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Cointegration Analysis of Factors Influencing Rice Production: A Study of Fertilizers, Rice Area, CO_2 Emission, and Rainfall

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Abstract: The research paper investigates the multifaceted impact of climatic and non-climatic factors on rice output through rigorous econometric analyses spanning from 1970 to 2021. By employing methodologies such as ARDL bound testing, Granger causality tests, and diagnostic assessments, the study unveils the intricate relationships between rice production, fertilizer usage, cultivation area, CO2 emissions, and rainfall patterns. The findings highlight enduring links between rice output and its determinants, emphasizing the significant influences of fertilizer application, cultivation area, CO2 emissions, and rainfall dynamics. Notably, Granger causality tests underscore the role of CO2 emissions in shaping rice production, emphasizing the critical influence of climate dynamics on agricultural outcomes. The robustness of the econometric model is confirmed through diagnostic assessments, enhancing the credibility of the research findings.In response to these results, the study advocates for proactive mitigation strategies to address the severe impacts of climate change on agricultural productivity. It emphasizes the crucial need for governmental bodies and policymakers to consistently implement measures aimed at safeguarding agricultural production, with a specific focus on staple crops like rice, to ensure food security within the country.

Keywords: Climate change, Rice production, econometric analysis, ARDL model.

JEL- Q15, Q16, Q51, Q54, Q59.

Introduction

Climate change has become one of the most serious challenges confronting global agriculture, primarily due to rising temperatures, erratic rainfall, altered sunshine duration, unpredictable wind patterns, and the progressive degradation of soil and water resources. These interlinked factors collectively exert a negative influence on agricultural productivity worldwide (Wassmann et al 2009). Crop survival and performance are highly sensitive to temperature, and extensive research has demonstrated that repeated increases in global mean temperature significantly reduce the yields of temperature-sensitive crops (Adams 1989). The Intergovernmental Panel on Climate Change (IPCC) projects that global mean temperatures could rise by 1.4 to 5.8°C by the end of the twenty-first century. For India, the projected increase ranges from 1.1 to 5.1°C by 2100 (Ravindra et al 2024).

Empirical evidence further indicates that during the last four decades, India has experienced warming trends of 0.1–0.3°C per decade during the pre-monsoon period and 0.2–0.4°C per decade in the post-monsoon season (Mulla et al 2023).

Climate change has already had a pronounced impact on the agricultural sector, affecting crop growth, yields, and overall food security (Kraehmer et al 2017; Peng et al 2019; Fahad et al 2019; Van and Ferrero 2006). Among major cereals, rice is particularly vulnerable to climatic variability. Several studies have established that changes in temperature and rainfall patterns significantly influence rice production across the world (Chang and Luh 1991; Dawe et al 2010; Mahajan et al 2017). The International Food Policy Research Institute (IFPRI) has warned that climate change could lead to a 10–15 percent decline in rice productivity, which may trigger a 32–37 percent increase in market prices (Liddle 2013). In India, the consequences are expected to be severe: without effective adaptation strategies, rainfed rice yields may decline by 20 percent by 2050 and as much as 47 percent by 2080, while irrigated rice yields could fall by 3.5 percent by 2050 and 5 percent by 2080 (PIB).

A substantial body of research in India has examined the effects of climate change on agricultural productivity in general and rice production in particular (Pattnayak and Kumar 2014; Soora et al 2013; Singh et al 2017; Vyankatrao 2017; Saravanakumar et al 2022). However, most existing studies primarily focus on climatic variables alone. In contrast, the present study aims to analyze the combined influence of both climatic factors—such as carbon dioxide emissions and average rainfall—and non-climatic factors, including area under rice cultivation and fertilizer consumption, on rice output. The significance of this study is therefore twofold: first, it evaluates the integrated effects of climatic and non-climatic determinants of rice production; second, it offers evidence-based policy recommendations to enhance rice productivity under changing climatic conditions. The analysis employs advanced econometric techniques, including the ARDL bounds testing approach for cointegration, the Granger causality test, and CUSUM diagnostics.

Rice remains the most important staple food in India and many other Asian countries (Agarwal and Mall 2002). India also holds a comparative advantage in producing aromatic rice varieties, especially basmati, which are highly valued in international markets (Mahajan et al 2017). As the world's second-largest rice producer after China, India contributes nearly 40 percent of global rice exports. West Bengal is the leading rice-producing state, followed by Uttar Pradesh and Punjab (PIB). Despite climatic uncertainties, rice production in India has shown a compound annual growth rate of about 2.7 percent during 2015–16 to 2020–21. Nevertheless, delayed monsoons and rainfall deficiencies during the Kharif season of 2022–23 led to a reduction in sown area. Even so, total Kharif rice production remained above the five-year average, underscoring both the resilience and vulnerability of India's rice sector in the face of climate change (Economic Survey 2022–23).

Figure 1 shows theseveral notable trends andpatterns in rice production from 1970 to 2021. Initially, the production remained relatively stable, with some fluctuations but no significant trend. However, there was a notable increase in production from the late 1970s to the early 1980s, reaching a peak in 1985 at 638.3 units. Subsequently, there were fluctuations in production, with occasional peaks and dips. The late 1980s and early 1990s saw a significant increase in rice production, reaching its highest level in 1999 at 896.8 units.

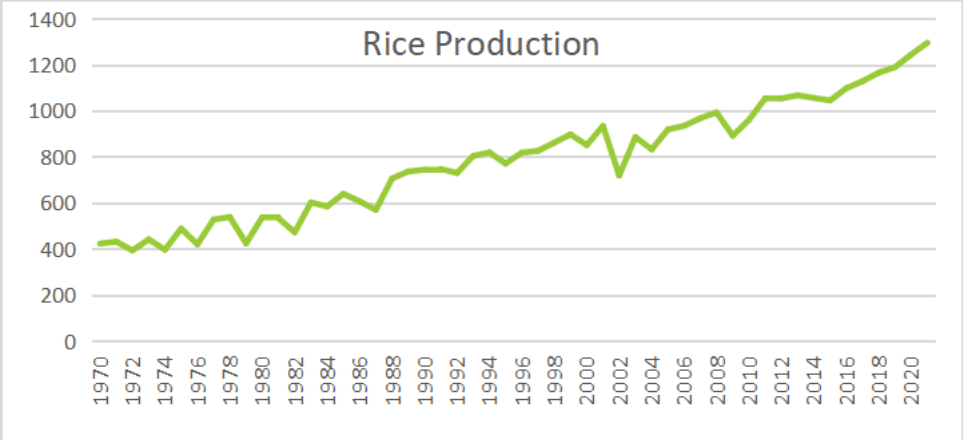

Fig 1. Productivity scenario of rice production in India (Source: RBI, Handbook of Statistics on Indian Economy)

This period might be attributed to advancements in agricultural technologies and practices. However, the production plateaued and even slightly declined in the early 2000s, possibly due to various factors such as changes in agricultural policies, market conditions, or environmental challenges. Notably, there was a substantial fluctuation in production around 2001, followed by a steady increase until 2007, reaching 966.9 units. The years following 2007 saw a relatively stable production trend until 2016. From 2016 to 2021, there was a consistent increase in production, with each year surpassing the previous one. This upward trend in recent years could be indicative of various factors such as technological innovations, increased investment in agriculture, improved irrigation methods, or favourable weather conditions. Overall, the data suggests a pattern of fluctuations and periods of growth in rice production over the past five decades, reflecting the complex interplay of various socio-economic, environmental, and technological factors. Further research into the specific drivers of these trends could provide valuable insights for policymakers, agricultural practitioners, and researchers aiming to ensure food security and sustainability in the future.

Literature review

Climate change has become a major concern for researchers across the globe, motivating extensive efforts to protect agricultural production through improved management practices, technological interventions, and policy support. A growing body of literature suggests that the effects of climate

change extend beyond rising temperatures to include significant adverse impacts on agricultural productivity and crop quality. Among all economic sectors, agriculture is particularly vulnerable to climate change because of its strong dependence on weather conditions and its direct link to rural livelihoods and food security (Kumar et al 2023). Even small variations in temperature and rainfall can lead to substantial fluctuations in crop yields, thereby threatening farm incomes and national food systems.

Several studies have highlighted the role of both climatic and non-climatic factors in shaping rice production trends. Nirmala Bandhula (2017) reported a marked increase in rice production between 2004 and 2013, largely driven by expansion of cultivated area and increased agricultural investments. Similarly, Kaul and Ram (2008) observed that nearly 28 percent of the variability in rice field conditions could be explained by factors such as fertilizer application and temperature. Fertilizer use, in particular, has played a crucial role in sustaining growth in rice production since the Green Revolution, as emphasized by Singh (2017). These findings underline the importance of technological inputs in offsetting some of the negative effects of climatic stress.

At the same time, empirical evidence increasingly points to the detrimental impacts of climate-related variables on rice productivity. Kabir et al (2021), using a Cobb–Douglas production function and the ARDL approach, examined the relationship between climate change indicators and rice production in the Humania province of the Netherlands during 1989–2018. Their results revealed strong long-run relationships among the variables, showing that a one percent rise in CO_2 emissions reduced rice yield by 1.3 percent, while a one-degree Celsius increase in temperature led to a 1.6 percent decline in productivity. Conversely, a one-millimetre increase in rainfall contributed to a 0.8 percent rise in rice output. Dubash (2013) similarly concluded that agricultural crops are highly sensitive to climatic variations, reinforcing concerns about future food security.

Studies focusing on Asia and India further demonstrate the severity of climate impacts on rice cultivation. Lin and Xu (2017) assessed the effects of elevated atmospheric CO_2 and rising temperatures on rice productivity across Asia and found an average global decline of about 4 percent in rice production, with colder regions experiencing more pronounced losses. In the Indian context, several researchers have examined climate–rice linkages and consistently reported negative yield responses to increasing temperatures (Auffhammer et al 2012; Gupta and Mishra 2019; Palanisami et al 2019). Elahi et al (2020), employing a Cobb–Douglas framework, showed that increases in minimum and average temperatures significantly reduced yields of rice, wheat, and maize in India.

Cross-country evidence also supports these findings. Chandio et al (2021) analyzed major Asian rice-producing countries over the period 1961–2016 using panel cointegration and DOLS techniques. Their study confirmed that climatic factors such as CO_2 emissions and temperature adversely affect

rice production, while precipitation and non-climatic factors—cultivated area, fertilizer use, and rural labor—positively contribute to output. Similarly, Gorst et al. (2018) reported yield reductions of 11 percent in rain-fed and 7 percent in irrigated rice areas of Bangladesh due to climatic stress. Zaied and Cheikh (2015) found that cereal yields declined by 2.9 percent for every 1°C rise in temperature, but increased with higher rainfall in Tunisia.

Overall, the literature strongly suggests that while climate change poses serious risks to rice production, the adoption of innovative technologies and adaptive strategies can help mitigate its adverse effects and sustain agricultural productivity (Kalra et al 2007).

Methodology

The present research employed yearly time series data from 1970 to 2021, with the studied variables including rice crop, area under rice production, CO2 emissions, average rainfall, fertilizer usage. Data for rice production and area under production was extracted from RBI handbook of statistics (2023), while the data for fertilizer usage was collected from Fertilizer Association of India. CO2 emission data was gathered from Statista, while rainfall data was obtained from the India Environment Portal.

$$\log(RP)=\beta 0+\beta 1\log(F)+\beta 2\log(A)+\beta 3\log(C)+\beta 4\log(R)+\epsilon$$

- RP represents the logarithm of rice production.
- F, A, C, and R denote the logarithms of the independent variables (fertilizers, area under production, CO2 emission, and rainfall respectively).
- $\beta 0$ is the intercept term.
- $\beta 1$, $\beta 2$, $\beta 3$, and $\beta 4$ are the coefficients associated with each independent variable, representing their respective effects on the dependent variable.
- ϵ is the error term.

Cointegration and causality tests: The purpose of this research is twofold: first, to assess the long- and short-term relationships between the variables; and second, to assess the nature of the underlying causal relationships between them. The study is analysed in three stages: (1) the use of unit root tests; (2) testing for cointegration among the variables; and (3) observing the nature of the underlying causal relationships.

Unit Root Test : The primary purpose of doing the unit root test is to assess the stationarity of the data. Stationarity refers to a property of data whereby the mean, variance, and covariance stay constant across time. In order to assess the stationarity of the variables, the Augmented Dickey-Fuller Test (1979) is used.

ECM: The Error Correction Model (ECM) is a model used to examine the long-run relationship between variables and the short-run dynamics of adjustment toward that long-run equilibrium. Gonzalo and Pitarakis, suggested the Error Correction Model/ECM) must be a valid model of the co integrated variables, so it must have a negative coefficient and statistically significant.

ARDL Model

Pesaran (1997) introduced the Autoregressive Distributed Lag (ARDL) model as an alternative to previous methods of cointegration analysis like the Engle and Granger (EG) procedure (Engle and Granger, 1987) and Johansen and Juselius' maximum likelihood-based test (Johansen and Juselius, 1990), highlighting several advantages it offers.Based on the stationary test by Augmented Dickey-Fuller test, in Table 1, there is one variable that are stationary at the level, and others are at first difference.

Due to the different level of stationary, the Auto Regressive Distributed Lag (ARDL) model is used in this analysis.

In interpreting the findings, we find that all variables, including rice output, fertilisers, area under production, and CO2 emissions, exhibit significant evidence against stationarity at the level, implying the existence of unit roots in their time series data. This means that these variables are likely to display trends or other non-stationary behaviours in their original form. On the other hand, "Rainfall" stands out since it only shows evidence of a unit root at the level, not after differencing.

Table 1 Augmented Dickey-Fuller Unit Root Test Analysis

Variables	Augmented Dickey-Fuller Unit Root Test	
		At Level and First Difference
Rice Production	T stat	-13.93 (I1)
	Prob value	0.00
Fertilisers	T stat	-5.64(I1)
	Prob value	0.00
Area under Production	T stat	-11.57(I1)
	Prob value	0.00
CO2 Emission	T stat	-7.33(I1)
	Prob value	0.00
Rainfall	T stat	-5.94(I0)
	Prob value	0.00

The subsequent phases of the Autoregressive Distributed Lag (ARDL) model include the optimum lag test, co-integration test, diagnostic testing, and stability assessment of the model.

Specification of the model

The fundamental framework for estimating Rice Production may be expressed as follows.

$$RP_t = \beta_t + \beta_t F_t + \beta_t A_t + \beta C_t + R_t + \mu_t \quad (1)$$

From the estimation equation above, the long-term equation (2) and short-term equation (3) in this study can be written as follows:

$$LnRPt = \beta 0 + \beta\ 1LnRP_{t-2} + \beta 2LnF_{t-2} + \beta 3LnA_{t-2} + \beta 4LnC_{t-2} + \beta 5LnR_{t-2} + \varepsilon t \quad (2)$$

While the short-term effect is written as:

$$\Delta LnRPt = \beta 0 + \sum \theta\ \rho i{=}0\ 1i\Delta LnRP_{t-2} + \sum \theta\ \rho i{=}0\ 2i\Delta F_{t-2} + \sum \theta\ \rho i{=}0\ 3i\Delta A_{t-2} + \sum \theta\ \rho i{=}0\ 4i\Delta LnC_{t-2} + \sum \theta\ \rho i{=}0\ 2i\Delta LnR_{t-2} + \varepsilon t \quad (3)$$

Granger Causality Test

The Granger Causality test was employed in this study to assess the causal relationship between variables. The Granger Causality test is a statistical tool that investigates the link between time series data. When p-values surpass 0.05, the null hypothesis cannot be rejected. This suggests that there is no substantial Granger causal relationship between the variables under consideration, and the opposite is also true. If the p-value is less than 0.05, this is sufficient evidence to reject the null hypothesis. This means that the variables in issue have a Granger causal connection, which holds in both directions. The Granger Causality equations are given below:

$$RP_t = \delta_0 + \sum_{i=1}^{k} \delta_1 RP_{t-1} + \sum_{j=1}^{k} \gamma_j X_{t-j} + \varepsilon_1$$

$$X_t = \beta_0 + \sum_{i=1}^{k} \beta_1 X_{t-1} + \sum_{j=1}^{k} \gamma_j RP_{t-1} + \varepsilon_2 t$$

Additionally, statistical tests, including Autocorrelation and Heteroskedasticity tests, are also addressed.

Results and discussion

Based on the results presented in Table 2, it's evident that the computed F-statistic (13.68581) surpasses both the upper critical threshold of 3.49 and the lower critical threshold of 2.56, both at a 5 per cent significance level. This indicates a statistically significant relationship among the variables analysed. Consequently, the null hypothesis, which suggests the absence of a long-term relationship, is rejected. Instead, the alternative hypothesis, proposing the existence of a long-term cointegration relationship between the factors under study, is supported.

Table 2: Applying the ARDL model to check for a level link between factors.

Number of Regressor	K=4
Computed F-statistics	13.68581
5% critical value	
Upper bound value	3.49
Lower bound value	2.56

Rainfall: The coefficient of 0.189704 signifies that a one-unit rise in rainfall corresponds to a 0.189704 unit increase in the natural logarithm of rice production, assuming other factors remain constant. The probability value of 0.0028 indicates statistical significance at the conventional level of 0.05, highlighting the significant impact of rainfall on rice production.

CO2: The coefficient of 0.221105 indicates that a one-unit increase in CO2 levels leads to a 0.221105 unit rise in the natural logarithm of rice production, all else equal. With a probability value of 0.00,

this relationship is highly statistically significant, demonstrating a strong association between CO2 levels and rice production.

Fertilizers: A coefficient of 0.129185 suggests that a one-unit increase in fertilizer usage results in a 0.129185 unit increase in the natural logarithm of rice production, holding other variables steady. The probability value of 0.0014 signifies statistical significance, indicating the substantial impact of fertilizer application on rice production.

Area Under Production: The coefficient of 1.077948 implies that a one-unit growth in the area under rice cultivation corresponds to a significant 1.077948 unit increase in the natural logarithm of rice production, with other factors unchanged. A probability value of 0.0005 underscores high statistical significance, underscoring the crucial role of production area in determining rice output.

Table 3: Estimated Long-Run Coefficients

Dependent Variable: lnRice Production		
Variable	Coefficient	Prob
Rainfall	0.189704	0.0028
CO2	0.221105	0.00
Fertilizers	0.129185	0.0014
Area Under Production	1.077948	0.0005

Error Correction Model:

Table 4, presents the estimated lagged error correction term ECM (-1)/ECt-1, which is found to be -1.14017. This coefficient is deemed highly significant at a 5per cent level of significance, as shown by its probability value of 0.0000.

CointEq(-1) is negative and P value is less than 0.05 which means there is presence of long run causality.

Here the speed of Adjustment is -1.14017*100=114.017 per cent.

Table 4

ECM Regression		
	Coefficient	Prob
CointEq(-1)*	-1.14017	0.00

The Granger Causality Test, Table 5, a fundamental tool in econometric analysis, provides essential insights into the complex relationships influencing rice production. This test assesses whether past values of one variable can predict future changes in another, offering a structured approach to uncover causal links in Rice agricultural systems. In analysis, which explores the interactions among CO2 emissions, fertilizer use, rainfall patterns, agricultural land area, and rice production, the test reveals detailed findings that enhance understanding of Rice agricultural efficiency and environmental sustainability. Notably, the significant F-statistic and low p-value for CO2 emissions in relation to rice production suggest a clear causal connection, emphasizing the impact of atmospheric carbon dioxide

levels on crop yields, potentially through processes like photosynthesis and climate dynamics. Conversely, the absence of significant causality from rice production to CO2 emissions implies that agricultural practices have limited influence on carbon emissions. Similarly, the non-significant outcomes for fertilizer use and rainfall patterns highlight the multifaceted nature of agricultural productivity, where various factors beyond these inputs affect crop yields significantly.

Table 5 Results of the Granger Causality Test

Null Hypothesis	F statistic	P-values	Direction of Causality
CO2 and Rice Production			
CO2 does cause Rice Production	4.35	0.018	YES
Rice Production does not cause CO2	0.44	0.643	NO
Fertilizer and Rice Production			
Fertilizer does not cause Rice Production	2.73	0.075	NO
Rice Production does not cause Fertilizer	2.90	0.065	NO
Rainfall and Rice Production			
Rainfall does not cause Rice Production	0.163	0.849	NO
Rice Production does not Rainfall	1.572	0.218	NO
Area and Rice Production			
Area of Production does cause not Rice Production	2.16	0.126	NO
Rice Production does cause Area of Production	3.22	0.049	YES

CO2 is an essential component in photosynthesis, which involves plants converting carbon dioxide into energy (in the form of carbohydrates) using sunlight (Zheng et al 2019). Elevated CO2 levels may boost photosynthesis, resulting in higher agricultural yields. This research emphasises the influence of atmospheric CO2 on rice production. Furthermore, CO2 emissions are connected to climate dynamics, which influence temperature, precipitation patterns, and general environmental conditions (Hille 2016). These elements have a direct impact on crop growth.Improper management of chemical fertilizers can lead to low fertilizer use efficiency, N leaching, and volatilization, impacting their effectiveness in enhancing rice yield. This highlights the importance of appropriate fertilizer management practices to optimize their impact on crop production (Hindrshah et al 2022). Climate change poses challenges to agricultural productivity, with temperature increases and irregular rainfall patterns affecting crop growth. These changes can lead to decreased yields in major rice-producing countries like China, India, Indonesia, and Bangladesh (Joseph et al 2022).Variations in rice production can influence farmers' decisions regarding how much land they dedicate to rice crops. When rice production increases, farmers may expand the cultivated area to meet the demand. Conversely, during periods of low rice production, farmers might reduce the area under cultivation.

In Table 6, for autocorrelation, as assessed through the Breusch-Godfrey LM test, the computed p-value is 0.696. This indicates that there is no statistically significant evidence to reject the null hypothesis of no autocorrelation in the residuals at conventional significance levels (0.05). Therefore, based on this test result, it can be inferred that autocorrelation is not present in the residuals of the model.

Similarly, for heteroskedasticity, as evaluated using the Breusch Pagan test, the associated p-value is 0.253. Like autocorrelation, this p-value exceeds common significance levels, suggesting that there is no significant evidence to reject the null hypothesis of homoskedasticity in the residuals. Hence, it can be concluded that there is no significant heteroskedasticity in the model's residuals based on this test result.

Table 6 Diagnostic Test Results

Examination	p-value
Autocorrelation (Breusch-Godfrey LM test)	0.696
Heteroskedacity (Breusch Pagan test)	0.253

In Figure 2, to ensure that the results are stable, CUSUM tests used for the level of stability, which were initially proposed by Brawn et al. (1975). If the displayed points in Figure 1 for the CUSUM statistics remain within the critical bounds of a 5per cent level of significance, the null hypotheses for all coefficients in the supplied regression are stable and cannot be rejected.

Figure 2, illustrates that CUSUM statistics remain within the crucial range of the 5per cent significance threshold. This indicates that all of the components in the ARDL error-correcting model are stable.

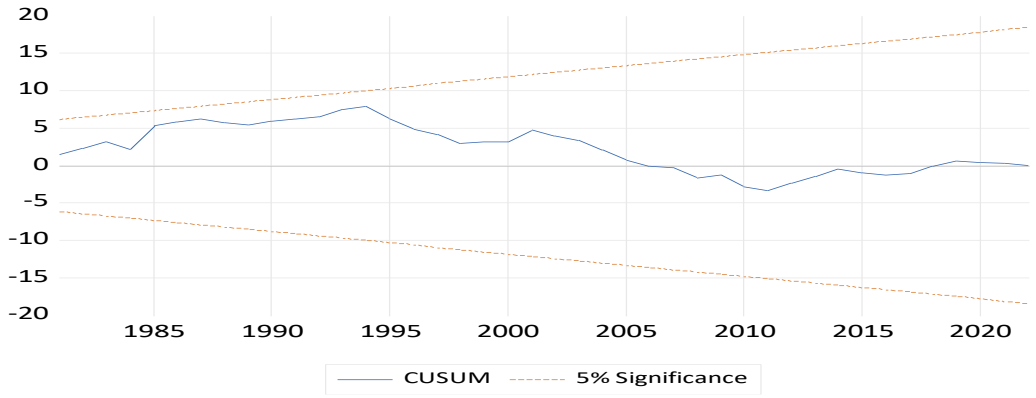

Figure 2: CUSUM test

Government's Key Role:

Enhancing rice productivity under changing climatic conditions requires a coherent and integrated policy approach that combines technological, environmental, and institutional interventions.

Advancing climate-resilient agricultural methods is a critical first step, particularly through the promotion of climate-smart practices that account for the influence of atmospheric CO_2 on photosynthesis and crop growth. Policies should encourage sustainable farming techniques that optimize CO_2 utilization to improve yields while simultaneously reducing the environmental costs associated with excessive emissions. Equally important is the regulation of fertilizer management. Establishing clear guidelines for the efficient and judicious use of chemical fertilizers can improve nutrient-use efficiency and minimize environmental problems such as nitrogen leaching and volatilization. Greater emphasis on organic fertilizers and integrated nutrient management can further enhance rice productivity in a sustainable manner.

In parallel, robust adaptation strategies are needed to address climate-induced stresses such as rising temperatures and erratic rainfall. Policy frameworks must focus on supporting farmers in major rice-producing regions of India by providing location-specific solutions that help them cope with climatic variability. Promoting incentives for sustainable land-use practices can also improve production efficiency by enabling farmers to adjust cultivation areas in response to changing productivity levels. Finally, strengthening capacity-building and training initiatives is essential. Investments in farmer education, technical assistance, and knowledge transfer will enhance adaptive skills, improve resource-use efficiency, and ensure long-term sustainability of rice-based farming systems.

Conclusion and policy recommendations

This empirical investigation analyses time-series data spanning the period from 1970 to 2021 to examine the key determinants of rice production in India. Using rigorous econometric techniques, including cointegration analysis, Granger causality tests, and a range of diagnostic assessments, the study yields several important insights. The results confirm the existence of long-run relationships between rice production and major explanatory variables such as fertilizer consumption, area under cultivation, CO_2 emissions, and rainfall. These findings highlight the complex and interdependent nature of agricultural systems, in which both environmental conditions and socio-economic factors jointly influence productivity. They also emphasize the need for sustainable agricultural practices, efficient resource utilization, and climate-resilient strategies to sustain rice production under changing climatic conditions.

The Granger causality analysis further elucidates the dynamic interactions among the variables. The results indicate that CO_2 emissions exert a significant causal influence on rice production, underscoring the critical role of climate-related factors in determining crop yields. In addition, a unidirectional causal relationship from rice production to agricultural land area suggests that land-use decisions are shaped by production outcomes, market signals, and policy interventions rather than acting solely as exogenous drivers.

Diagnostic tests confirm the robustness and reliability of the estimated model. Tests for autocorrelation and heteroskedasticity are statistically insignificant, indicating the absence of specification errors, while CUSUM tests validate the stability of model coefficients over time. Based on these findings, the study underscores the urgent need for government and policymakers to strengthen awareness and implementation of climate change adaptation measures. Given rice's central role as a staple food in India, protecting its productivity is essential to meet the demands of a growing population. Furthermore, rising CO_2 emissions are intensifying environmental stress, making it imperative to adopt mitigation measures such as reducing deforestation, limiting agricultural residue burning, and promoting organic and sustainable farming practices over the long term.

Limitations and suggestions for future research

While the study provides valuable insights into the complex interplay of factors influencing rice production, it is important to acknowledge several limitations and opportunities for future research.In future research, the influence of temperature on rice crop, labour, water availability, use of machinery could be considered for the study. Furthermore, exploring the role of emerging technologies and conducting longitudinal studies to track temporal trends could offer invaluable insights. By embracing these avenues for further inquiry, researchers can contribute significantly to enhancing agricultural sustainability and resilience in the face of evolving environmental and societal challenges, ultimately ensuring food security and prosperity for generations to come.

Data declaration

The study uses data from reliable and authoritative sources to ensure accuracy and credibility. Information on rice production and the area under rice cultivation is taken from the RBI Handbook of Statistics on the Indian Economy. Data on carbon dioxide (CO_2) emissions are sourced from Statista, a widely recognized global statistics platform. Rainfall data are obtained from the India Environment Portal, which provides comprehensive environmental information for India. Fertilizer consumption data are collected from the Fertilizer Association of India, an official body maintaining national fertilizer statistics. Together, these datasets provide a robust foundation for analyzing the determinants of rice production in India.

Conflict of Interest Declaration

The authors declare no conflicts of interest related to this study. There are no financial, personal, professional, or funding-related influences affecting the research. The study adheres to high standards of transparency, integrity, and objectivity, and the authors affirm the accuracy, reliability, and validity of the data and conclusions presented.

References

Adams R M (1989). Global climate change and agriculture: an economic perspective. American journal of agricultural economics, 71(5), 1272-1279.

Aggarwal P K & Mall R K (2002). Climate change and rice yields in diverse agro-environments of India. II. Effect of uncertainties in scenarios and crop models on impact assessment. Climatic Change, 52(3), 331-343.

Auffhammer M, Ramanathan V & Vincent J R (2012). Climate change, the monsoon, and rice yield in India. Climatic change, 111, 411-424.

Bandumula N (2018). Rice production in Asia: Key to global food security. Proceedings of the National Academy of Sciences, India Section B: Biological Sciences, 88, 1323-1328.

Ben Zaied Y & Ben Cheikh N (2015). Long-run versus short-run analysis of climate change impacts on agricultural crops. Environmental Modeling& Assessment, 20, 259-271.

Bouman B A M, Barker R, Humphreys E, Tuong T P, Atlin G, Bennett J, Dawe D, Dittert K, Dobermann A, Facon T, Fujimoto N, Gupta R, Haefele S, Hosen Y, Ismail A, Johnson D, Johnson S, Khan S, Shan L, . . . Wassman R (2007). Rice: feeding the billions. AgEcon Search. https://doi.org/10.22004/ag.econ.157924.

Chandio A A, Jiang Y, Ahmad F, Adhikari S & Ain Q U (2021). Assessing the impacts of climatic and technological factors on rice production: Empirical evidence from Nepal. Technology in Society, 66, 101607.

Chang T T & Luh B S (1991). Overview and prospects of rice production. In Rice: Volume I. Production/Volume II. Utilization (pp. 1-11). Boston, MA: Springer US.

Dawe D, Pandey S & Nelson A (2010). Emerging trends and spatial patterns of rice production. Rice in the global economy: strategic research and policy issues for food security. Los Banos, Philippines: International Rice Research Institute (IRRI).

Dubash N K (2013). The politics of climate change in India: narratives of equity and cobenefits. Wiley Interdisciplinary Reviews: Climate Change, 4(3), 191-201.

Elahi E, Khalid Z, Weijun C & Zhang H (2020). The public policy of agricultural land allotment to agrarians and its impact on crop productivity in Punjab province of Pakistan. Land Use Policy, 90, 104324.

Fahad S, Adnan M, Noor M, Arif M, Alam M, Khan I A, ... & Wang D (2019). Major constraints for global rice production. In Advances in rice research for abiotic stress tolerance (pp. 1-22). Woodhead Publishing.

Gorst A, Dehlavi A & Groom B (2018). Crop productivity and adaptation to climate change in Pakistan. Environment and development economics, 23(6), 679-701.

Gupta, R., & Mishra, A. (2019). Climate change induced impact and uncertainty of rice yield of agro-ecological zones of India. Agricultural Systems, 173, 1-11.

Hille K B (2023, July 26). NASA Study: Rising Carbon Dioxide Levels Will Help and Hurt Crops - NASA. NASA.

Hindersah R, Kalay,A M &Talahaturuson A (2022, January 1). Rice yield grown in different fertilizer combination and planting methods: Case study in Buru Island, Indonesia. Open Agriculture.

Johansen S, Juselius K (1990) Maximum likelihood estimation and inference on cointegration—with applications to the demand for money. Oxford Bull Econ Stat 52(2):169–210

Joseph M, Moonsammy S, Davis H, Warner D, Adams A & Timothy Oyedotun T D (2023, April). Modelling climate variabilities and global rice production: A panel regression and time series analysis. Heliyon, 9(4), e15480.

Kabir A, Amin M N, Roy K & Hossain M S (2021). Determinants of climate change adaptation strategies in the coastal zone of Bangladesh: implications for adaptation to climate change in developing countries. Mitigation and Adaptation Strategies for Global Change, 26(7), 30.

Kalra N, Chander S, Pathak H, Aggarwal P K, Gupta N C Sehgal M & Chakraborty D (2007). Impacts of climate change on agriculture. Outlook on AGRICULTURE, 36(2), 109-118.

Kraehmer H, Thomas C &Vidotto F (2017). Rice production in Europe. Rice production worldwide, 93-116.

Kumar P, Sahu N C, Ansari M A & Kumar S (2023). Climate change and rice production in India: role of ecological and carbon footprint. Journal of Agribusiness in Developing and Emerging Economies, 13(2), 260-278.

Liddle B (2013). Population, affluence, and environmental impact across development: evidence from panel cointegration modeling. Environmental modelling & software, 40, 255-266.

Lin B, & Xu B (2017). Which provinces should pay more attention to CO2 emissions? Using the quantile regression to investigate China's manufacturing industry. Journal of Cleaner Production, 164, 980-993.

Mahajan G, Kumar V & Chauhan B . (2017). Rice production in India. Rice production worldwide, 53-91.

Mall R K & Aggarwal P K (2002). Climate change and rice yields in diverse agro-environments of India. I. Evaluation of impact assessment models. Climatic Change, 52, 315-330.

Mulla S, Ahmed R, Singh K K, Singh S K, Deshmukh N & Inamdar F K (2023). Climate Change Effect On-Climate Parameters Like Temperature, Rainfall and Water Resources Sectors in India. In Climate Change Impacts in India (pp. 9-59). Cham: Springer International Publishing.

Palanisami K, Kakumanu K R, Nagothu U S & Ranganathan C (2019). Climate Change and future rice production in India. Springer.

Pattanayak A & Kumar K K (2014). Weather sensitivity of rice yield: evidence from India. Climate Change Economics, 5(04), 1450011.

Prasad R, Shivay Y S & Kumar D (2017). Current status, challenges, and opportunities in rice production. Rice production worldwide, 1-32.

Rao A N, Wani S P, Ramesha M S & Ladha J K (2017). Rice production systems. Rice production worldwide, 185-205.

Ravindra K, Bhardwaj S, Ram C, Goyal A, Singh V, Venkataraman C, ... & Mor S (2024). Temperature projections and heatwave attribution scenarios over India: A systematic review. Heliyon, 10(4).

Samal P, Pandey S, Kumar G & Barah B C (2011, September 1). Rice Ecosystems and Factors Affecting Varietal Adoption in Rainfed Coastal Orissa: A Multivariate Probit Analysis. https://doi.org/10.22004/ag.econ.109515.

Saravanakumar V, Lohano H D & Balasubramanian R (2022). A district-level analysis for measuring the effects of climate change on production of rice: evidence from Southern India. Theoretical and Applied Climatology, 150(3), 941-953.

Saseendran S A, Singh K K, Rathore L S, Singh S V & Sinha S K (2000). Effects of climate change on rice production in the tropical humid climate of Kerala, India. Climatic Change, 44, 495-514.

Singh K, McClean C J, Büker P, Hartley S E & Hill J K (2017). Mapping regional risks from climate change for rainfed rice cultivation in India. Agricultural systems, 156, 76-84.

Singh V K (2017). Fertilizer management in rice. Rice production worldwide, 217-253.

Soora N K. Aggarwal P K, Saxena R, Rani S, Jain S & Chauhan N (2013). An assessment of regional vulnerability of rice to climate change in India. Climatic change, 118, 683-699.

Thiry A, Davies W J & Dodd I C (2023, January 1). Isolating higher yielding and more stable rice genotypes in stress environments: fine-tuning a selection method using production and resilience score indices. Frontiers of Agricultural Science and Engineering.

Van Nguyen, N & Ferrero A (2006). Meeting the challenges of global rice production. Paddy and Water Environment, 4, 1-9.

Vyankatrao N P (2017). Impact of climate change on agricultural production in India: effect on rice productivity. BiosciDiscov, 8(4), 897-914.

Wang B X, Hof A R & Ma C (2022, January 1). IMPACTS OF CLIMATE CHANGE ON CROP PRODUCTION, PESTS AND PATHOGENS OF WHEAT AND RICE. Frontiers of Agricultural Science and Engineering. https://doi.org/10.15302/j-fase-2021432.

Wassmann,R, Jagadish S V K, Heuer S, Ismail A, Redona E, Serraj R, ... &Sumfleth K (2009). Climate change affecting rice production: the physiological and agronomic basis for possible adaptation strategies. Advances in agronomy, 101, 59-122.

Yang J (2015, January 1). Approaches to achieve high grain yield and high resource use efficiency in rice. Frontiers of Agricultural Science and Engineering. https://doi.org/10.15302/j-fase-2015055.

Zheng Y, Li F, Hao L, Yu J, Guo L, Zhou H, Ma C, Zhang X, & Xu M (2019, June 13). Elevated CO2 concentration induces photosynthetic down-regulation with changes in leaf structure, non-structural carbohydrates and nitrogen content of soybean. BMC Plant Biology.