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Climate Change, Greenhouse Gas Emissions, and Agricultural Productivity in Pakistan: Evidence from an ARDL-ECM Framework (1980-2024)

Dr. Qurra-tul-ain Ali Sheikh*
Associate Professor and Head of Economics Department, Government Girls Degree College, Nawabshah (Sindh), Pakistan. Email: anne3_libra@yahoo.com
ORCID ID**:** https://orcid.org/0000-0001-9268-5411

Prof. Dr. Bashir Ahmad
Professor and Dean Management and Social Sciences, Al-Kawthar University, Pakistan
E-mail: dr.bashirahmad@alkawthar.edu.pk
ORCiD: https://orcid.org/0000-0003-2843-7506

Dr. Muhammad Meraj
Associate Professor and Head of Department (Humanities and Social Sciences), Al-Kawthar University, Pakistan Email: Muhammad.meraj@Alkawthar.edu.pk

Altaf Hussain Solangi
MSEF, Mohammad Ali Jinnah University, Karachi, Pakistan
Email: hossainyaltaf@gmail.com

ABSTRACT

This study examines the nexus between agricultural productivity and agricultural greenhouse gas emissions in Pakistan from 1980 to 2024. This paper investigates the short and long-run effects of methane (CH4) and nitrous oxide (N2O) on agricultural gross domestic product (AGDP) using the Autoregressive Distributed Lag (ARDL) bounds testing approach. Variables controlled for in the model include rainfall, temperature, fertilizer use, and irrigated land. The ARDL Bounds Test indicates a long-run relationship among these variables. The results demonstrate that temperature has a positive, statistically significant effect on agricultural productivity in both the short- and long-term. However, rainfall negatively affects production in the short run. The short-term effect of increased agricultural productivity is associated with nitrous oxide emissions, but methane emissions have no significant long-term effects. The large negative error-correction term supports the stability of the long-run equilibrium. The paper promotes climate-resilient agricultural policies, improved irrigation management, sustainable fertilizer practices, and effective emission-mitigation techniques to enhance agricultural output and environmental preservation in Pakistan.

Keywords: Agricultural emissions; Climate change; Methane; Nitrous oxide; ARDL; Agricultural productivity; Pakistan

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Introduction

Climate change has become one of the most significant worldwide environmental and developmental challenges of contemporary times. It indicates long-term variations in temperature and climatic patterns, primarily driven by human activities over the past few decades. The warming of the atmosphere is due to the buildup of greenhouse gases (GHGs), for instance, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which trap heat in the atmosphere and contribute to global warming. According to the Intergovernmental Panel on Climate Change (IPCC, 2022), the major contributors to the observed climate change are the anthropogenic emissions from fossil fuel combustion, industrial operations, agriculture, and land-use change.

The increase in GHGs has led to substantial perturbations in the global climate system, including rising average temperatures, altered rainfall patterns, and more frequent and intense extreme weather events. These changes have increased climate variability, leading to more frequent floods, droughts, and heat waves, and putting both ecosystems and human lives at risk. IPCC (2022) indicates that continued warming will likely increase the severity of climate extremes, further impacting food systems and water supplies. The climate-smart agricultural literature highlights the increasing vulnerability of the global food system to climatic stressors, which must be urgently addressed through adaptation and mitigation (Lou et al., 2024).

Agriculture is in a double bind worldwide: it is both a victim of climate change and a major contributor to it. Agricultural activities, such as rice growing, animal husbandry, fertilizer use, and soil management, are major sources of methane and nitrous oxide emissions. Rice farming has been reported as a substantial source of CH_4 emissions through anaerobic decomposition in flooded regions (Wang et al., 2023). The N_2O has a high global warming potential, and nitrogen fertilizers are the major source (Jia et al., 2023). Conversely, mitigation techniques such as biochar application and enhanced nutrient management have shown promise in reducing GHG emissions while supporting productivity (Jeffery et al., 2016). The relationships are complicated, with trade-offs and collaborations between carbon reductions and additional yields.

The consequences of climate change are not evenly distributed, with the greatest risk concentrated in emerging and climate-vulnerable countries. Although Pakistan produces less than 1% of the world's GHG emissions (Abubakar, 2020), it is one of the countries most affected by climate change. Geographical considerations, reliance on agriculture, and low adaptive capacity further make it highly vulnerable. The country experiences several climatic dangers, including glacial lake outburst floods (GLOFs), droughts, and irregular monsoon precipitation (Baigal, 2016). "There has been an increase in the unpredictability of rainfall and rising temperatures, adding to the climate concerns in various regions," says the Pakistan Meteorological Department (2022).

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The 2022 floods in Pakistan, affecting over 33 million people and killing thousands of people, as well as causing billions of dollars in economic damages, notably underscored the depth of climatic repercussions in the country. Such catastrophes were the result of extraordinary monsoon rainfall and glacial melting, which are signs of more severe global climate change (Germanwatch, 2025). Such tragedies highlight the vulnerability of Pakistan's population and economy to climate-related shocks and the need for climate-resilient and adaptation strategies.

Agriculture is the backbone of Pakistan's economy and a key driver of GDP, employment, and rural life. It is, however, quite vulnerable to climate swings. Changes in temperature and precipitation directly affect water availability, which in turn affects agricultural production and cattle productivity. Empirical literature indicates that climatic variability has already affected agricultural productivity across several agro-ecological zones of Pakistan (Hussain & Bangash, 2017). Agricultural operations are also a major source of environmental deterioration through emissions of CH_4 and N_2O, particularly in livestock systems, rice cultivation, and the overuse of fertilizers.

Besides environmental challenges, the Pakistani agricultural system also suffers from structural weaknesses, such as poor water management, limited adoption of technology, and climate-sensitive planting patterns. These issues have significant implications for climate change, food security, and rural livelihoods. Research indicates that ongoing changes in monsoon patterns and rising temperatures are impacting major crops, for example, wheat, rice, cotton, and maize, jeopardizing the long-term viability of agriculture (Ahmad et al., 2015).

Various studies have examined climate change and agriculture, but there is a gap in empirical research on the dynamic association between agricultural methane (CH_4) and nitrous oxide (N_2O) emissions and production in Pakistan, employing long-term time-series econometric approaches. The study employs the Autoregressive Distributed Lag (ARDL) model to assess the influence of agricultural greenhouse gas emissions on agricultural output in Pakistan during the period 1980-2024. This research contributes to the field by offering insights into short and long-term interactions among components and by providing evidence-based policy recommendations for sustainable agricultural expansion and climate change mitigation in Pakistan.

Review of Literature

The links between climate change, greenhouse gas emissions, and agricultural production have been widely studied in the literature. Earlier research has found that higher greenhouse gas emissions lead to greater climate variability, which in turn affects agricultural output, food security, and rural livelihoods. Many experts have highlighted agriculture as a significant source of greenhouse gas emissions. Agriculture is projected to be responsible for around 50% of global anthropogenic CH_4 emissions and about 75% of global anthropogenic N_2O emissions (Mbow et al. 2019). Livestock, dairy, and rice production are leading sources of greenhouse gas emissions in

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agriculture (Lynch et al., 2021). Forster et al. (2021) reported that the global warming potentials of CH_4 and N_2O are much higher than those of carbon dioxide. Methane has a fairly short lifetime in the atmosphere yet contributes significantly to atmospheric warming, whereas N_2O lingers in the atmosphere for over a century and contributes to ozone depletion. At the COP26 climate summit in 2021, more than 100 countries signed up to the Global Methane Pledge to reduce human CH_4 emissions by 30% by 2030. The promise is that this is the best approach to meet the 1.5°C temperature target of the Paris Agreement, considering the short atmospheric lifetime of CH_4 (Wang et al, 2023). Gupta et al. (2021) examined CH_4 and N_2O emissions from rice fields in India and found that rice cultivation is an important source of greenhouse gas emissions from agriculture. The research showed that crop and soil management methods play a key role in emissions and proposed that better agricultural management practices can help reduce greenhouse gas emissions and alter climate change.

Barnett et al. (2014) also highlighted that developing nations are further susceptible to the impacts of climate change due to limited adaptation capacity and limited resources. Research has shown the importance of irrigation systems and water management for preserving agriculture in Pakistan. As Boone (2008) points out, water security, flood security, and irrigation infrastructure in Pakistan are particularly vulnerable to climatic fluctuations. Câmpeanu (2014) argues that irrigation systems are vital for maintaining agricultural productivity amid changing climatic conditions. Climatic zone shifts have been linked to increased food insecurity and poverty. Davidson (2018) stated that floods, droughts, glacier melting, and rising sea levels significantly impact livelihoods, agricultural output, and household income. Hughes (2020) projected that climate change will lead to rising global food insecurity and malnutrition in the coming decades. Climate change has threatened agricultural output over much of the sector. Higher atmospheric temperatures harm vegetation, wildlife, and agricultural producers. It links aridity and land degradation to depletion of water resources (Ghalib, 2017).

Current reports have increasingly emphasized the need for climate-smart agriculture and sustainable farm practices. Xiang (2022) and Ménard (2023) emphasize the need for afforestation and ecosystem restoration to enhance carbon sequestration and mitigate environmental degradation. Saran et al. (2025) assessed agricultural management practices for reducing CH_4 and N_2O emissions in low and middle-income countries. The study emphasized that there is significant scope to reduce greenhouse gas emissions and enhance agricultural productivity through better fertilizer management, livestock nutrition, manure management technologies, and rice-water management approaches. However, the authors emphasized that information on the efficacy of these interventions is scattered and not adequately aggregated across different agricultural systems and areas.

Research on the climate change implications in Pakistan indicates that the country is extremely vulnerable due to its reliance on agricultural and water resources. Awan (2017) reported that higher temperatures, floods, droughts, and water scarcity have

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increased agricultural vulnerability and threaten food security in Pakistan. Hussain & Bangash (2017) assessed the effect of key meteorological variables (Rainfall and Temperature) on agricultural productivity in four agro-ecological zones of Pakistan. Temperature and precipitation were the major factors determining agricultural productivity across all agro-climatic zones of Pakistan. Chaudhary (2017) predicted that an increase in temperature may decrease wheat output by about 6% and basmati rice yield by 15-18% across different agro-climatic zones. Haq et al. (2021) found that wheat and rice yields decreased due to changing climatic conditions and rising temperatures. Anwar et al. (2020) indicated that increasing population growth and urbanization in Pakistan could exacerbate climate-related agricultural challenges. Syed et al. (2022) report that the rainfed sector is particularly vulnerable to climate change, as a large proportion of Pakistan's population depends on rainfed agriculture. Climate change influences overall temperature and rainfall patterns and has a specific effect on the monsoon system, negatively impacting the production of main crops such as wheat, rice, cotton, sugarcane, and maize. Such climate disturbances undermine agricultural output, jeopardize farming livelihoods and agribusiness infrastructure, and exacerbate food instability and malnutrition.

There is a considerable body of literature on climate change and agricultural productivity. However, empirical studies on the direct influence of agricultural CH_4 and N_2O emissions on agricultural output in Pakistan have been limited and have used recent econometric techniques. Most earlier studies have concentrated on climate conditions or greenhouse gas emissions separately. The present study attempts to fill this gap by testing the short- and long-run links between agricultural methane and nitrous oxide emissions and agricultural productivity in Pakistan, using the ARDL approach over the period 1980-2024.

Methodology

The Autoregressive Distributed Lag (ARDL) model is used to identify both short and long-run relationships in the study.

Model Specification (Log-Linear Form)

$$\ln(AGDP_t) = \alpha + \sum_{i=0}^{p} \beta_{1i} \ln(CH4_{t-i}) + \sum_{j=0}^{q} \beta_{2j} \ln(N2O_{t-j}) + \sum_{k=0}^{r} \beta_{3k} \ln(RAIN_{t-k}) + \sum_{m=0}^{s} \beta_{4m} \ln(TEMP_{t-m}) + \sum_{n=0}^{u} \beta_{5n} \ln(FERT_{t-n}) + \sum_{o=0}^{v} \beta_{6o} \ln(IRR_{t-o}) + \varepsilon_t$$

Estimation Procedure

In this paper, we analyze the nexus between agricultural output and N_2O/CH_4 emissions

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in Pakistan by employing a robust econometric model. The stationarity of the data series is tested using the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests at the beginning. The order of integration of the variables is used to determine the optimal lag length using the Akaike Information Criterion (AIC) and the Schwarz Bayesian Criterion (BIC). Then, an Autoregressive Distributed Lag (ARDL) model is estimated to examine both short and long-run relationships among the variables. The ARDL Bounds testing approach is used to test for cointegration. Having shown the existence of cointegration, the long-run coefficients are estimated, and an Error Correction Model (ECM) is estimated to capture the short-run dynamics. Finally, several diagnostic tests are conducted to assess the model's stability, validity, and reliability.

Data and Variables

The research employs yearly time-series data to analyze the influence of agricultural methane and nitrous oxide emissions on agricultural output in Pakistan. Agricultural productivity is denoted by Agricultural Gross Domestic Product (AGDP), quantified in constant 2015 US dollars. The study includes agricultural methane emissions, nitrous oxide emissions, average annual Rainfall (RAIN), average annual temperature (TEMP), fertilizer use (FERT), and irrigated land (IRR) as explanatory variables. The study measures CH_4 and N_2O emissions in kilotons of CO_2-equivalent. The study measures Rainfall in millimetres, expresses temperature in degrees Celsius, measures fertilizer use in kilograms per hectare, and reports irrigated area as a percentage of total agricultural land. These variables are chosen to capture the cumulative impacts of agricultural emissions, climatic factors, and agricultural inputs on agricultural productivity. The study's statistics are sourced from reputable international entities, including the World Bank, FAOSTAT, the Pakistan Meteorological Department, and the Food and Agriculture Organization.

Results and Discussion

The graphical analysis provides strong primary evidence for the dynamic linkages, and the study subsequently assesses these relationships using the ARDL framework and Error Correction Mechanism. The trends collectively suggest the existence of both long-term equilibrium shifts and short-term variations in agricultural output, emissions, and climatic factors in Pakistan.

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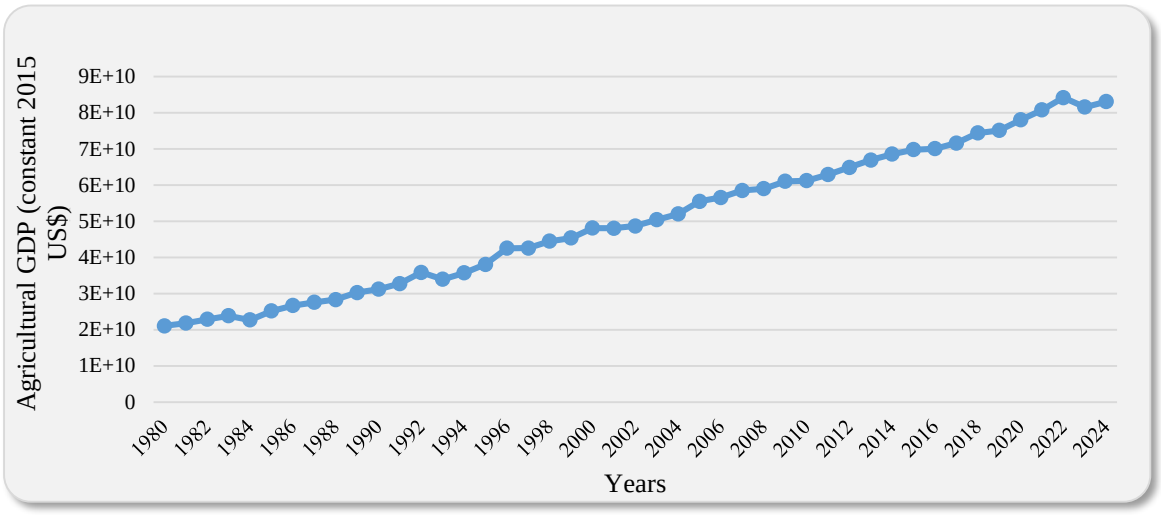
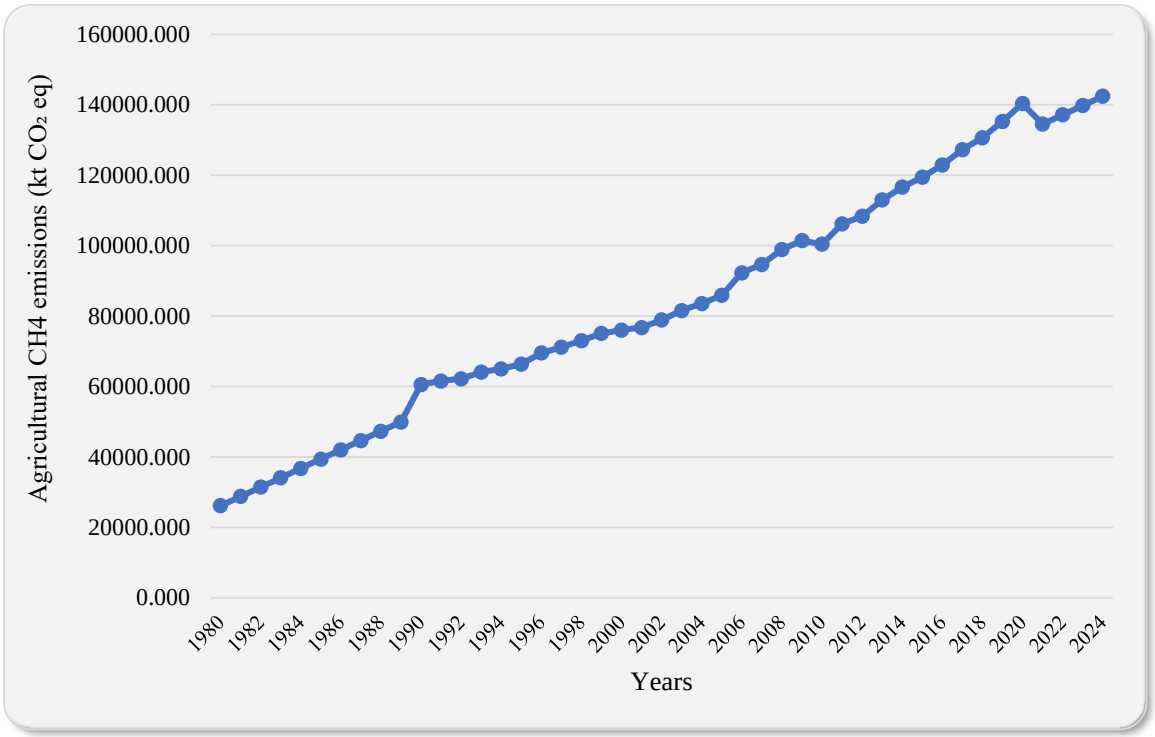


Figure 1 Trend of Agricultural GDP in Pakistan (1980-2024)

Figure 1 illustrates the upward trend in agricultural GDP, indicating a robust long-term growth trajectory for the agriculture sector. In ARDL terminology, this signifies a stable dependent variable, i.e., Agricultural GDP, demonstrating integration with macro-structural elements such as emissions, climatic conditions, and input intensification. The gradual upward trend indicates a long-term stable relationship between agricultural output and the explanatory factors, validating the application of cointegration-based ARDL modelling.



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Figure 2 Trend of Methane (CH_4) emissions from Agriculture in Pakistan (1980-2024)

Methane emissions exhibit a consistent upward trajectory, signifying that agricultural growth has been associated with escalating environmental externalities (Fig. 2). From an ECM standpoint, CH_4 serves as a long-term explanatory variable that may significantly influence agricultural GDP. The concurrent trend in GDP and methane emissions suggests a possible long-term co-movement, consistent with the cointegration assumptions of the ARDL model. The increasing trend in N_2O emissions (fig. 3) indicates greater fertilizer application and improved soil management. The rapid growth in recent years signifies structural intensification in agriculture. We expect this variable to influence long-run disequilibrium corrections in the ECM, as emissions-induced environmental degradation partially explains variations in productivity.

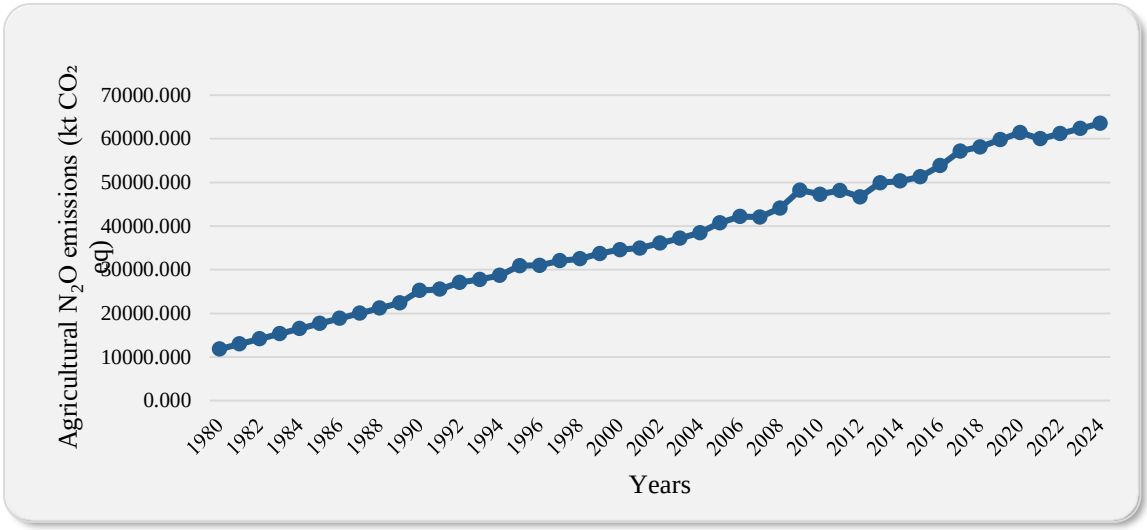


Figure 3 Trend of Nitrous Oxide (N_2O) Emissions from Agriculture (1980-2024)

Fertilizer consumption exhibits a significant upward trajectory, especially after the mid-sample period, indicating agricultural intensification (fig. 4). Within the ARDL paradigm, this variable serves as a crucial short-term catalyst that may simultaneously boost productivity and increase emissions. Their dynamic behaviour indicates both immediate favourable output effects and long-term environmental costs.

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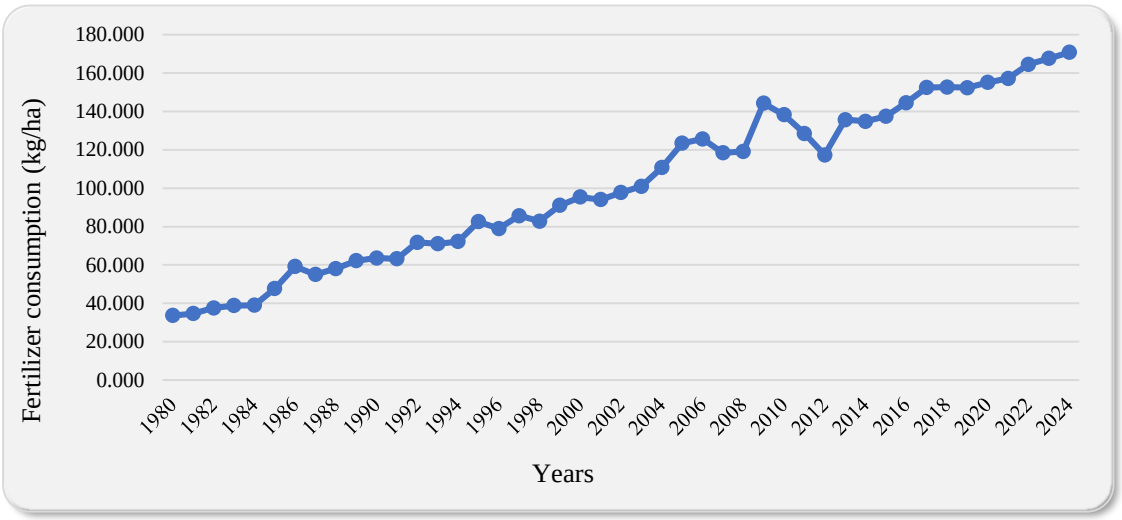


Figure 4 Trend of Fertilizer Consumption in Agriculture (1980-2024)

The gradual increase in irrigated area is indicative of the improvements in agricultural infrastructure. In the context of ECM interpretation, expansion of irrigation is a contributor to the long-term stability of production as a partial adjustment mechanism that reduces output volatility (fig. 5). However, its slow growth indicates a weak buffering capacity against climate-induced shocks.

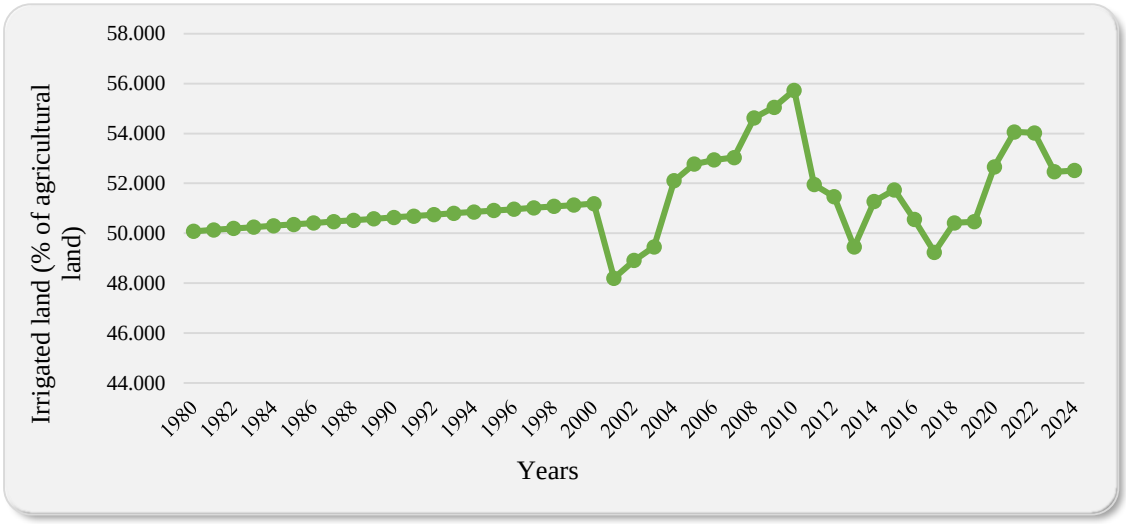


Figure 5 Trend of Irrigated Land in Pakistan (1980-2024)

Rainfall shows large variability during the research period, reflecting irregular climatic conditions (fig. 6). In ARDL-ECM models, we generally link this variability to short-run disturbances that temporarily shift agricultural GDP away from its long-run equilibrium trajectory. We expect the error-correction term to gradually correct these disturbances over time.

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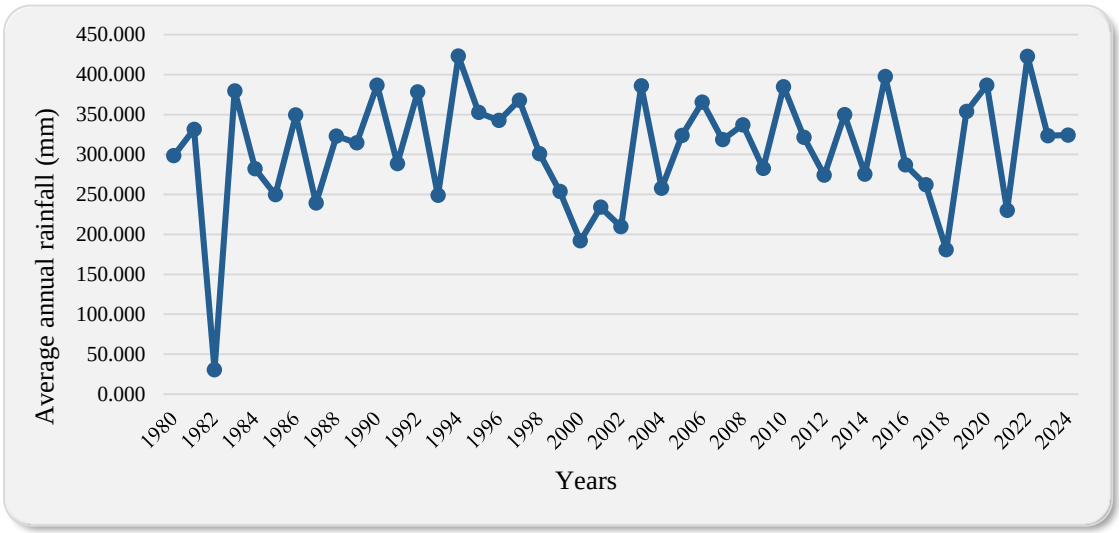


Figure 6 Rainfall Variability in Pakistan (1980-2024)

Figure 7 shows that the steady increase in temperature reflects the continued warming of the planet. Temperature is a structural exogenous variable influencing long-term agricultural productivity under the ARDL paradigm. We expect rising temperatures to have a long-term negative impact by increasing the probability of disequilibrium in the ECM specification. Figure 8 shows the long-term equilibrium relationship between agricultural GDP and methane emissions, indicating that increased methane emissions accompany agricultural economic growth. In the ECM, the short-run divergence between the two variables should be expected to return to a long-run stable path. The adjustment may be slow because of environmental trade-offs. The fact that both farming GDP and N_2O emissions are rising simultaneously indicates a strong long-term link, showing that the benefits of fertilizers in farming are tied to the environmental costs they impose. In the ECM framework, N_2O serves a dual role, helping to set the long-run equilibrium and simultaneously exerting short-run adjustment forces.

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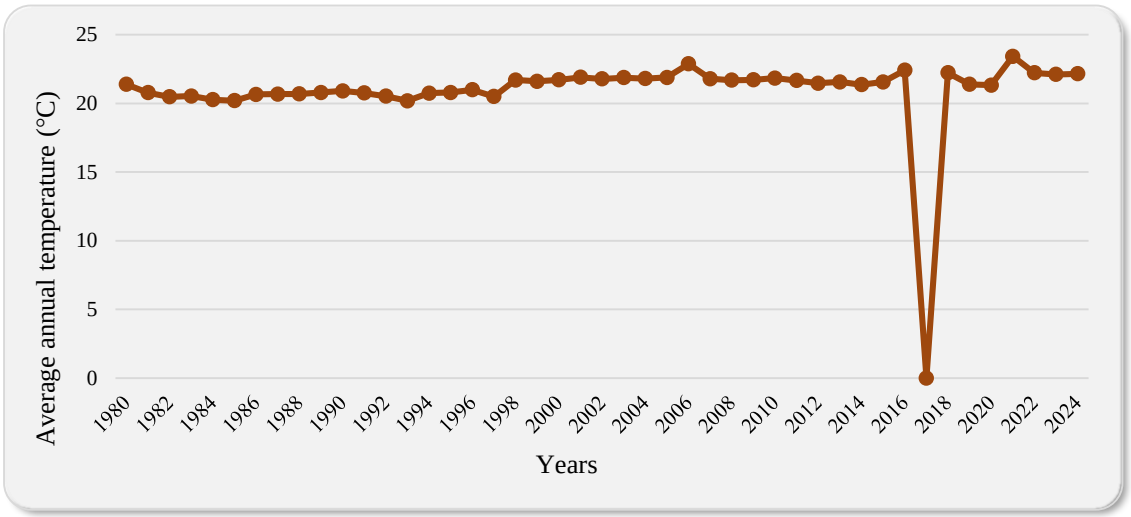


Figure 7 Temperature Trend in Pakistan (1980-2024)

The difference between sporadic Rainfall and gradually increasing temperature is a combination of short and long-term climate effects (fig. 9). Rainfall is a shock variable with a short lag. On the other hand, temperature is a long-run structural trend affecting equilibrium agricultural output.

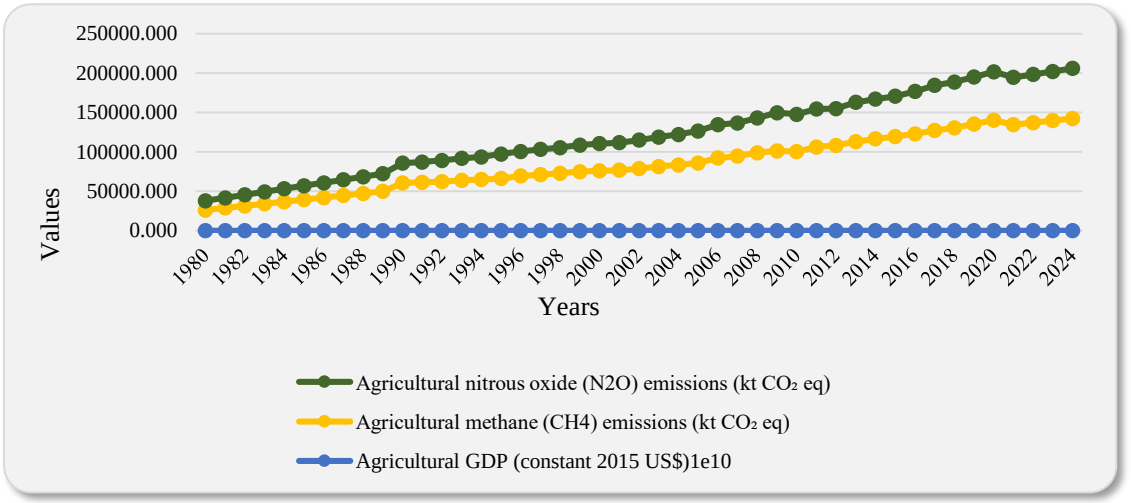


Figure 8 Relationship amongst Agricultural GDP, CH_4, and N_2O Emissions

The graphical demonstration firmly establishes the existence of a long-run equilibrium relationship among agricultural output, emissions, and climate factors, as well as short-run fluctuations driven by weather variability and input shocks, confirming the suitability of the ARDL bounds testing method for models with continuous correction of short-run deviations towards long-run equilibrium.

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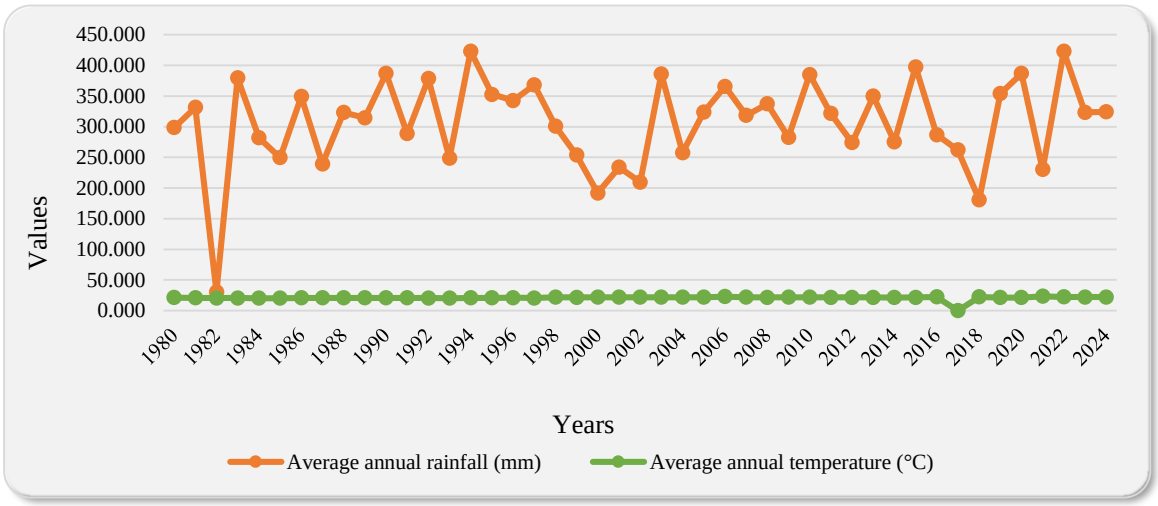


Figure 9 Climate Variability: Rainfall and Temperature Trends in Pakistan

Unit Root Test

The stationarity of the variables in level and first-difference forms was tested using the Augmented Dickey-Fuller (ADF) test. This test is applied to determine the integration order of every variable before applying ARDL bounds testing approach. The ARDL method assumes that the variables are integrated of order I(0) or I(1), implying that the unit root test is a required condition for estimation.

Table 1 Unit Root Test Results

Variable	***Level***	***1st Difference***	***Order of Integration***
lnAGDP	-3.0036	-8.2047	I(0)
$lnCH_4$	-4.7319	-5.1067	I(0)
lnN_2O	-5.1060	-5.6721	I(0)
lnRAIN	-7.3541	-12.528	I(0)
lnTEMP	-2.3452	-8.8406	I(I)
lnFERT	-3.4421	-6.3617	I(0)
lnIRR	-2.4660	-5.4907	I(I)

Note: The ADF test was performed with intercept and trend specifications as applicable. Lag lengths were determined with Akaike Information Criterion (AIC). Statistical significance was assessed at the 1%, 5%, and 10% thresholds.

The results in Table 1 show that the variables have mixed orders of integration, with some variables being stationary at level I(0) and others becoming stationary after first differencing, i.e., I(1). The Augmented Dickey-Fuller (ADF) test statistics for lnAGDP (-3.0036), $lnCH_4$ (-4.7319), lnN_2O (-5.1060), lnRAIN (-7.3541), and lnFERT (-3.4421) were statistically significant in their level form, confirming that these variables are stationary at I(0). On the other hand, the variables lnTEMP (-2.3452) and lnIRR (-

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2.4660) were non-stationary in levels, indicating the presence of a unit root. However, their ADF statistics improved substantially to -8.8406 for lnTEMP and -5.4907 for lnIRR after the first difference was taken, thus confirming stationarity at first differences, i.e., I(1).

Furthermore, the first difference statistics for the remaining variables also demonstrated strong stationarity, with values of -8.2047 for lnAGDP, -5.1067 for lnCH_4, -5.6721 for lnN_2O, -12.528 for lnRAIN, and -6.3617 for lnFERT. These values are considerably greater in absolute terms than the critical values at conventional significance levels, reaffirming the absence of unit root problems. Significantly, none of the variables was found to be integrated of order 2 (I(2), which meets the basic assumption of the ARDL bounds testing methodology. Thus, the ARDL approach is appropriate for estimating the long- and short-run relationships among agricultural productivity, methane and nitrous oxide emissions, Rainfall, temperature, fertilizer consumption, and irrigated land.

Besides, the first-difference statistics for the remaining variables also indicated robust stationarity, namely -8.2047 for lnAGDP, -5.1067 for lnCH_4, -5.6721 for lnN_2O, -12.528 for lnRAIN, and -6.3617 for lnFERT. In absolute terms, these values are much larger than the critical values at conventional levels of significance, which suggests that there are no unit root problems. Crucially, it was found that none of the variables was integrated of order 2, i.e., I (2), which satisfies the fundamental assumption of the ARDL bounds testing methodology. Hence, the ARDL approach is appropriate for estimating the long- and short-term relationships among agricultural productivity, methane and nitrous oxide emissions, Rainfall, temperature, fertilizer consumption, and irrigated land.

Bounds Test for Cointegration

The ARDL Bounds Testing approach was used to test for the existence of a long-run equilibrium relationship between agricultural productivity, agricultural emissions, and climate-relatedvariables after confirming stationarity using the Augmented Dickey-Fuller (ADF) unit root test. The calculated F-statistic was compared with the critical bounds values at the conventional significance levels. Pesaran et al. (2001) bounds testing framework supports cointegration if the approximate F-statistic exceeds the upper bound critical value.

Table 2 Bounds Test

F-statistic	***Critical Value (5%)***		***Cointegration Status***
8.7190	10% 5% 2.5% 1%	1.99 2.27 2.55 2.88	Yes Cointegration Confirmed

Note: Cointegration is established when the calculated F-statistic surpasses an upper-

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bound critical value at the designated significance level.

The ARDL Bounds Test (Table 2) shows that the estimated F-statistic is 8.7187, which stands substantially higher than the upper bound critical value of 3.863 at a 5% significance level for the finite sample size (n = 40). Since the calculated F-statistic is larger than the upper critical value, we reject the null hypothesis of no cointegration. The outcome provides robust, realistic evidence of the long-run equilibrium correlation among agricultural productivity, methane emissions, nitrous oxide emissions, rainfall, temperature, fertilizer consumption, and irrigated land. The cointegration test results validate the use of the ARDL Error Correction framework to estimate the long-run coefficients and short-run dynamics, suggesting that although the variables may exhibit short-term fluctuations, they tend to gravitate toward a long-term equilibrium relationship. In summary, the findings indicate a systematic connection among agricultural emissions, climate-related factors, and agricultural productivity, underscoring the long-term significance of environmental preservation and climate-smart agricultural policies.

Long-Run Results

Subsequent verification of cointegration via an ARDL Bounds Test yielded long-run coefficients to examine the impact of agricultural CH_4 and N_2O emissions, as well as climate-related variables, on agricultural productivity. The long-run estimates provide important evidence on the magnitude, direction, and statistical significance of the correlation between agricultural productivity and the explanatory variables.

Table 3 Long-Run Coefficients

Variable	*Coefficient*	*Std. Error*	*t-Statistic*	*Significance*
lnCH_4	-3.60E-06	2.79E-06	-1.290996	0.2122
lnN_2O	7.20E-06	9.69E-06	0.742767	0.4667
lnRAIN	9.37E-05	8.61E-05	1.087669	0.2903
lnTEMP	0.038953	0.014147	2.753426	0.0126
lnFERT	0.001454	0.001452	1.001048	0.3294
lnIRR	-0.00479	0.005084	-0.943110	0.3575

Note: All variables are converted to their natural logarithms. The stated coefficients thus signify long-term elasticities. Statistical significance is assessed at the 1%, 5%, and 10% thresholds.

Table 3 shows that the projected long-term coefficient for agricultural methane (CH_4) emissions is -3.60E-06, indicating that CH_4 emissions adversely affect agricultural output. A 1% rise in CH_4 emissions is associated with a slight reduction in agricultural GDP, assuming other variables remain constant. The coefficient is not statistically significant (p-value = 0.2122), such that CH_4 emissions do not significantly affect agricultural output in the long run. The coefficient for N_2O emissions is 7.20E-06,

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indicating a positive relationship between N_2O emissions and agricultural output, suggesting a link between increased agricultural activity and higher emissions. However, the variable is not statistically significant (p-value = 0.4667), suggesting that N_2O emissions do not significantly affect agricultural GDP.

The coefficient of the rainfall variable (RAIN) is positive 9.37E-05, meaning that an increase in rainfall increases the agricultural productivity. This finding is consistent with Pakistan's dependence on the prevailing water supply and climatic situations in an agricultural economy. The coefficient is statistically negligible at standard significance levels (p-value=0.2903), indicating that rainfall variability does not have a strong independent long-term influence on its own in the model. The coefficient for the variable Temperature (TEMP) is positive and statistically significant, with a value of 0.038953, a t-statistic of 2.753426, and a p-value of 0.0126, indicating that, in the long run, a 1% rise in average annual temperature is associated with a 0.039% increase in agricultural GDP. Results show that temperature variations significantly affect agricultural productivity in Pakistan. The positive association may reflect the fact that small increases in temperature during the study period were associated with good agricultural conditions or increased cropping intensity.

The coefficient for fertilizer (FERT) is 0.001454, indicating that fertilizer use increases agricultural output. The coefficient is statistically insignificant (p-value = 0.3294), indicating that fertilizer use has not had a strong long-term effect within the model. Furthermore, irrigated land (IRR) shows a negative association (-0.00479), suggesting that an upsurge in irrigated land is coupled with a slight long-run decline in agricultural productivity. The link is statistically insignificant (p-value of 0.3575); the result may reflect inefficiencies in the irrigation system, water management problems, or other structural limitations in the agricultural industry.

The long-run study shows that (TEMP) is the only explanatory variable that exerts a statistically significant long-run impact on agricultural productivity. Although potentially large connections exist among CH_4 and N_2O emissions, Rainfall, fertilizer use, and irrigated land with agricultural productivity, their effects are shown to be statistically insignificant over the entire period of the investigation. The findings highlight the association between climate conditions and agricultural performance, emphasizing the need for climate-resilient agricultural policy and sustainable environmental management.

Short-Run Dynamics (ECM)

After confirming a long-run relationship among the variables using the ARDL Bounds Test, we employed an Error Correction Model (ECM) to examine the short-run dynamics. ECM measures the short-term impact of short-term shocks on agricultural productivity, as it converges towards the long-run stability monitoring shocks to agricultural emissions and climate variables. The coefficient of the (ECM) at -1 is crucial because it captures the pace of adjustment of deviations from the long-run

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equilibrium during the period.

Table 4 Error Correction Model

Variable	*Coefficient*	*Std. Error*	*t-Statistic*	*Significance*
D(lnCH_4)	-132534	392870.3	-0.33735	0.768
D(lnN_2O)	0.219797	0.090941	-2.41691	0.0259
D(lnRAIN)	-0.000384	7.97E-05	-4.822248	0.0001
D(lnTEMP)	0.018262	0.016046	1.138126	0.2692
D(lnFERT)	0.006613	0.007637	0.865954	0.3973
D(lnIRR)	-0.0026	0.0063	-0.4115	0.6853
ECM(-1)	-0.2198	0.0225	-9.7697	0.0000

D(.) are the first differences of the variables, and ECM(-1) is the lagged error correction component from the estimated long-run ARDL equation. Statistical significance is tested at 1%, 5%, and 10% levels.

The short-run coefficient for methane emissions, D(CH_4), is estimated at -132534, indicating that short-run increases in CH_4 emissions negatively impact agricultural productivity, as shown in Table 4. The coefficient is not statistically significant (p-value = 0.768), which implies that CH_4 emissions have a modest, statistically inconsequential short-run impact on agricultural GDP. The short-term impact of N_2O emissions on agricultural output was positive, as indicated by the coefficient for N_2O emissions, D(N_2O), which was 0.219797. The relationship is significant at the 5% level (p-value=0.0259), suggesting a significant short-term association between N_2O emissions and agricultural GDP. This positive link could reflect improved farming practices and increased use of nitrogen-based inputs that temporarily boost yields.

The coefficient for the rainfall variable D(RAIN) is negative (- 0.000384), and the p-value is very significant (0.0001). This result suggests that short-term precipitation variability negatively impacts agricultural productivity. The statistically significant negative link implies that heavy or variable rainfall can lead to unfavourable agricultural conditions, such as flooding, waterlogging, and crop damage, thereby reducing short-term agricultural productivity. The coefficient for the variable temperature (D(TEMP)) is positive (0.018262) and statistically significant at the 5% level (p-value = 0.2692). This research reveals that a transient increase in average annual temperature raises agricultural productivity by about 1.82%. The results indicate that a moderate increase in temperature throughout the study period was associated with better crop growing conditions or increased cropping intensity in some agricultural regions of Pakistan.

The coefficient estimate for D(FERT) is 0.006613, indicating a positive short-run association between fertilizer use and agricultural productivity. But the coefficient is statistically negligible (p-value = 0.3973), indicating that fertilizer usage has no

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sufficiently robust short-run independent effect in the model. Similarly, irrigated land D(IRR) has a negative coefficient of -0.002585, which indicates that short-term gains in irrigated land are associated with a marginal decline in agricultural productivity. The connection is statistically insignificant (p-value = 0.6853), which may indicate systemic inefficiencies in irrigation management or trailing productivity outcomes of irrigation investments.

The coefficient on ECM(-1) is estimated at -0.219797 and is statistically significant at the 0.0000 level. The negative sign suggests a stable, long-term equilibrium among the variables. The magnitude of the coefficient indicates the speed of adjustment to equilibrium, which is around 21.98% per year, suggesting that deviations from the long-run equilibrium path are gradually adjusted over time. This adjustment speed describes a moderate speed of convergence to equilibrium after exogenous shocks. The short-run dynamics imply that climate-related factors, particularly rainfall and temperature, are highly important for agricultural productivity. The ECM coefficient is important and confirms the strength and accuracy of the obtained model (ARDL).

Diagnostic Tests

A set of diagnostic tests was conducted to examine the reliability and robustness of the estimated model. These tests examine the main econometric assumptions, for instance, autocorrelation, heteroskedasticity and residual normality, coupled with the functional-form specification. To measure the robustness, in addition to reliability, of the assessed model, we conducted several diagnostic tests, including a Breusch-Godfrey Serial Correlation LM test, a Breusch-Pagan heteroskedasticity test, a Jarque-Bera normality test, and a Ramsey RESET specification test (Table 5). The Breusch-Godfrey Serial Correlation LM test indicates that the model residuals are not serially correlated, as the test statistic (1.2745) and p-value (0.2593) are not significant at the 0.05 level. So, the null hypothesis of no serial association cannot be rejected. The Breusch-Pagan test is evidence for the assumption of homoscedasticity. The test statistic is 1.6873, and the p-value is 0.2146, both of which indicate that the residuals are homoskedastic.

Table 5 Diagnostic Results

Test	*Statistic*	*p-value*	*Result*
Breusch-Godfrey Serial Correlation LM Test	1.2745	0.2593	No evidence of serial correlation (fail to reject H_0)
Breusch-Pagan Heteroskedasticity Test	1.6873	0.2146	Homoskedasticity assumed (fail to reject H_0)
Jarque-Bera Normality Test	1.8432	0.476	Residuals are approximately normal (fail to reject H_0)
Ramsey RESET Specification Test	0.6164	0.5326	Model correctly specified (fail to reject H_0)

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The Jarque-Bera test suggests that residuals are roughly normally distributed, with a test statistic of 1.8432 (p-value = 0.4760), which validates the standard statistical conclusion. The Ramsey RESET test indicates that the model is correctly specified, with a test statistic of 0.6164 and a p-value of 0.5326, providing no evidence of omitted-variable or functional-form misspecification. The diagnostic results indicate that this model is well specified and satisfies the required econometric assumptions, thereby enhancing the reliability and robustness of the estimated results.

Conclusion and Policy Implications

The outcomes of this study reveal a significant link between agricultural greenhouse gas emissions (CH_4 and N_2O) and agricultural production in Pakistan, indicating that environmental pressures from intensive agricultural practices have implications for long-term productivity. Both long and short-term dynamics support the econometric results and show that agricultural emissions and important inputs, such as fertilizer application, irrigation, Rainfall, and Temperature, have a major impact on agricultural GDP. The diagnostic tests further demonstrate the model's correct specification and reliability for inference, thereby strengthening the credibility of these results.

The results suggest that although short-term increases in agricultural inputs could improve productivity, the resulting increases in CH_4 and N_2O emissions could threaten sustainable agricultural development in the long run, highlighting a systemic trade-off between productivity enhancement and environmental sustainability in Pakistan's agricultural industry. The findings highlight the need for urgent climate-smart farming strategies. Policymakers should focus on reducing CH_4 emissions by improving livestock management, optimizing rice cultivation practices and developing manure management systems. The nitrous oxide (N_2O) emissions can be reduced by promoting balanced fertilizer application, organic and precision agriculture, and improved soil nutrient management.

Moreover, it is critical to invest in efficient irrigation systems, such as drip and sprinkler technologies, to minimize water waste and emissions intensity. Resilience can be strengthened by improving climate adaption measures, such as growing heat-resistant crop varieties, improving weather forecasting systems, and conducting farmer education campaigns. Future studies can expand this approach by combining regional datasets, farm-level microdata, and spatial differences across provinces. Furthermore, analyzing asymmetric and nonlinear relationships between emissions and productivity could yield deep insights into threshold effects and persistent environmental constraints to agricultural development in Pakistan.

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