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Dynamic Relationship Between Rainfall and Wheat Production in Balochistan: A Time Series Analysis Using the VAR Model

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ABSTRACT
This paper investigates the dynamic relationship between rainfall and wheat production in Balochistan using a Vector Autoregression (VAR) framework with annual data from 2000–2025. Stationarity tests reveal that rainfall is stationary, while wheat production is non-stationary and requires differencing. Lag order selection identifies two lags as optimal for capturing short-term dynamics. VAR estimation shows that rainfall significantly influences wheat production at the second lag, whereas wheat production does not affect rainfall. Granger causality confirms unidirectional causality from rainfall to wheat production. Impulse response functions and forecast error variance decomposition further demonstrate that rainfall shocks exert strong and persistent effects on wheat output, while wheat production shocks have negligible influence on rainfall. Forecasting analysis highlights the sensitivity of wheat production to rainfall variability, with negative shocks leading to sharp declines followed by recovery. These findings underscore the dominant role of climatic variability in shaping agricultural productivity in Balochistan.
Keywords: *Rainfall variability, Wheat production, Vector Autoregression (VAR)*

Introduction

Agriculture remains a cornerstone of global food systems, shaping economic growth, food security, and rural livelihoods. At the world level, agricultural markets are undergoing structural transformation driven by climate volatility, technological innovation, and shifting consumption patterns. The OECD–FAO Agricultural Outlook 2025–2034 projects global agricultural and fish production to increase by 14% over the next decade, largely enabled by productivity growth in middle-income countries. Rising incomes and urbanization are expected to increase demand for animal-source foods, while productivity gains will help reduce emission intensity, limiting direct agricultural greenhouse gas emissions to about 6% growth despite higher output (OECD–FAO, 2025; FAO, 2025). These global trends highlight both opportunities and challenges, as climate change continues to threaten sustainability (World Bank, 2025; Wikifarmer, 2025).

At the national level, Pakistan's agriculture contributes nearly 20% to GDP and employs about 38% of the workforce. However, the sector faces mounting challenges from climate variability, water scarcity, and rising input costs. The Finance Division (2025) reported that in FY 2025, agriculture grew by only 0.56%, with major crops contracting by 13.5% due to adverse weather conditions. Livestock showed resilience, growing by 4.72%, while fisheries and forestry also contributed positively. Despite having the world's largest irrigation system, Pakistan struggles with declining soil fertility, inefficient water use, and increasing climate shocks, making agricultural sustainability a pressing concern (State Bank of Pakistan, 2025; Pakistan Bureau of Statistics, 2025).

Within Pakistan, Balochistan represents a unique case. The province is characterized by semi-arid climatic conditions, fragile ecosystems, and limited irrigation infrastructure, making agriculture predominantly rainfed. Wheat is the staple crop, and its yields are highly sensitive to rainfall variability. Recent government initiatives in 2025 sought to strengthen resilience by converting more than 27,000 agricultural tube wells to solar power, a project costing Rs55 billion (Balochistan Pulse, 2025; Dawn, 2025). The provincial agricultural policy envisions doubling production by 2030, focusing on water productivity and sustainable practices (Agriculture Department Balochistan, 2025). Despite these efforts, wheat output remains volatile, reflecting unstable rainfall patterns and underscoring the need for advanced econometric analysis to quantify rainfall–production dynamics (Rees et al., 1989; CRS Balochistan, 2024).

A shaded relief map of Pakistan highlights Balochistan in red, showing its geographic location in the southwest, bordering the Arabian Sea and neighboring Iran and Afghanistan. This visualization underscores the province's strategic importance and vulnerability to climatic shocks.

This study aims:

1. To analyze long-term trends of rainfall and wheat production (2000–2025).
2. To estimate the dynamic relationship between rainfall and wheat output using VAR.
3. To evaluate rainfall's predictive role through Granger causality, impulse response functions, and variance decomposition, providing policy-relevant insights for food security.

Methodology

Data Sources

Annual time series data (2000–2025) on rainfall (mm) and wheat production ('000 tons per hectare) in Balochistan were collected from meteorological records and the Crop Reporting

Services (CRS Balochistan, 2025). Historical studies on rainfed systems provide contextual support (Rees et al., 1989).

Econometric Framework

The study employs the Vector Autoregression (VAR) model (Sims, 1980), which captures dynamic causal relationships between rainfall and wheat production without imposing restrictive assumptions.

Stationarity Testing

Augmented Dickey–Fuller (ADF) tests confirmed rainfall as stationary, while wheat production was non-stationary. First differencing was applied to wheat production to achieve stationarity (Enders, 2014; Gujarati & Porter, 2009).

Lag Order Selection

Lag length was determined using AIC, FPE, and HQIC criteria, with lag 2 selected to capture short-term dynamics without overfitting.

VAR Estimation and Stability

The VAR model was estimated using OLS. Eigenvalue analysis confirmed stability, with all values inside the unit circle (Enders, 2014).

Granger Causality

Granger causality tests rejected the null hypothesis that rainfall does not cause wheat production, confirming rainfall's predictive role (Hussain & Mudasser, 2007; Khan & Akhtar, 2019).

Impulse Response & Variance Decomposition

Impulse response functions traced rainfall shocks on wheat production, while Forecast Error Variance Decomposition quantified rainfall's contribution to output variability (Enders, 2014).

Forecasting

Short-term forecasts generated from the VAR model highlight wheat's sensitivity to rainfall variability, offering policy-relevant insights for food security (Ahmad & Farooq, 2010; IPCC, 2021).

Data and Variables

Data Sources

Rainfall data (mm/year) were obtained from meteorological records, validated with satellite datasets (Abro et al., 2025). Wheat production data (000 tons/ha) were sourced from CRS Balochistan (2024).

Variables

- Rainfall (RF): Independent variable, representing climatic variability.
- Wheat Production (WP): Dependent variable, representing agricultural output and food security.

Transformations

ADF tests confirmed rainfall as stationary; wheat production required first differencing (Enders, 2014; Gujarati & Porter, 2009). Lag 2 was selected for VAR estimation (Sims, 1980).

Justification

Rainfall is the dominant climatic factor influencing wheat yields in semi-arid regions. Prior studies confirm rainfall's significant impact on wheat production in Pakistan (Hussain & Mudasser, 2007; Khan & Akhtar, 2019). Wheat is chosen as the dependent variable due to its central role in food security (Ahmad & Farooq, 2010; IPCC, 2021).

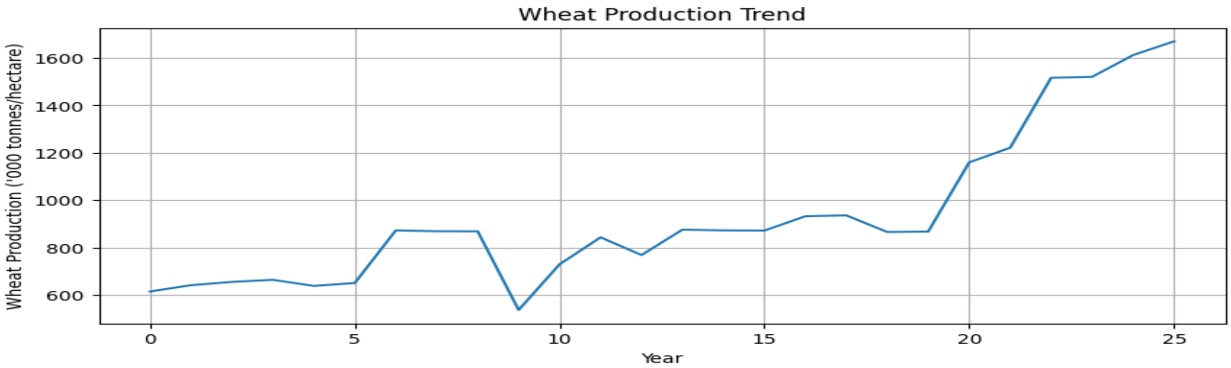
Results

Table-1: Descriptive Statistics of Rainfall and Wheat Production

Statistic	Rainfall (mm)	Wheat Production (000 tons/ha)
Mean	**290.49**	**933.17**
Standard Error	6.71	63.17
Median	291.65	868.40
Mode	N/A	872.10
Standard Deviation	34.22	322.12
Sample Variance	1171.22	103758.33
Kurtosis	0.32	0.48
Skewness	0.22	1.20
Range	152.50	1133.80
Minimum	221.60	536.20
Maximum	374.10	1670.00
Sum	7552.80	24262.34
Observations	26	26
Confidence Level (95%)	±13.82	±130.11

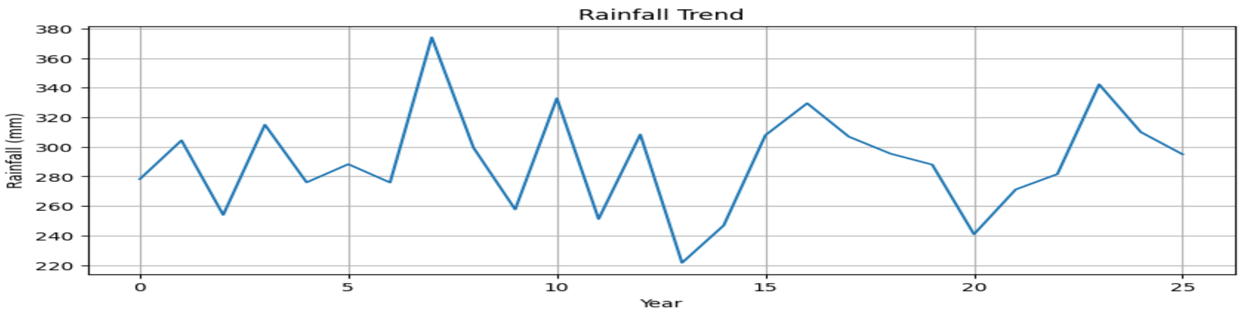
Table shows rainfall in Balochistan, averages 290.49 mm with moderate variability (SD = 34.22), showing generally stable climatic conditions. Wheat production averages 933.17 thousand tons per hectare but exhibits high volatility (SD = 322.12) and positive skewness, indicating recent growth trends alongside output instability. Overall, the statistics reveal moderate climatic variability and substantial agricultural fluctuations, supporting the use of advanced time-series methods like VAR to capture dynamic interactions.

Figure-1. Wheat Production Trend



This Graph shows wheat production in Balochistan shows substantial fluctuations over 25 years but maintains an overall upward trend. Notable growth appears around years 6, 20, and 23, while a dip occurs near year 9. Despite variability, the long-term trajectory reflects progressive growth, consistent with positive skewness, highlighting resilience and potential for expansion under favorable conditions.

Figure-2: Trend Analysis Rainfall



This graph shows rainfall in Balochistan over 26 years shows moderate variability between 220–380 mm, with recurrent peaks and troughs. Higher rainfall aligns with productivity gains, while declines reflect stress conditions. Overall, variability emerges as a key driver of wheat production, reinforcing the need for time-series modeling to capture climatic–agricultural dynamics.

Table-2: Augmented Dickey–Fuller (ADF) Unit Root Test Results

Variable	ADF Statistic	P-value
Rainfall	-5.1649	0.00001
Wheat Production	0.2132	0.9730

Rainfall: ADF statistic −5.16 ($p < 0.01$) confirms stationarity, making rainfall suitable for direct VAR inclusion.

Wheat Production: ADF statistic 0.21 ($p = 0.97$) shows non-stationarity, requiring differencing before VAR analysis

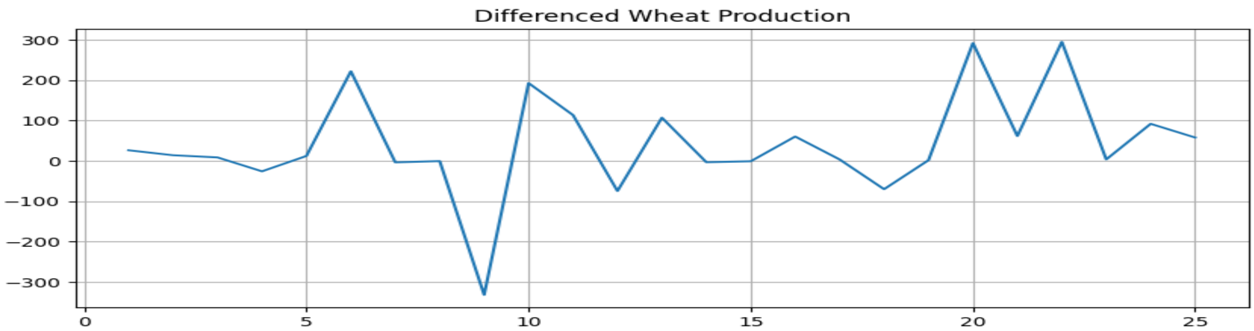
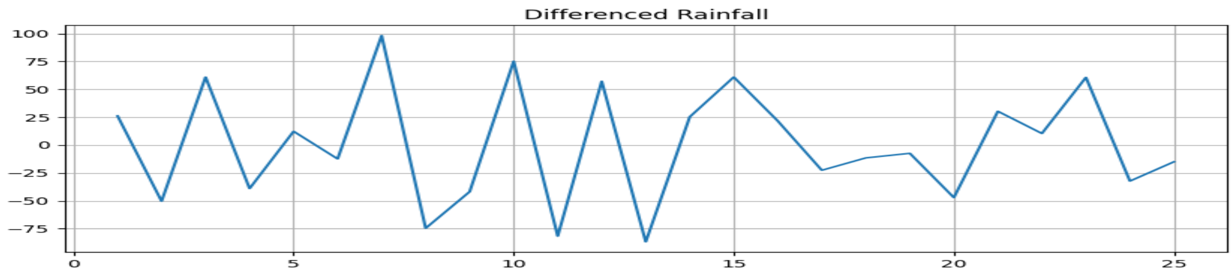


Figure-3: Differenced Wheat Production Series

The differenced wheat production series fluctuates around zero (−350 to +300), reflecting short-term variability rather than long-term growth. This volatility, consistent with climatic or agricultural shocks, confirms the series is now stationary and suitable for VAR modeling.

Figure-4: Differenced Rainfall Series



The difference in rainfall series also fluctuates around zero, with values ranging approximately between -100 and +100. These oscillations represent year-to-year changes in rainfall, rather than absolute levels. The absence of a clear upward or downward trend confirms that rainfall differences are stationary, capturing cyclical climatic variations. This transformation ensures that rainfall data can be directly used in VAR estimation without further adjustment.

Table-3: VAR Lag Order Selection Criteria

Lag	AIC	BIC	FPE	HQIC
0	17.93	18.03*	6.101e+07	17.95
1	17.86	18.16	5.727e+07	17.92
2	**17.74***	**18.24**	**5.191e+07***	**17.84***
3	18.02	18.72	7.138e+07	18.16

4	18.22	19.12	9.442e+07	18.40
5	18.52	19.61	1.445e+08	18.73

Lag selection shows AIC, FPE, and HQIC favor Lag 2, while BIC prefers Lag 0. Since AIC and FPE are more reliable for dynamic analysis, Lag 2 is chosen to capture short-term rainfall–wheat interactions without overfitting.

Table-4: Summary Statistics of VAR Model

Statistic	Value
Model	VAR (OLS)
No. of Equations	2
Observations (Nobs)	23
Log Likelihood	-256.583
AIC	17.5054
BIC	17.9991
HQIC	17.6295
FPE	4.06076e+07
Det (Omega_mle)	2.73998e+07

The VAR model fit is adequate, with log likelihood −256.58 and information criteria supporting lag choice. AIC (17.50) versus BIC (17.99) indicates balanced explanatory power and parsimony, while FPE and Det (Omega_mle) confirm model stability.

Table-5: Results for Equation Rainfall mm

Variable	Coefficient	Std. Error	t-stat	Prob
Const	-5.2044	10.3374	-0.503	0.615
L1. Rainfall mm	-0.7215	0.2195	-3.288	0.001
L1. Wheat Production (000 tons/ha)	0.1011	0.0787	1.285	0.199
L2. Rainfall mm	-0.3450	0.2312	-1.492	0.136
L2. Wheat Production (000 tons/ha)	0.0979	0.0742	1.319	0.187

Rainfall's first lag has a significant negative effect (p = 0.001), showing mean-reverting behavior, while wheat lags are insignificant, indicating minimal influence on rainfall

Table-6: Results for Equation Wheat Production (000 tons/ha)

Variable	Coefficient	Std. Error	t-stat	Prob
Const	46.4330	27.5152	1.688	0.091
L1. Rainfall mm	0.0364	0.5842	0.062	0.950
L1. Wheat Production (000 tons/ha)	0.0451	0.2094	0.215	0.830
L2. Rainfall mm	-1.4637	0.6154	-2.378	0.017
L2. Wheat Production (000 tons/ha)	-0.0031	0.1975	-0.016	0.987

The wheat production equation highlights that the second lag of rainfall (L2. Rainfall_mm) is statistically significant (p = 0.017), showing that rainfall two years earlier negatively impacts current wheat production. Other coefficients, including wheat production lags, are not significant, indicating weaker short-term self-dependence in production.

Table-7: Correlation Matrix of Residuals

	Rainfall_mm	Wheat Production (000 tonnes/ha)
Rainfall_mm	1.0000	0.0336
Wheat Production (000 tonnes/ha)	0.0336	1.0000

residual correlation between rainfall and wheat production is very low (0.0336), suggesting that the VAR model successfully captures the dynamic relationship between the two variables. Minimal unexplained correlation indicates robustness of the model specification.

Table-8: Eigenvalues of VAR (1) Representation

Eigenvalue	Value
λ_1	0.6904
λ_2	0.6904
λ_3	0.5503
λ_4	0.5503

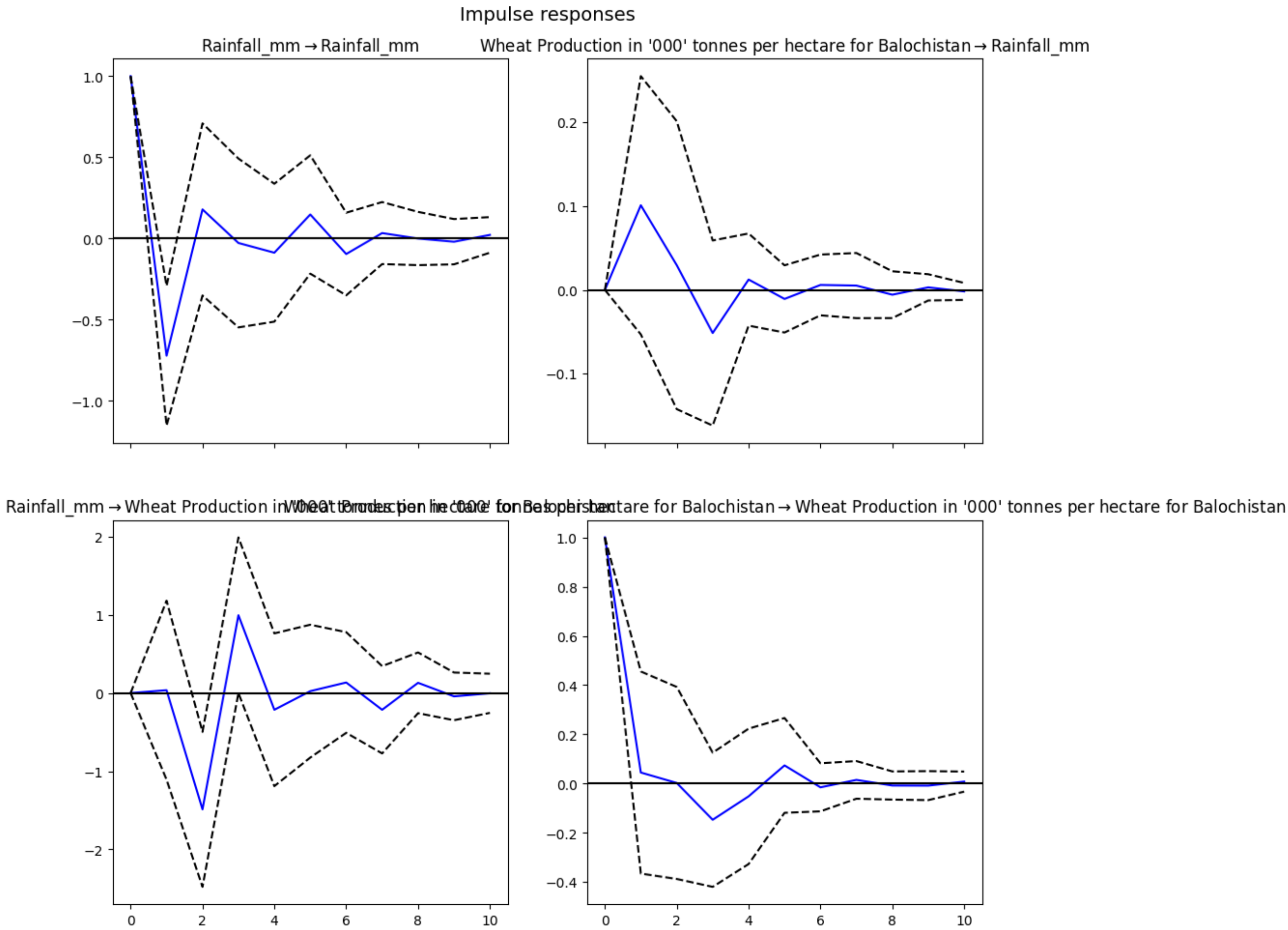
The eigenvalues of the VAR (1) representation are all **less than 1**, with values of approximately **0.69** and **0.55** (each repeated twice). This confirms that the estimated VAR model is **stable** and satisfies the stationarity condition, since all eigenvalues lie inside the unit circle.

Table-9: Granger Causality F-Test Results

Null Hypothesis (H_0)	Test Statistic	Critical Value	p-value	df	Conclusion
Rainfall does not Granger-cause of Wheat Production	4.309	3.259	0.021	(2, 36)	Reject H_0 at 5%

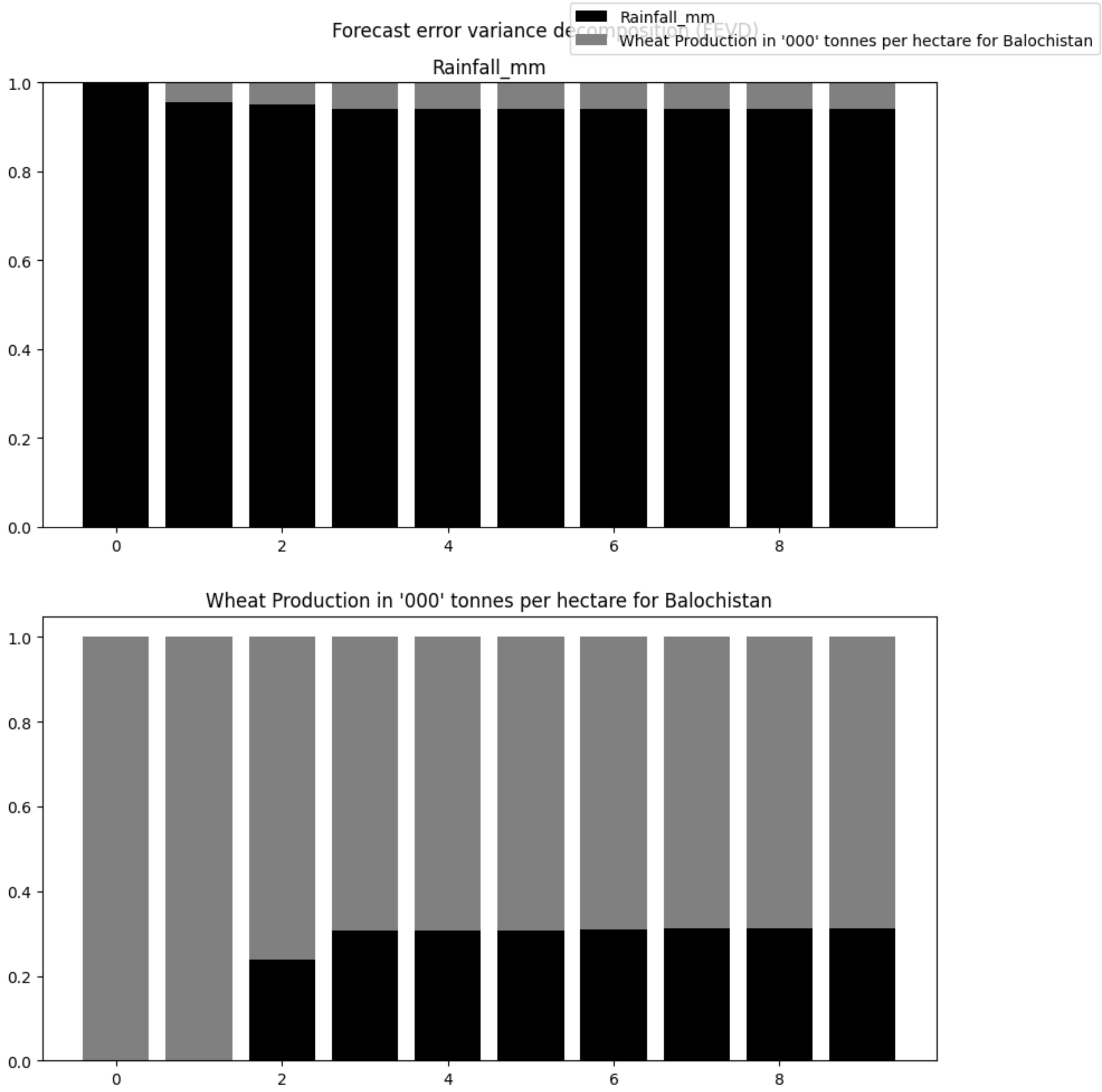
Granger causality test (F = 4.309, p = 0.021) rejects the null, confirming rainfall significantly predicts wheat production in Balochistan.

Figure-5: Impulse Responses between Rainfall and Wheat Production



Impulse Response Graphs Show:
Rainfall: Shows initial negative persistence, then gradually stabilizes, confirming rainfall shocks dissipate over time.
Rainfall: Response is insignificant and close to zero, indicating no feedback effect of wheat on rainfall.
Wheat: Wheat output declines after rainfall shocks, most pronounced at lag 2–3, before stabilizing, confirming rainfall's causal impact.
Wheat: Production shocks show short-term persistence but fade, indicating temporary effects without long-term instability.

Figure-6: Forecast Error Variance Decomposition (FEVD) between Rainfall and Wheat Production.



FEVD Graphs Shows:

- **Rainfall:** Variance is largely explained by its own shocks, with wheat contributing minimally across horizons.

- **Wheat Production:** Initially driven by its own shocks, rainfall's role grows over time, showing climatic influence on output variability.

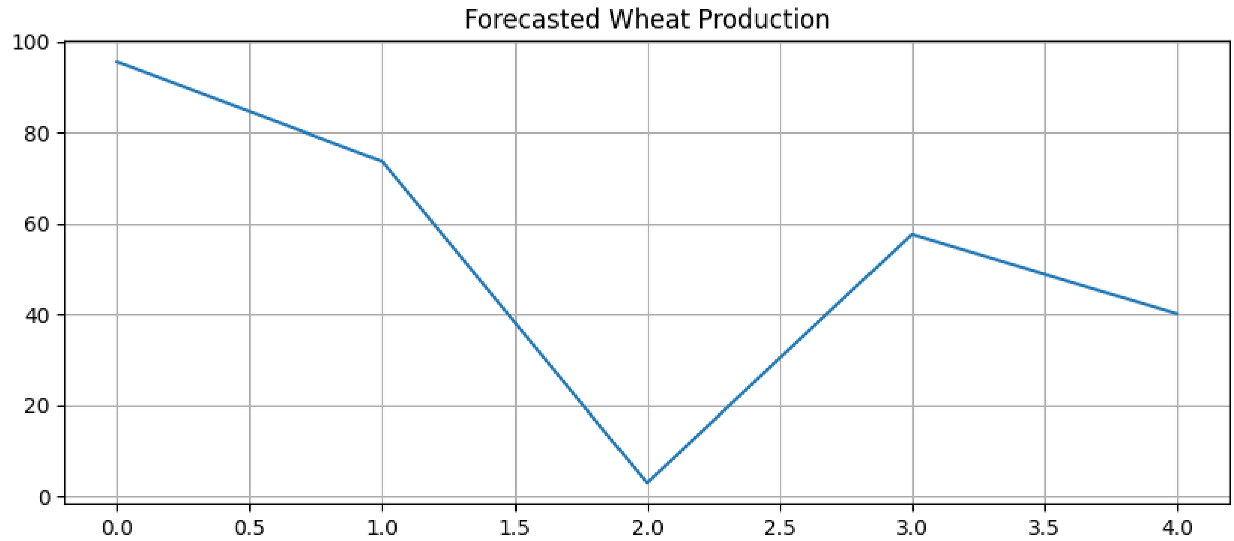
Table-10: Forecasts for Rainfall and Wheat Production in Balochistan

Horizon	Rainfall (mm)	Wheat Production (000 tons/ha)
0	31.63	95.49
1	−7.52	73.66
2	6.11	2.89
3	0.49	57.57
4	−1.56	40.10

Forecast

- **Rainfall:** Forecast values fluctuate around zero, showing moderate short-term variability.
- **Wheat Production:** Forecasts vary widely, reflecting output volatility with alternating peaks and troughs.
- **Overall:** The forecasts capture short-term dynamics, consistent with climatic shocks and agricultural fluctuations

Figure-7: Forecasted Wheat Production



The forecast shows a decline in wheat output up to horizon 2, followed by recovery at horizon 3 and slight moderation at horizon 4. This pattern highlights short-term volatility with eventual stabilization, consistent with rainfall-driven dynamics observed in the VAR model.

Discussion

The VAR analysis confirms rainfall as the dominant driver of wheat production variability in Balochistan. Impulse response functions show that rainfall shocks dissipate over time, while wheat output declines in the short run (lags 2–3) before stabilizing. Granger causality tests reinforce this finding, rejecting the null hypothesis and establishing rainfall as a significant predictor of wheat production. Variance decomposition further highlights that rainfall increasingly explains wheat output variability across horizons, underscoring its persistent influence.

These results align with earlier studies. Hussain and Mudassar (2007) demonstrated that wheat yields in mountain regions are highly sensitive to rainfall shocks, while Khan and Akhtar (2019) confirmed rainfall's strong impact on wheat output across Pakistan. Abro et al. (2025) emphasized rainfall variability as a key factor in drought vulnerability, and Rees et al. (1989) documented the reliance of upland Baluchistan's farming systems on rainfed wheat. Together, these studies validate the present findings and highlight the broader relevance of rainfall–production dynamics.

From a policy perspective, the implications are significant. Ahmad and Farooq (2010) noted that climate variability directly threatens Pakistan's food security, while the IPCC (2021) projects intensifying rainfall extremes under climate change. In Balochistan, where agriculture is predominantly rainfed, investment in water management, drought-resilient wheat varieties, and climate-smart practices is essential to mitigate volatility. Recent provincial initiatives, such as solar tube wells (Balochistan Pulse, 2025; Dawn, 2025), represent steps toward resilience but must be complemented by broader adaptive strategies.

Overall, the study confirms that rainfall shocks exert persistent and lagged effects on wheat production, while production shocks are temporary and self-correcting. By situating these findings within the wider literature, the analysis strengthens understanding of the climate–agriculture nexus in Pakistan and provides evidence for targeted interventions to safeguard food security under increasing climatic uncertainty.

Conclusion

This study confirms that rainfall is the key driver of wheat production variability in Balochistan. The VAR analysis showed that rainfall shocks have significant lagged effects, particularly at lags 2–3, while wheat production shocks are temporary and self-correcting. Granger causality tests established rainfall as a predictor of wheat yields, and variance decomposition highlighted rainfall's growing influence on wheat output over time.

These findings align with earlier research on Pakistan's vulnerability to climate variability and emphasize the province's dependence on rainfed agriculture. Policy implications are clear: investment in water management, drought-resilient wheat varieties, and climate-smart practices is essential to stabilize production. Recent initiatives, such as solar tube wells, are promising but must be scaled up to strengthen resilience.

Overall, rainfall shocks remain the most persistent threat to food security in Balochistan. Addressing this challenge requires targeted interventions and adaptive strategies to safeguard agricultural sustainability under increasing climatic uncertainty.

Recommendations

Based on the findings, rainfall variability is the dominant factor influencing wheat production in Balochistan. Policymakers should prioritize investment in climate-smart agriculture, including drought-resilient wheat varieties and improved irrigation systems. Expanding solar tube wells and water harvesting structures can reduce dependence on erratic rainfall. Strengthening meteorological monitoring and early warning systems will help farmers plan sowing and harvesting more effectively. Capacity-building programs for farmers on adaptive practices, such as crop diversification and soil moisture conservation, are also essential to enhance resilience and ensure food security.

Limitations of the Study

This study is limited by its reliance on annual time series data (2000–2025), which may not fully capture intra-seasonal rainfall variability or short-term shocks. The analysis focuses only on rainfall and wheat production, excluding other important factors such as temperature, irrigation practices, soil fertility, and market dynamics. Additionally, the dataset is provincial in scope, which may mask district-level heterogeneity in rainfall and crop responses. These limitations suggest caution in generalizing results beyond the study area.

Future Research Directions

Future studies should incorporate multi-factor models that include temperature, irrigation, soil quality, and socio-economic variables to provide a more comprehensive understanding of wheat productivity. Using higher-frequency data (monthly or seasonal) would allow for more precise modeling of rainfall impacts. Expanding the analysis to other provinces of Pakistan could highlight regional differences in climate–agriculture dynamics. Finally, integrating climate change scenarios and simulation models would provide valuable insights into long-term risks and adaptive strategies for sustainable food security.

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