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Assessing the Impact of Fertilizer Use, Irrigation, and Rainfall on Crop Productivity in India

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Abstract
Indian agricultural sector is facing multiple challenges because of rising competition for land resources and water access and changing climate patterns. This study examines the impact of fertilizer consumption, irrigation, and annual rainfall on crop productivity in India. The study is based on secondary data from 1981 to 2023. Trend analysis indicates that crop productivity increased at an average annual rate of 2.09%, fertilizer use at 3.88%, and irrigation coverage at 1.46%. Rainfall showed a negligible and statistically insignificant increase of 0.11% per year. The Auto Regressive Distributed Lag model establishes a long-run cointegrating relationship between crop productivity and its determinants. The error correction term was found significant and suggests that short-run deviations adjust toward long-run equilibrium, thereby confirming the stability of the model. The application of fertilizers consistently enhances productivity, whereas irrigation efficiency represents a critical area for enhancement. The findings highlight the necessity of balanced fertilizer application, effective water management, and climate-resilient strategies to promote sustainable agricultural development and ensure long-term food security in India.

Keywords: Crop productivity, fertilizer use, agricultural growth, Auto Regressive Distributed Lag model

Introduction

The agricultural sector in India holds significant importance. The agricultural sector generates 16-18% of GVA while employing nearly half of the total Indian workforce. It ensures food security, generates employment, and drives overall economic development. The agricultural sector shapes rural incomes and livelihoods, provides food and raw materials, and offers employment for a considerable portion of the population. India has been increasingly attaining self-sufficiency with impressive gains in agricultural production. But climate change and increasing population growth during the last several decades have made pressures on India's crop productivity. Some of the most important determinants of productivity are rainfall patterns, irrigation systems, and the use of fertilizers. To create sound policies for the agricultural sector, the government needs to understand the quantitative relationships between these determinants.

Indian soils are typically regarded as low fertile soils because of significant deficiencies in micronutrients such as zinc, iron, and boron, as well as nitrogen, phosphorus and potassium. The low amount of soil organic carbon (SOC) in Indian soils is a major contributing factor to the decreased fertilizer use efficiency. (Srinivasarao, 2021) [14]. India ranks second globally and first in the South Asian Association for Regional Cooperation (SAARC) region in terms of total fertilizer consumption. This highlights India's intensive input-based farming system and significant contribution to the global fertilizer demand. According to Rao *et al*. (2018), balanced fertilizer application greatly increases cereal yields, especially in irrigated areas. Chaudhary (2021) [1, 12] promoted precision nutrient management by highlighting the possible yield and environmental constraints associated with excessive fertilizer use. Patra *et al*. (2016) [11] investigated how fertilizer use affected agricultural output in Hooghly district of West Bengal. They found that there is no significant relationship between increased chemical fertilizer use and increases in agricultural yield and production.

Irrigation is essential for increasing agricultural output as it guarantees a consistent supply of water and lessens reliance on erratic monsoon rains.

Irrigation also improves food security and stabilizes farmers' incomes by facilitating multiple cropping and promoting high-yield crops. Higher irrigation coverage reduces rainfall variability and produces more consistent yields (Singh and Sharma, 2019) [13]. Rainfall variability limits fertilizer efficiency, underlining the significance of supplemental irrigation (Kumar *et al.*, 2020) [6]. Narayanamoorthy, Bhattarai, and Jothi (2018) studied the economic effects of drip irrigation in the production of vegetables in Tamil Nadu. They found that drip irrigation boosts crop yield by 52 percent while lowering the need for other inputs, like fertilizers, by 31 percent. According to a study by Jin, Yu, Jansen, and Muraoka (2012) [4] on the effect of irrigation on crop productivity in India found that irrigation has a significant and strong influence on agricultural productivity.
Most farming in India still depends on monsoon rains and rainfall has a direct and substantial impact on agricultural output. While irregular or insufficient rainfall can result in droughts, crop failures, and decreased agricultural output, adequate and well-distributed rainfall promotes crop growth, boosts yields, and permits timely sowing and harvesting. As a result, agricultural production and food security are all significantly affected by rainfall patterns. According to Onyeji & Fischer (1993) [10], climate change has resulted in lower consumer incomes, higher food prices, and decreased crop yields. Compared industrial and service sectors, agricultural sector is more economically and physically vulnerable to climate change (Gbetibouo and Hassan, 2005) [2]. This study also found that agricultural production is severely impacted by climate change. According to Nandhini *et al.* (2006), low rainfall and input scarcity in Tamil Nadu, India, are causing a decline in arable land for rice cultivation. According to Kapur *et al.* (2009) [5], by the middle of the twenty-first century, rainfall could reduce crop yields by thirty percent. This study also observed that a decrease in arable land might put additional strain on India's agricultural output.
These studies show that a variety of interrelated factors affect crop productivity, necessitating a thorough empirical investigation. Numerous studies examine agricultural inputs independently. A more comprehensive understanding of the relationships and relative contributions of fertilizer use, irrigation, and rainfall to crop productivity can be obtained by evaluating these factors together.

Objectives

- to study the long-term trends in crop productivity, fertilizer use, irrigation and rainfall.
- to examine the short run and long run relationship between crop productivity and its major determinants.

Methodology

Data Sources: The study is based on secondary data over the period from 1981 to 2023. Data on fertilizer consumption (kg/ha), Crop productivity (kg/ha) and land area equipped for irrigation (ha) is obtained from FAOSTAT. Data on annual all-India Rainfall is collected from India Meteorological Department (IMD).
Analytical Tools: The long-term trends in crop productivity, fertilizer consumption, irrigation, and rainfall during the period 1981-2023 were studied using a log-linear regression model. The short run and long run relationship between variables was examined using ARDL model.

Results and Discussion

Trends in Crop Productivity, Fertilizer Use, Irrigation, and Rainfall

The long-term trends in crop productivity, fertilizer consumption, irrigation, and rainfall during the period 1981-2023 were studied using a log-linear regression model

$$\ln Y_t = \alpha + \beta t + \varepsilon_t$$

where β shows the average annual growth rate of the variable.
The regression results are summarized in Table 1

Table 1: Trends in Crop Productivity, Fertilizer Use, Irrigation, and Rainfall

Variable Coefficient	Growth Rate (% per annum)	p-value	R^2	Trend Direction
Crop Productivity 0.02093	2.09	<0.001	0.968	Increasing
Fertilizer Use 0.0387659	3.88	<0.001	0.940	Increasing
Irrigation 0.0146091	1.46	<0.001	0.964	Increasing
Rainfall 0.00108962	0.11	0.160	0.063	Slightly Increasing

Average annual growth of crop productivity is 2.09% and was statistically significant at 1% level. This suggests steady productivity gains over the last four decades. Average annual growth of fertilizer consumption is 3.88%, and was statistically significant at 1% level. This reflects the input-intensive nature of Indian agriculture during the study period. Irrigation coverage increased at an average rate of 1.46% per annum. This indicates gradual but continuous improvements in water resource infrastructure. Rainfall exhibited a negligible and statistically insignificant increase of 0.11% per annum. This shows absence of a consistent long-term trend in rainfall.

Regression Analysis

ARDL Model Estimation

The short run and long run relationship between variables was examined using ARDL model. The dependent variable was crop productivity and the independent variables were fertilizer, irrigation and rainfall. All the variables were expressed in natural logarithms. Unit root tests were done to confirm that the variables satisfy the conditions for ARDL model. The optimal lag structure (4, 0, 0, 0) was decided based on Akaike Information Criterion (AIC).

Table 2: ARDL Estimated Short-Run Model

Variable	Coefficient	Std. Error	t-Statistic	Prob.
ln_crop_productivity(-1)	0.518	0.167	3.097	0.004
ln_ crop_productivity (-2)	0.132	0.181	0.731	0.470
ln_ crop_productivity (-3)	-0.061	0.157	-0.386	0.702
ln_ crop_productivity (-4)	0.355	0.143	2.490	0.018
ln_fertilizer	0.202	0.069	2.910	0.007
ln_irrigation	-0.462	0.207	-2.235	0.033
ln_rainfall	-0.045	0.111	-0.405	0.689
C	8.112	3.148	2.577	0.015

Model summary: $R^2 = 0.983$; Adj. $R^2 = 0.979$, F-statistic = 254.70 ($p < 0.01$); DW = 2.06.

Adjusted R square shows that 98% of the variation in crop productivity is explained by the model. Durbin-Watson statistic near 2 shows that there is no autocorrelation. The model shows strong overall fit because the R^2 value is high and the F-statistic is statistically significant.

Bounds Test for Cointegration

Pesaran, Shin, and Smith Bounds Test was used to determine if crop productivity, rainfall irrigation and fertilizer use have a long-run equilibrium relationship.

Table 3: ARDL Bounds Test for Cointegration

Test Statistic	Value	Significance	(0)Bound	I(1)Bound	Decision
F-statistic	5.8599	5%	2.79	3.67	Cointegration exists
k (regressors)	3				

As the computed F-statistic value (5.86) is larger than the upper bound critical value (3.67) at 5% significance level, we reject the null hypothesis of no relationship between levels. This proves the existence of a long-run cointegrating relationship between crop productivity and its determinants.

Long-Run Relationship

The long-run coefficients derived from the levels equation is given below

Table 4: Long-Run Coefficients

Variable	Coefficient	Std. Error	t-Statistic	Prob.
ln_fertilizer	3.657	6.924	0.528	0.601
ln_irrigation	-8.381	18.567	-0.451	0.655
ln_rainfall	-0.812	2.580	-0.315	0.755
Constant	147.130	312.961	0.470	0.642

The long run coefficients were not found significant. Fertilizer use has a positive long-run effect on crop productivity. This suggests that continuous application of fertilizer boosts farm productivity. Both rainfall and irrigation have negative long-run coefficients. This might be due to poor irrigation technology, soil salinization, or too much reliance on unpredictable rainfall patterns. The presence of cointegration indicates that despite short-run fluctuations, the variables move together towards a long-run equilibrium path.

Short-Run Dynamics and Error Correction Model (ECM): The short-run dynamics were studied using the Error Correction Representation of ARDL model.

Table 5: Error Correction Model Results

Variable	Coefficient	Std. Error	t-Statistic	Prob.
D (ln crop_productivity(-1)	-0.427	0.144	-2.958	0.006
D (ln_crop_productivity (-2)	-0.295	0.136	-2.173	0.038
D (ln_crop_productivity (-3)	-0.355	0.128	-2.786	0.009
Coint Eq (-1)	-0.055	0.0096	-5.752	0.000
R^2 = 0.356	Adj. R^2 = 0.301	DW = 2.06	AIC = -3.99	

The presence of a stable long-term relationship was confirmed by the highly significant ($p < 0.01$) and negative (-0.055) error correction term. A relatively slow but steady adjustment toward long-run equilibrium is indicated by the magnitude of the error correction term (-0.055). This suggests that about 5.5% of the short-run disequilibrium is corrected annually. The coefficients of lagged ΔLN_crop_productivity terms were negative and significant which indicates yield adjustments in response to previous fluctuations, demonstrating persistence and partial adjustment in agricultural productivity.

Diagnostic Tests

Diagnostic tests were conducted to validate the model

Table 6: Diagnostic Test Results

Test	Statistic	Prob.	Inference
Breusch-Godfrey Serial Correlation LM Test	F = 0.132	0.877	No autocorrelation
Breusch-Pagan-Godfrey Heteroskedasticity Test	F = 0.472	0.847	Homoskedastic residuals
Durbin-Watson Statistic	2.06	—	No serial correlation
R^2 of ECM	0.356	—	Moderate short-run fit

The diagnostic results indicated that there is no serial correlation, no heteroskedasticity, and a stable error structure. Hence, the parameter estimates are statistically reliable and efficient. The model stability test was conducted using CUSUM and CUSUMSQ tests. The results indicates that the ARDL model is structurally stable over the study period and the parameters are consistent.

Conclusion

Understanding the impacts of fertilizers, irrigation, and rainfall on agricultural productivity helps policymakers to design focused interventions. The results of ARDL analysis have several policy implications with regard to agricultural development. The error correction term is significant which indicates that short run deviations adjust toward their long run equilibrium. This suggests the stability and validity of the estimated model for policy inferences. The empirical results of the ARDL model indicate that crop productivity is cointegrated with fertilizer, irrigation and rainfall in the long run. The results also reveal that fertilizer use is a consistent positive determinant of productivity. The results also points out that there is some scope for efficiency enhancement in irrigation practices to increase yield performance. Agricultural productivity can be greatly increased through the formulation of policies supporting balanced and economic fertilizer use. This requires interventions such as farmer trainings on nutrient management, enhanced access to soil testing services and targeted subsidies for eco-friendly or crop-specific fertilizers. Although irrigation contributes to increased crop productivity, the results suggest that there is a need for enhancing water-use efficiency rather than merely increasing irrigated area. Policymakers need to invest in modern irrigation systems like drip and sprinkler, encourage conjunctive use of surface water and groundwater and externalize the costs for adopting water saving technologies. Importance of rainfall in affecting crop yield emphasizes how agriculture is exposed to climatic change. This will require enhancing climate adaptation strategies, including the development of drought-resistant crop varieties, improved weather forecasting, and risk management instruments such as crop insurance. Such measures are important for enhancing food security and ensuring sustainable agricultural growth.

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