An Integrated Assessment of Climatic and Non-Climatic Determinants of Wheat Production and Food Security in Pakistan

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Abstract: Wheat is a staple crop in Pakistan and its production is directly linked with ensuring national food security. Pakistan is amongst the top ten counties which have been adversely affected by climate change. The wheat yield heavily depends on the climate variability and farmers' economic constraints. This study was carried out to integrate climatic and economic variables into a single analytical model using the Autoregressive Distributed Lag (ARDL) approach. The data from 1995 to 2024 was derived from secondary sources of Government of Pakistan. The model showed highest robustness and withstood necessary validation. The model captured both short-run and long-run relationships between wheat production and key variables such as temperature, rainfall, water availability, and fertilizer use. The results indicated that in the short run, water availability and fertilizer use had the most significant positive effect on wheat production while excessive rainfall showed a delayed negative impact. In the long run, all variables positively influenced wheat production, yet water availability and fertilizer use played the most critical role. These findings underscored the importance of effective water management and input optimization in maintaining and improving wheat yields under changing climatic conditions. It was recommended that the irrigation efficiency may be enhanced along with promotion of timely and balanced fertilizer application. The climate-smart practices such as use of drought-resistant varieties and precision farming may also be encouraged by the government. Meanwhile, supporting research and policy development were deemed to be essential for building resilience and ensuring long-term food security.

Key Words: Wheat Production, Climate Change, ARDL Model, Water Availability, Fertilizer Use, Agricultural Policy, Pakistan

Introduction

Pakistan's economy heavily relies on agriculture sector which contributes around 24% to the national Gross Domestic Product (GDP) and provides employment to approximately 37.2% of the workforce. This makes it the major source of livelihood in rural areas. The sector includes both major crops, such as wheat, rice, cotton, and sugarcane, and a range of minor crops like vegetables, fruits, and pulses. Major crops account for about 20.67% of value addition in agriculture sector and nearly 4.97% of the total GDP. This illustrates the sector's central role in sustaining the country's economy and food security (GoP, 2024).

The agriculture sector is highly sensitive to variability in climate because it depends heavily on weather conditions, seasonal rainfall, and water availability. Pakistan's agriculture is under growing threat from climate change and resource degradation. Pakistan is frequently exposed to extreme weather events e.g. floods, droughts, heatwaves, and unseasonal rains which disrupt crop cycle and reduce yields. According to the Global Climate Risk Index, Pakistan ranks among the top 10 countries which are most affected by climate-related disasters (GCRI, 2021).

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One of the most alarming climate trends is the consistent rise in average temperatures. Since 1960s, Pakistan has experienced a temperature increase of roughly 0.5°C per decade. This warming has led to significantly hotter summers and the winters are both shorter and less predictable (Rasul & AHMAD, 2012). These shifts in climate have direct consequences for agricultural productivity. Many crops are sensitive to heat, particularly during flowering and grain development stages. Wheat, a staple crop, experiences yield reductions when temperatures exceed 30–32°C during these phases. Cotton yields can drop by up to 20% when temperatures go above 35°C. Heat also affects grain filling in crops like rice and maize, reducing their yields by 10–15% (Lu, et al., 2025).

Wheat, in particular, plays a central role in ensuring Pakistan's food security. It is consumed daily by the vast majority of the population and is essential for dietary stability. However, wheat cultivation is facing pressure from multiple directions. Alongside climate challenges, economic issues such as rising inflation, high input costs, and volatile market prices are making wheat less accessible to many households. As a result, disruptions in wheat production can quickly escalate into broader food crises, affecting nutrition and economic stability alike.

In addition to climate threats, wheat production is also being damaged by unsustainable farming practices. One key problem is the uneven use of fertilizers in Pakistan. Farmers heavily rely on urea but apply much less phosphate fertilizer. Phosphorus application is essential for soil health. This imbalance leads to nutrient shortages, weakening crops and harming the land. As a result, more than 4.7 million hectares of farmland in Pakistan are suffering from declining soil fertility (Wakeel et al., 2022).

Water scarcity is another major threat to agriculture. Since the early 2000s, the availability of canal water has dropped by about 42%, forcing farmers to rely more heavily on groundwater. In many areas, over-extraction has led to rising salinity, making the water less suitable for irrigation. This not only harms crop yields but also degrades the soil over time. On top of this, irrigation techniques used in most regions are outdated and inefficient. Pakistan's water productivity in agriculture remains just half of its potential, indicating a significant gap in efficiency (Baocheng et al., 2024).

Pakistan is already dealing with a serious food security crisis. Pakistan ranks 109th out of 127 countries on the Global Hunger Index 2024. Around 33.2% of children under the age of five are affected by stunting, reflecting long-term malnutrition and poor access to nutritious food (Miriam Wiemers & Holger Mann, 2024). A total of 36.9% of the population struggles with food insecurity, mainly because of poverty and increasing food prices. Food could be available in markets in Pakistan; however, many families simply cannot afford as per their need and choice (GoP, 2018). To tackle the issue, the government introduced the National Food Security Policy in 2018 which focused on improving food access, availability, and stability across Pakistan. However, progress on this policy has been uneven and slow implementation along with weak coordination between federal and provincial authorities has limited its overall impact. Without stronger political will, adequate funding, and long-term planning, such efforts are unlikely to succeed (AHMAD & Saboor, 2022).

There is a lot of research on agriculture and climate change in Pakistan. Most of the studies focus on either environmental or economic issues separately. This limited view makes it hard to understand how these factors influence each other. The current study fills that gap by combining both climate and economic factors in one analysis. The Autoregressive Distributed Lag (ARDL) method has been used to examine both short- and long-term relationships between temperature, rainfall, water availability, and fertilizer use in Pakistan. This approach gives a clearer understanding of the factors influencing wheat production and offers stronger evidence to guide agricultural and climate policy decisions.

Literature Review

The climate factors like rainfall and temperature are of highest importance for wheat production. The wheat yield suffers a lot when temperature rises too high along with drop in rainfall. On the other hand, adequate rainfall and moderate temperatures can lead to better yield of wheat in Pakistan. The impact of climate change can vary depending on how severe and long-lasting it exists. To combat these challenges, Pakistan's wheat farmers need effective strategies like improved irrigation and crop management to protect their yields from climate-related threats.

Liu et al. (2020) conducted a study in China about wheat and looked at conclusions of 126 relevant studies and input data from 1980 to 2018. They found that adding water and nitrogen improved wheat yield but only up to certain limits. For example, yield increased with water up to 295 mm and nitrogen up to 226 kg per hectare. The study also showed that soil nutrients, especially nitrogen and potassium, were important. Wan et al. (2022) looked at how drought affected wheat yield and quality in different parts of the world. They used data from 48 studies across 15 countries to perform a meta-analysis. They focused on grain yield, protein yield, protein content, and nitrogen content. The study found that drought greatly reduced grain and protein yields but slightly increased protein and nitrogen content. Continuous drought caused more harm than short-term drought. Yu, et al. (2020) explored the impact of deficit irrigation effects on wheat yield. They found that deficit irrigation increased water use efficiency by 6.6% but reduced wheat yield by 16.2%. The amount and timing of irrigation were the most important factors influencing success.

Wilcox and Makowski (2014) examined how future climate change might affect wheat yields. They conducted a meta-analysis to understand the effects of temperature, rainfall, and CO_2 levels on wheat yield. They found that wheat yields were likely to decrease when temperatures rose above 23 °C, rainfall did not increase, or CO_2 levels stayed below 395 ppm. Challinor et al. (2014) analysed the climate change and adaptation strategies and their impact on crop yields by focusing on wheat, rice, and maize cultivation. They found that without adaptation, crop yields were expected to decline with 2 °C of local warming in both tropical and temperate regions. Adaptation measures such as changing planting dates or crop varieties improved yields by 7–15%, especially for wheat and rice.

Knox et al. (2012) in a study of crop productivity in Africa and South Asia showed that without adaptation, wheat yields in South Asia (including Pakistan) were expected to decrease by about 8–17% by the 2050s due to combined effects of higher temperatures and changing rainfall patterns. Similarly, in several other studies the CO_2 and climate adaptation were explored. It was suggested that the elevated CO_2 partially offset yield losses from heat and drought but the overall effect was often negative unless adaptation strategies (like improved irrigation and crop management) were adopted (Ben Mariem et al., 2021; Wang et al., 2023).

In Pakistan, factors like water availability and fertilizer use have a significant impact on wheat production. The adoption of best practices in irrigation and fertilizer use can help counterbalance the negative effects of climate change. Kiani and Iqbal (2018) studied the climate change impact on the yield of wheat in Pakistan. They concluded that the irrigation and water usage were strongly linked to higher wheat yields. Both short- and long-term analyses showed that increased water availability, whether through irrigation or effective water management, supported wheat production in Pakistan. Mahmood et al. (2019) conducted a study of climate change in Pakistan and explored the response of inputs and socioeconomic factors on wheat yield. They concluded that in rainfed areas, cumulative precipitation and access to supplementary irrigation were key determinants of yield sustainability and economic efficiency.

Shah et al. (2024) studied the climate trends and changes in wheat yield in Pakistan. They recommended that increased fertilizer use was directly associated with higher wheat productivity across various regions in Pakistan. Raza et al. (2019) conducted a study in southern parts of Punjab in Pakistan and showed that the amount of fertilizer applied per hectare had increased over time and it was correlated with improvements in yield. Optimal fertilizer management was highlighted as a critical adaptation strategy to maintain and enhance wheat production under changing climatic conditions.

Additional factors such as the number of tractors, area under wheat cultivation, and access to input markets also significantly influenced wheat yields. These inputs supported better land preparation, timely sowing, and efficient crop management (Gul et al., 2022). Arshad et al. (2018) conducted a study in Pakistan across eight agro-ecological zones. They showed that the climate variability affected the economic efficiency of rice and wheat production. The analysis of statistical models showed that high temperatures, above 34 °C for wheat and 35.5 °C during rice flowering, significantly reduced economic efficiency. Even slight increase in seasonal average temperatures had negative effects.

To boost wheat productivity, it is essential to know what is holding it back the most. Research across different regions showed that water availability including rainfall and irrigation was the key factor. Temperature and fertilizer use were important too, but they were secondary to water. In areas where water was scarce, managing it effectively was crucial to getting the most out of wheat crops. Fertilizer and temperature management were important, but they played a supporting role to water management.

Ding et al. (2021) modelled the combined effect of deficit irrigation and rise in temperature with respect to wheat production in a high-temperate region in Egypt. They showed that water availability, whether from rainfall or irrigation was repeatedly identified as the primary factor influencing wheat yield, especially in rainfed and arid environments.

Barrett-Lennard et al. (2024) analysed the effects of climate and management variables on crop yields using an aridity index-based model yield in Australia. The results showed that water availability was the primary yield determinant with minor effects from nitrogen and extreme temperatures. Over time, yield and water-use efficiency improved, particularly in wet areas. Tomaz et al. (2021) analyzed the water footprints of wheat in the mediterranean climate conditions and found that supplemental irrigation could stabilize or increase yields in dry years. Further, the rainfall distribution during the growing season could make or break productivity.

Mon et al. (2016) studied the effect of nitrogen fertilization with respect to irrigation on crop yield. They found that nitrogen fertilizer increased wheat yield and water use efficiency, but its impact was most pronounced when water was not limiting. They suggested that high nitrogen use efficiency, a strong influence of irrigation on canopy temperature, and an optimal yield at moderate nitrogen and full irrigation levels.

Patanita et al. (2019) analyzed the crop yield under mediterranean conditions of Southern Portugal. The benefits of fertilizer reached a plateau at higher application rates and optimal yields was achieved when both water and nitrogen were managed together. Huang et al. (2024) compared fertilizer and water-saving strategies across multiple field trials and analyzed their effects on wheat yield, efficiency, and emissions. Compared to traditional practices, optimized nitrogen, optimized water, and integrated water-nitrogen management significantly reduced inputs while increasing yields by up to 11% and doubling nitrogen use efficiency. Integrated water and nitrogen management yielded the best results, but water remained the limiting factor if not adequately supplied.

Abbas et al. (2022) showed that rising temperatures negatively affected wheat yield, but their impact was generally less than that of water availability. High temperatures can shorten the growing season and reduced yields, but cannot be fully offset by increased fertilizer or compost use. Li et al. (2018) showed by large-scale syntheses and modelling consistently that water-related factors (rainfall, irrigation, water management) explained more variation in wheat yield than fertilizer or temperature alone. Soil nutrient status and management practices were important, but their effects were often contingent on sufficient water availability.

Climate change threatens wheat production in two big ways: it reduces average yields and makes them more unpredictable from year to year. Rising temperatures, changing rainfall patterns, and extreme weather events are the main culprits. Regions that rely heavily on rainfed agriculture are especially vulnerable. The impact varies by location, with some areas facing much bigger risks than others. To protect wheat production and food security, we need effective adaptation strategies like better irrigation systems, climate-resilient crops, and tailored management practices.

Schierhorn et al. (2021) in a detailed climatic study concluded that rising temperatures generally reduced wheat yields while adequate precipitation supported them. However, both factors also increased yield variability especially when combined with drought or heat waves. Shayanmehr et al. (2020)recommended that heat waves, droughts, and erratic rainfall during critical growth stages (like grain filling) sharply reduced yields and increased the risk of crop failure. Raimondo et al. (2021) suggested that the impact of climate variability was not uniform. For example, in China, precipitation variability was the main limiting factor in some wheat regions, while in Pakistan and Iran, rainfed wheat was highly vulnerable to both temperature and precipitation changes.

The wheat production is under threat by climate change in Pakistan due to rising temperature and unpredictable rainfall. Climate-resilient farming practices, efficient resource management, and farmer education are suggested by the policy makers to combating such challenges. A comprehensive approach involving resilient crops, better water management, farmer training, and robust support systems is required. Abbas et al. (2022) studied the impact of climate change on food security in Punjab. They found that the development and adoption of climate-resilient wheat varieties were required to be promoted by the government in Pakistan. These varieties withstood higher temperatures, drought, and wind stress. Similarly, Azmat et al. (2021) conducted a comprehensive study and endorsed the modification of crop management practices, such as adjusting sowing dates, planting density, and fertilizer use, to better align with changing climate patterns in Pakistan. Habib-Ur-Rahman et al., 2022 studied the issues and opportunities in Asia with respect to climate change and crop production. They supported crop rotation with legumes, agroforestry, and mixed farming systems to enhance soil health and reduce vulnerability to climate extremes.

Research Methodology

Study Variables

The wheat production is often used as a dependent variable in the literature for measuring agricultural output (Ali et al., 2017). Climate related variables such as temperature and rainfall are taken as key explanatory variables which directly influence the crop yields (Chandio et al., 2021). The non-climatic variables such as fertilizer use and water availability have a crucial roles in enhancing agricultural productivity (Akhtar & Athar, 2020). The data for these variables from 1995 to 2024 was derived from reliable sources from Government of Pakistan i.e. Economic Survey of Pakistan and Pakistan Meteorological Department.

Table 1

Study Variables and Data Sources

Sr. No.	Study Variables	Data Unit	Notations	Data Sources
1	Wheat Production	Annual data in thousand tones	WH	Economic Survey of Pakistan
2	Temperature	Average Annual value in Degree Celsius	TM	Pakistan Meteorological Department
3	Rainfall	Average Annual value in millimeter	RF	Pakistan Meteorological Department
4	Fertilizer use	Annual value of total off-take in thousand tones	FER	Economic Survey of Pakistan
5	Water availability	Million Acre feet	WA	Economic Survey of Pakistan

Economic model

The relationship between wheat production and its determinants was based on the literature review, The economic model is given as following:

WH = *f*(TM, RF, FER, WA)

In this model, the wheat production (WH) served as the dependent variable which was taken as to be influenced by a combination of climatic factors and agricultural inputs. Specifically, the climatic factors considered were temperature (TM) and rainfall (RF) while the agricultural inputs included fertilizer use (FER) and water availability (WA).

ARDL Model

This study employed the Autoregressive Distributed Lag (ARDL) model due to its flexibility and robustness in handling variables with mixed orders of integration whether stationary at level I (0) or first difference I (1). The ARDL bounds testing approach enabled the detection of long-run relationships between variables without requiring uniform integration orders. The model simultaneously estimated short-run adjustments and long-run equilibrium relationships and offered a comprehensive understanding of variable dynamics. Its suitability for small sample sizes and incorporation of an error correction term further enhanced its applicability in capturing the speed of adjustment to restore equilibrium aftershocks.

Econometric Function

The econometric form of the ARDL model was specified as:

$$\Delta WHt = \beta_0 + \sum_{i=1}^{n} \beta_{1i}\,\Delta WH_{t-i} + \sum_{i=1}^{n} \beta_{2i}\,\Delta TM_{t-i} + \sum_{i=1}^{n} \beta_{3i}\,\Delta RF_{t-i} + \sum_{i=1}^{n} \beta_{4i}\,\Delta FER_{t-i} + \alpha_1\,ECT_{t-1} + \epsilon_t$$

Where:

Δ: First difference operator (e.g., $\Delta WH_t = WH_t - WH_{t-1}$); WH_t: Wheat production at time t; TM_t: Temperature at time t; RF_t: Rainfall at time t; FER_t: Fertilizer use at time t; β_0: Constant term; β_{1i}, β_{2i}, β_{3i}, β_{4i}: Short-run coefficients for lagged differences of wheat production, temperature, rainfall, and fertilizer use, respectively; α_1: Speed of adjustment coefficient (must be negative and statistically significant for the model to be valid); ECT_{t-1}: Error Correction Term (ECT), representing deviations from the long-run equilibrium in the previous period; ϵt: Error term at time t;

The Error Correction Term (ECT) was derived from the long-run equilibrium relationship and was calculated as following:

$$ECT_{t-\Omega 1} = WH_{t-1} - \alpha_1 TM_{t-1} - \alpha_2 RF_{t-1} - \alpha_3 FER_{t-1} - \alpha_4 WA_{t-1}$$

Where:

$\alpha_1, \alpha_2, \alpha_3, \alpha_4$: Long-run coefficients for temperature, rainfall, fertilizer use, and water availability, respectively.

Estimation Procedure

The analysis involved several key steps. First, unit root tests (ADF and PP) were conducted to determine the variables' order of integration. Next, the ARDL bounds test confirmed the existence of long-run relationships between the variables. The ARDL model was then estimated using Ordinary Least Squares (OLS). The optimal lag length was selected on the based information provided by Akaike Information Criterion (AIC). Finally, diagnostic tests for serial correlation, heteroscedasticity, and normality of residuals were performed to ensure the model's robustness.

Results and Discussion

The Unit Root Test

The Augmented Dickey-Fuller (ADF) test was used to check the stationarity of the variables. According to the results, the variables of Temperature (LnTM) and Rainfall (LnRF) were found to be stationary at level and the results were significant at 5% level. The other three variables of Wheat Production (LnWH), Fertilizer Use (LnFER), and Water Availability (LnWA) were non-stationary at level. Their ADF test statistics at level were -1.985, -1.983, and -2.896 which were found to be insignificant. However, these variables became stationary at first difference with highly significant ADF test statistics.

Table 2

Unit Root Test Results

Variables	ADF at Level (P-value)	ADF at First Difference (P-value)	MacKinnon Critical Value (5%)	Order of Integration
LnWH	-1.985 (0.2914)	-10.280* (0.0000)	-3.670	I(1)
LnTM	-3.254* (0.0272)	-7.732 (0.0000)	-2.971	I(0)
LnRF	-4.028* (0.0040)	-9.299 (0.0000)	-3.661	I(0)
LnFER	-1.983 (0.2919)	-8.973* (0.0000)	-3.670	I(1)
LnWA	-2.896 (0.0572)	-7.409* (0.0000)	-3.677	I(1)

Regression Results

According to the results presented in Table 3, water availability (LnWA) had a positive and significant impact (0.692998, p = 0.0238) on wheat production, while its lagged terms showed mixed effects. LnWA (-1) was negative and significant (-0.301996, p = 0.0434), whereas LnWA (-2) had a strong positive influence (0.851511, p = 0.0172). Rainfall was also an important variable for wheat production, with LnRF and its lagged values contributing positively; LnRF (-3) had the strongest effect (0.117964, p = 0.0021). Temperature and fertilizer were key determinants as well, both showing positive and significant impacts. Notably, LnFER (-1) had the highest impact (0.431915, p = 0.0001), while LnFER (-2) turned negative (-0.095400, p = 0.0024), indicating a delayed reversal effect. The constant term was also significant (2.006103, p = 0.0166), suggesting a positive baseline influence.

Table 3

Regression Results

Variable	Coefficient	Std. Error	t-Statistic	Prob.
LnWH (-1)	-0.0021	0.1840	-0.0113	0.0011
LnWA	0.6930	0.2735	2.5343	0.0238
LnWA (-1)	-0.3020	0.3079	-0.9807	0.0434
LnWA (-2)	0.8515	0.3150	2.7030	0.0172
LnWA (-3)	-0.4635	0.3144	-1.4739	0.0126
LnRF	0.0055	0.0318	0.1739	0.0044
LnRF (-1)	0.0784	0.0311	2.5186	0.0246
LnRF (-2)	0.0561	0.0334	1.6773	0.0157
LnRF (-3)	0.1180	0.0313	3.7678	0.0021
LnTM	0.2155	0.1830	1.1771	0.0088
LnTM (-1)	0.3538	0.1608	2.2002	0.0451
LnFER	0.3106	0.0698	4.4512	0.0005
LnFER (-1)	0.4319	0.0770	5.6115	0.0001
LnFER (-2)	-0.0954	0.0891	-1.0708	0.0024
C	2.0061	0.7378	2.7191	0.0166

Model Goodness-of-Fit Criteria

The regression model demonstrated excellent explanatory power, as indicated by the high R-squared value of 0.980695, meaning that approximately 98.07% of the variation in the dependent variable was explained by the independent variables. The Adjusted R-squared value of 0.961390 further confirmed the model's robustness, accounting for the number of predictors. The standard error of the regression (0.014293) was low, suggesting precise estimates. The F-statistic of 50.79969 (p = 0.000000) confirmed the overall significance of the model. Additionally, the Durbin-Watson statistic of 2.164410 indicated no significant autocorrelation in the residuals. Model selection criteria, such as the Akaike info criterion (-5.351885) and Schwarz criterion (-4.644663), suggested a well-fitted model. Overall, the model was highly reliable and effectively captured the relationship between the variables.

Table 4

Model Goodness-of-Fit Criteria

Sr. No.	Statistic	Value	*P*-Value
1	Akaike info criterion	-5.3519	
2	Schwarz criterion	-4.6447	
3	Hannan-Quinn criteria	-5.1304	
4	Durbin-Watson stat	2.1644	
5	R-squared	0.9807	
6	Adjusted R-squared	0.9614	
7	S.E. of regression	0.0143	
8	Sum squared resid	0.0029	
9	Log likelihood	92.6023	
10	F-statistic	50.7997	
11	Prob(F-statistic)	0.0000	
12	Mean dependent var	7.3279	
13	S.D. dependent var	0.0727	

Bound Test for Cointegration

The F-statistic of 7.5510 exceeded all critical value bounds at the 1%, 2.5%, 5%, and 10% significance levels, indicating strong evidence of cointegration among the variables. This suggested that a stable long-run relationship existed between the dependent and independent variables in the model. The results confirmed that the variables moved together over time, supporting the validity of the estimated relationships.

Table 5

Results of Bound Test

Significance	Lower Bound	Upper Bound
F-Statistic = 7.5510		
10%	2.45	3.53
5%	2.86	4.01
2.5%	3.25	4.49
1%	3.74	5.06

ARDL Cointegration Analysis and Short-Run Estimates

The results indicated that water availability and fertilizer use played a crucial role in enhancing wheat production in Pakistan. Water availability had a positive and significant short-run impact, though its lagged effects suggested fluctuations in yield. Fertilizer application showed a strong positive influence, underscoring its importance in boosting productivity. In contrast, rainfall exhibited a delayed negative impact, implying that excessive or ill-timed precipitation could harm yields. Temperature variations had an insignificant effect, showing limited short-term influence. The error correction term confirmed a long-run equilibrium relationship, with deviations adjusting rapidly at a rate of 87% per period. These findings emphasized the importance of efficient water and fertilizer management alongside climate adaptation strategies.

Table 6

Cointegration and Short Run Results

Variables	Coefficient	T-Statistic	Probability Value
D(LnWA)	0.6930	2.5343	0.0238
D (LnWA (-1))	-0.8515	-2.7030	0.0172
D (LnWA (-2))	0.4635	1.4739	0.0226
D(LnRF)	0.0055	0.1739	0.0144
D (LnRF (-1))	-0.0561	-1.6773	0.0157
D (LnRF (-2))	-0.1180	-3.7678	0.0021
D(LnTM)	0.2155	1.1771	0.0088
D(LnFER)	0.3106	4.4512	0.0005
D (LnFER (-1))	0.0954	1.0708	0.0024
CointEq (-1)	-0.8702	-5.4458	0.0001

ARDL Cointegration Analysis and Long-Run Estimates

The positive and statistically significant coefficients indicated that a 1% increase in water availability, rainfall, temperature, and fertilizer use led to wheat production rising by approximately 0.777%, 0.257%, 0.568%, and 0.646%, respectively. Among these, water availability had the strongest impact, highlighting its vital role in boosting yields. The positive temperature coefficient suggested that moderate temperature increases may have favoured wheat growth. The significant constant term (2.0019) reflected the influence of other underlying factors affecting production.

Table 7

Long-Run Estimates of ARDL Model

Regressors	Coefficients	T-Statistic	Prob.
LnWA	0.7774	3.0499	0.0087
LnRF	0.2574	5.1053	0.0002
LnTM	0.5681	2.4495	0.0281
LnFER	0.6457	17.0867	0.0000
Constant	2.0019	3.8322	0.0018

Diagnostic Tests for Model Validation

The diagnostic tests were performed in order to ensure the reliability of the regression model. The Breusch-Godfrey LM test (F = 0.677, p = 0.526) confirmed the absence of serial correlation. The Breusch-Pagan / Cook-Weisberg test (Chi-square = 1.551, p = 0.211) indicated no heteroskedasticity, reflecting stable residual variance. The Ramsey RESET test (F = 0.997, p = 0.337) suggested no omitted variable bias, affirming proper model specification. Lastly, the Jarque-Bera test (Chi-square = 0.571, p = 0.752) showed that residuals were normally distributed.

Table 8

Diagnostic test

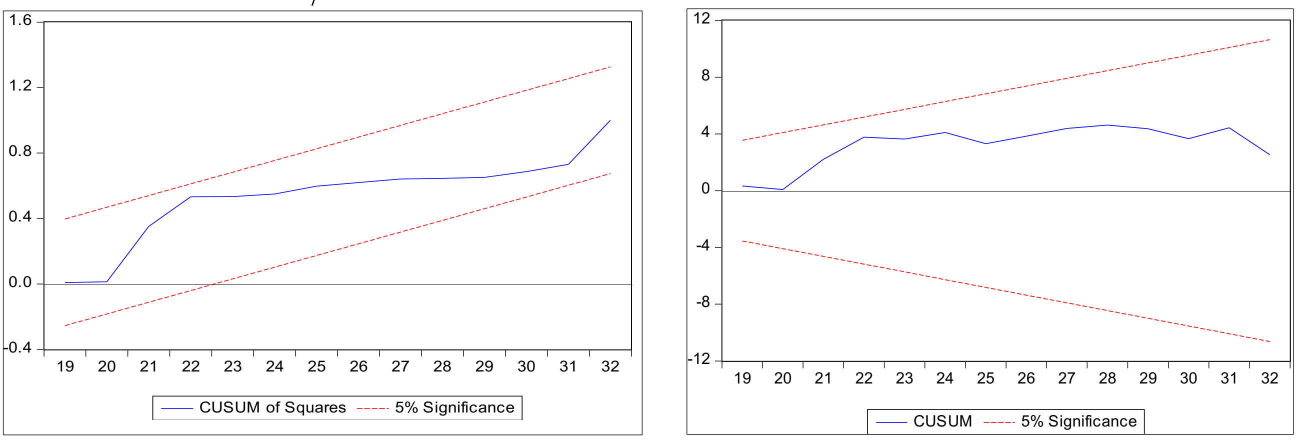
Problems	Test Applied	F-stat/Chi-square	Probabilities
Autocorrelation	Breusch-Godfrey LM test	0.6775	0.5263
Heteroskedasticity	Breusch-Pagan / Cook-Weisberg	1.5514	0.2107
OV Test (Omitted Variables)	Ramsey RESET Test	0.9974	0.3368
Normality	Jarque-Bera Normality Test	0.5713	0.7515

CUSUM and CUSUM of Square

The CUSUM test showed that the blue line remained within the 5% significance boundaries, indicating stable model coefficients over the sample period. In the CUSUM of Squares test, the blue line largely stayed within the red boundaries, though a slight upward trend near the end suggested minor potential structural instability, which was not considered severe

Figure 1

CUSUM and CUSUM of Square



Conclusions

This study looked at how climatic and non-climatic factors affected wheat production in Pakistan using the ARDL method. It was found that water availability, fertilizer use, rainfall, and temperature all played important roles. In the short run, water and fertilizer had the biggest positive effects, while too much rain had a delayed negative impact. In the long run, all four factors helped increase production, however, water availability appeared to have highest impact for increasing wheat production after fertilizer use.

The study highlighted the need for efficient irrigation and proper fertilizer use to keep wheat production stable as the climate changes. It was concluded that climate-smart strategies like drought-resistant crops and precision farming needed to be adopted. Finally, more investment in sustainable farming and infrastructure was emphasized in order to support long-term food security in Pakistan.

Recommendations

1. Water and fertilizer management may be enhanced by developing efficient irrigation systems and promoting proper fertilizer use to optimize productivity while minimizing environmental impact.
2. Climate-smart farming may be promoted by the Government through development of drought-resistant wheat varieties, precision farming techniques, and providing farmers with training and resources to adapt to changing climatic conditions.
3. Research and policy development may be focused on sustainable agriculture, resource efficiency, and climate-resilient crop technologies, while creating policies that reward resource-efficient practices and provide support during climate-induced shocks.

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