (CUSUM) test was conducted for testing the stability of the model parameters. The results clearly indicate that the model has passed all the major econometric tests and is stable over the sample period.

4. Results and Discussion

Table-1 Descriptive statistics

Variables	Obs	Mean	Std. dev.	Min
Foodgrain	34	239.2021	51.25813	168.38
Rainfall	34	863.2206	70.64054	698.2
Fertilizer	34	22.62853	7.13838	12.15
GIA	34	87.95353	14.79404	65.68

Source: Author’s Estimation

The descriptive statistics of the various variables under consideration, as obtained from the given data set comprising 34 observations, provide valuable insights into the dynamics of agricultural production. For instance, the mean and standard deviation of foodgrain production, at 239.20 and 51.26, respectively, indicate significant variability in the data set, possibly due to the influence of both climatic and input-related factors. Similarly, the mean and standard deviation of rainfall, at 863.22 and 70.64, respectively, indicate that rainfall is more stable, possibly due to the prevalence of a particular climatic condition. However, the moderate variability in fertiliser consumption, as indicated by the mean and standard deviation at 22.63 and 7.14, respectively, highlights the differences in the usage of agricultural inputs, as reflected in the data set. Furthermore, the moderate variability in gross irrigated area, as indicated by the mean and standard deviation at 87.95 and 14.79, respectively, highlights the differences in the usage of agricultural inputs, as reflected in the data set. The findings suggest that rainfall is stable, whereas the variability in agricultural inputs and climatic factors plays a crucial role in influencing foodgrain production.

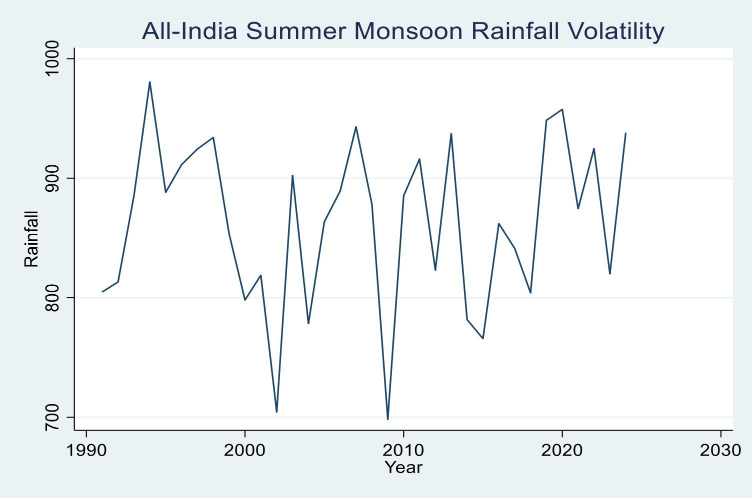
Table 2 Correlation Matrix

	Foodgrain	Rainfall	Fertilizer	GIA
Foodgrain	1			
Rainfall	0.2508	1		
Fertilizer	0.9501	0.1087	1	
GIA	0.9814	0.1551	0.973	1

Source: Author's Estimation

The correlation matrix also reveals strong correlations between the variables that influence agricultural production. Food grain production is found to have a very strong positive correlation with Gross Irrigated Area (0.9814) and fertiliser use (0.9501), indicating that agricultural output is highly related to increased irrigation coverage and fertiliser usage. However, the relationship between rainfall and food grain production is not strong (0.2508), suggesting that agricultural output is not highly dependent on rainfall, which could be due to the increased usage of irrigation systems to support agricultural output. In addition, fertiliser usage and GIA also reveal a strong relationship (0.973), indicating that agricultural output in regions with better irrigation facilities is also high due to the usage of fertilisers. The relationship between rainfall and fertiliser usage (0.1087), as well as rainfall and GIA (0.1551), is not strong, indicating that agricultural output is not highly dependent on rainfall, but rather on the usage of other agricultural inputs.

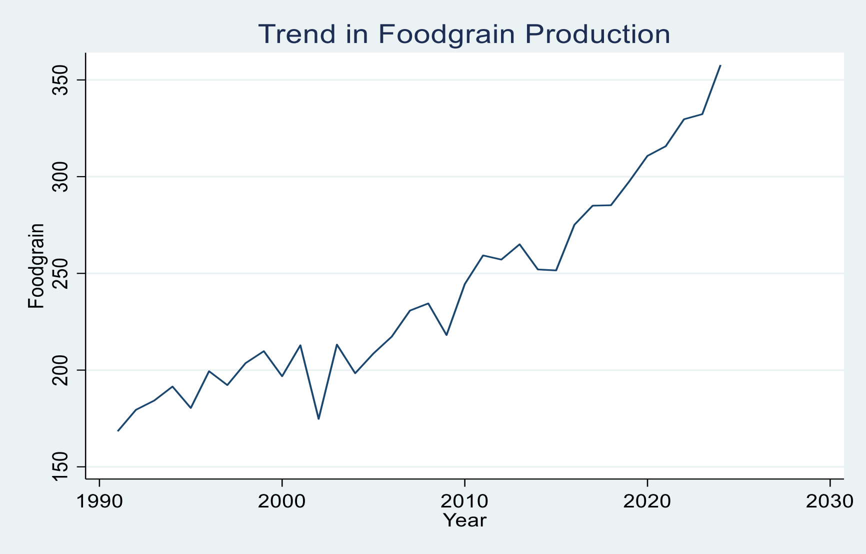
Fig. 1 Trends of Summer Monsoon Rainfall Volatility



Source: Author's Estimation

The figure shows that summer monsoon rainfall in India fluctuates considerably over time, with no clear long-term increasing or decreasing trend. There are periods of sharp decline (around the early 2000s and 2009) and peaks (mid-1990s and around 2020), indicating high inter-annual variability in rainfall.

Fig. 2 Trends in Foodgrain Production



Source: Author's Estimation

The figure shows a clear upward trend in foodgrain production over time, despite minor fluctuations. This indicates a steady improvement in agricultural output, likely driven by better irrigation, increased fertiliser use, and technological advancements.

Table 3 Unit Root Test

Variable	ADF Test Statistic (Level)	p-value (Level)	ADF Test Statistic (1st Diff)	p-value (1st Diff)	Order of Integration
Foodgrain Production	-2.318	0.4239	-9.909***	0	I(1)
Fertilizer Consumption	-1.809	0.7006	-4.459***	0.0002	I(1)
Gross Irrigated Area (GIA)	-2.05	0.5737	-6.835***	0	I(1)
Summer Monsoon Rainfall	-5.134***	0	-	-	I(0)

Source: Author's Estimation

The results of the Augmented Dickey-Fuller (ADF) test show that Foodgrain Production, Fertiliser Consumption, and Gross Irrigated Area are non-stationary at levels, as their p-values are greater than 0.05. However, when these variables are tested for their stationarity at first differences, all three variables are found to be stationary at a 1% significance level. This confirms that these three variables are integrated of order one, i.e., I(1). On the other hand, Summer Monsoon Rainfall is found to be stationary at levels, as its ADF value is -5.134, and its p-value is almost equal to 0. This confirms that Summer Monsoon Rainfall is integrated of order zero, i.e., it is I(0). The variables are of mixed order of integration, so an ARDL model would be suitable for further analysis, as it can accommodate both I(0) and I(1) variables.

Table 4 ARDL Bound Test

Bounds Test for Cointegration	
F-Statistic	**10.192*** **
Critical Values (k=3)	**Lower Bound I(0)**
10% Significance Level	2.72
5% Significance Level	3.23
1% Significance Level	4.29

Source: Author's Estimation

The bounds test for cointegration using the ARDL approach also supports the cointegration relationship among the variables. This is evident from the fact that the F-statistic value (10.192) is substantially higher than the upper critical bounds (4.29) at a 1% significance level, thereby rejecting the null hypothesis that there is no cointegration relationship among the variables. This implies that the foodgrain production, fertiliser consumption, gross irrigated area, and rainfall variables are cointegrated in the long-run equilibrium relationship.

Table 5 Long-Run Estimates

Variable	**Coefficient**	**Standard Error**	**t-Statistic**	**p-value**	**Significance**
Monsoon Rainfall	0.2009	0.0692	2.9	0.008	***
Fertilizer Consumption	1.1497	1.5979	0.72	0.479	
Gross Irrigated Area	3.3484	0.7329	4.57	0	***

Source: Author's Estimation

The long-run estimates indicate that monsoon rainfall and gross irrigated area (GIA) have a positive and statistically significant impact on foodgrain production, while fertiliser consumption appears insignificant. Specifically, rainfall has a positive coefficient (0.2009) and is significant at the 1% level ($p = 0.008$), suggesting that higher rainfall contributes to increased agricultural output in the long run. Similarly, GIA shows a strong positive effect (coefficient = 3.3484, $p = 0.000$), highlighting the crucial role of irrigation in enhancing foodgrain production. In contrast, fertiliser consumption, although positively related (coefficient = 1.1497), is statistically insignificant (p = 0.479), indicating that its long-run impact is not robust in this model. Overall, the findings emphasise the dominant role of irrigation and climatic factors over fertiliser use in determining long-term agricultural productivity.

Table 6 Short-Run Dynamics (SR)

Variable	Coefficient	Standard Error	t-Statistic	p-value	Significance
ΔMonsoon Rainfall	0.0854	0.0193	4.44	0	***
ΔFertilizer Consumption	-1.12	0.971	-1.15	0.26	
ΔGross Irrigated Area	2.9577	0.7649	3.87	0.001	***
Δ Gross Irrigated Area, Lagged	-2.9282	0.5869	-4.99	0	***

Source: Author's Estimation

The short-run dynamics reveal that monsoon rainfall and gross irrigated area (GIA) significantly influence foodgrain production in the short term, while fertilizer consumption remains insignificant. Specifically, the change in rainfall (ΔRainfall) has a positive and statistically significant effect (coefficient = 0.0854, $p < 0.01$), indicating that short-term increases in rainfall lead to immediate improvements in agricultural output. Similarly, the change in GIA (ΔGIA) shows a strong positive impact (coefficient = 2.9577, p = 0.001), highlighting the importance of irrigation expansion in boosting production in the short run. However, the lagged change in GIA carries a significant negative coefficient (-2.9282, $p < 0.01$), suggesting a short-term adjustment effect or possible over-expansion in the previous period. In contrast, fertiliser consumption has a negative but statistically insignificant coefficient, indicating that its short-run effect on foodgrain production is not meaningful in this model. Overall, the results emphasise that rainfall variability and irrigation dynamics are key drivers of short-run agricultural performance.

Table 7 Error Correction and Constant

	Coefficient	Standard Error	t-Statistic	p-value	Significance
Error Correction Term ($ECTt_{-1}$)	-0.4253	0.1246	-3.41	0.002	***
Constant (α)	-102.698	23.5626	-4.36	0	***

Source: Author's Estimation

The findings from the error correction results again verify the existence of a stable long-run equilibrium relationship between the variables. The error term is negative and statistically significant (coefficient = -0.4253 and p-value = 0.002), indicating that the short-run disequilibrium is corrected by about 42.53% in each period towards the long-run equilibrium. This indicates a moderate speed of adjustment towards the equilibrium, indicating that the disequilibrium is corrected slowly and gradually towards the equilibrium. Moreover, the constant term is also negative and statistically significant (p-value < 0.01), indicating a constant adjustment towards the equilibrium even in the absence of the regressors.

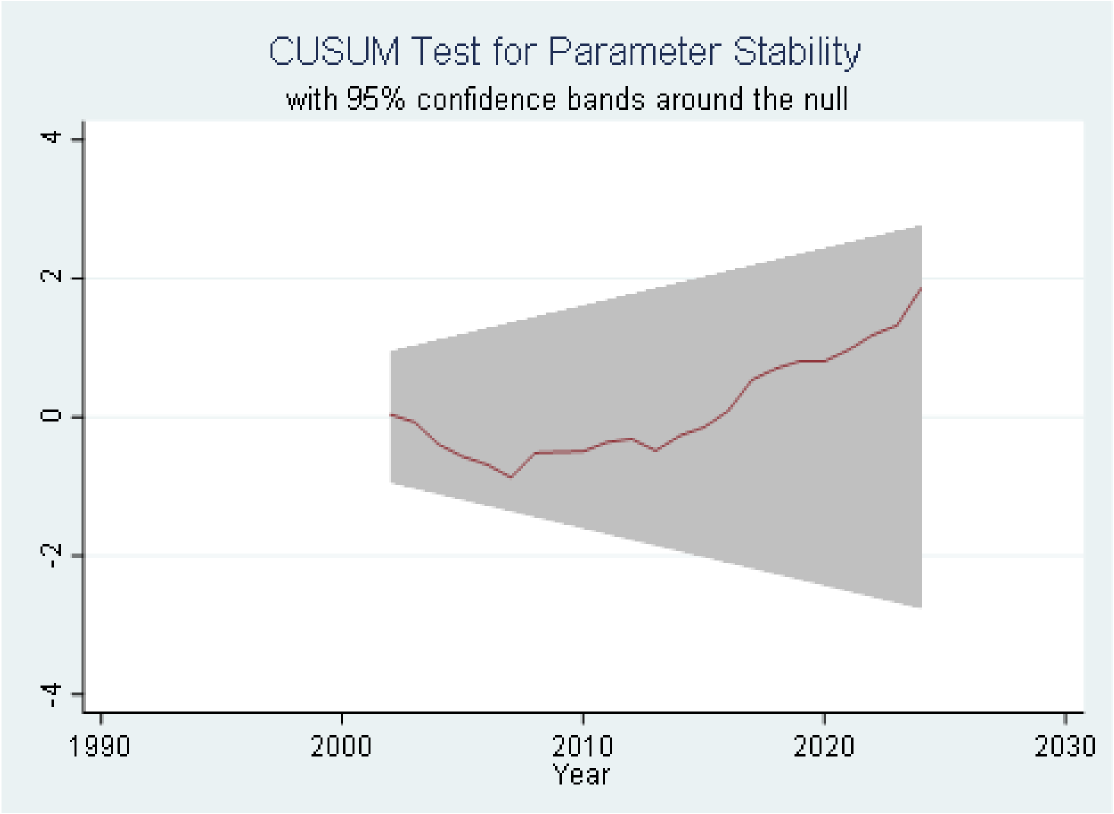
Table-8 Diagnostic Test

Diagnostic Check	Test Applied	Null Hypothesis (H0)	Test Statistic (χ2)	p-value	Conclusion
Serial Correlation	Breusch-Godfrey LM Test	No serial correlation	0.429	0.5127	Fail to reject H_0
Heteroskedasticity	Breusch-Pagan / Cook-Weisberg	Constant variance	2.47	0.1158	Fail to reject H_0
Normality	Skewness and Kurtosis Test	Residuals are normally distributed	5.12	0.0772	Fail to reject H_0

Source: Author's Estimation

The results obtained from the diagnostic test indicate that the estimated model is robust and well-specified. From the results of the Breusch-Godfrey LM test, it is clear there is no serial correlation of the errors since p = 0.5127. This indicates that the residuals of the model are independent over time. Moreover, based on the results of the Breusch-Pagan/Cook-Weisberg test, there is no heteroscedasticity of the errors since p = 0.1158. This indicates that the error variances of the model are constant. Finally, based on the results of the test on skewness and kurtosis, the residuals of the model are normally distributed since p = 0.0772. However, not all null hypotheses were rejected. This indicates that the model passes all the assumptions of a classical linear regression model. This indicates that the results of the model are reliable and valid.

Fig. 3 CUSUM Test for Parameter Stability



Source: Author's Estimation

The CUSUM test results show that the model is stable over time since the cumulative sum line remains within the 95% confidence bands. This shows that there are no structural breaks or parameter instability, which confirms the reliability of the estimated model.

5. Conclusion

This article aims to investigate the impact of rainfall variability on agricultural productivity in India, employing the ARDL approach from 1991 to 2024. The results suggest that, even though rainfall is one of the crucial climatic factors, its impact is not as significant as non-climatic factors, like irrigation, in determining foodgrain production. The results suggest that, in the long-run, rainfall and gross irrigated areas are significant determinants of agricultural productivity, with irrigation being the most significant factor. Fertiliser consumption, however, is found to be statistically insignificant, indicating that fertiliser consumption might be conditional upon other factors. In the short-run, rainfall and irrigation variability are seen to be crucial factors in determining agricultural output, and the model is found to have a moderate speed of adjustment towards long-run equilibrium. Additionally, various tests suggest that the model is robust, reliable, and not subject to econometric problems. Overall, the study concludes that although monsoon rainfall remains vital, the increasing role of irrigation infrastructure has reduced agriculture's dependence on rainfall variability.

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