The Impact of CO_2 Emissions, Climate Change and Natural Disasters on Agricultural Production in Pakistan

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Abstract

The consistency of agricultural productivity is fundamental to global food safety, but it is increasingly under threat from climate change, natural disasters, and CO2 Emissions. Rising CO2 emissions, along with other natural disasters, alter crop-growing patterns and the broader climate system, including temperatures. This causes agricultural yields to decline, become more variable, be of lower quality, be less certain, and be lower across the board. The primary objective of this research is to examine the relationships among climate change, natural disasters, CO2 emissions, and food safety, with an emphasis on their effects on crop yield quality. We used secondary time-series data from 2000 to 2024 and employed econometric techniques, including the Correlation Matrix and the ARDL model, to estimate these relationships. The findings reveal that decoupled changes in the period and level of temperature, rainfall, and the occurrence of natural disasters are outcomes of climate change and CO2 emissions, and these negatively affect agricultural production. which acts unsustainably on agricultural production. The study suggests global cooperation and strong policy initiatives to control climate change and reduce CO2 emissions, as the UN's SDG 13 emphasises the urgent need for a global response to curb the release of greenhouse gases, particularly CO2.

Keywords: Climate Change; Natural Disasters; Global Warming; CO2 Releases

Introduction

In Pakistan, agriculture is the backbone of the economy, contributing about 24% to the Gross Domestic Product (GDP), employing approximately 38% of the active labor force, and underpinning the food safety and rural livings of the country (Pakistan Bureau of Statistics, 2024). However, the area under cultivation is increasingly under threat from environmental stressors, particularly rising carbon dioxide (CO2 emissions), climate change, and recurrent natural disasters. These challenges not only negatively affect agricultural production but also pose significant threats to economic growth (Ali et al., 2022). Climate variation is considered a serious global issue of the 21st century. Industrialisation, energy consumption, deforestation, global warming, and changing rainfall patterns have raised average temperatures (IPCC, 2022). Rapid environmental changes are negatively affecting crop yields, soil fertility, water resources, and pest infestations (Arora, 2019).

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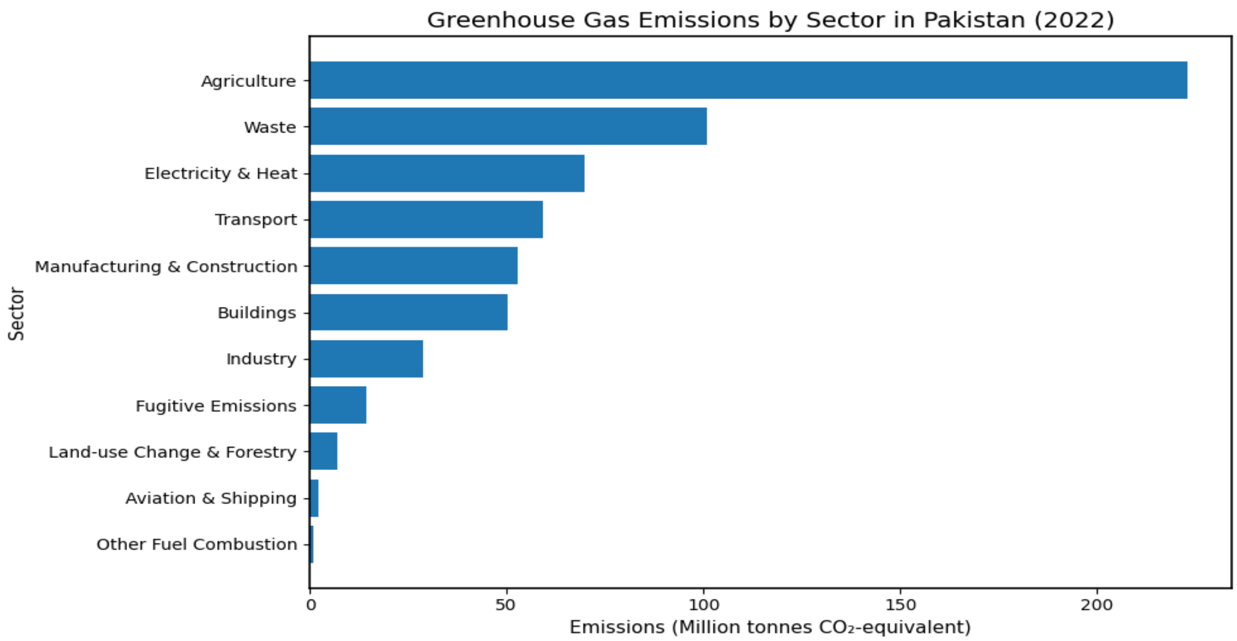
CO2 Emission

The Pakistan agricultural sector is a major source of national greenhouse gas emissions. Recent academic studies identifying energy use for irrigation and machinery, fertilizer application, livestock, and residue burning as key drivers of rising CO_2 emissions in the country (Raza et al., 2023; Global Carbon Project, 2025) Empirical literature on climate-smart agriculture also demonstrates that targeted CSA practices—improved irrigation efficiency, precision nutrient management, and renewable-powered pumping—can simultaneously enhance productivity and lessen the agriculture sector's carbon intensity. The studies such as Taylor, & Schlenker, 2021; Raza et al., 2023; Ali & Mujahid, 2024; Iftikhar et al., 2024; Tunio et al., 2024 suggest that effective mitigation in agriculture sector need integrated policies that combine energy transition on farms, improved input management, and provide incentives for climate-smart practices to achieve significant CO_2 reductions without undermining rural livelihoods. Figure 1 shows that the agriculture sector is the major driver of greenhouse gas emissions.

Figure 1: Sectoral greenhouse gas emissions contribution

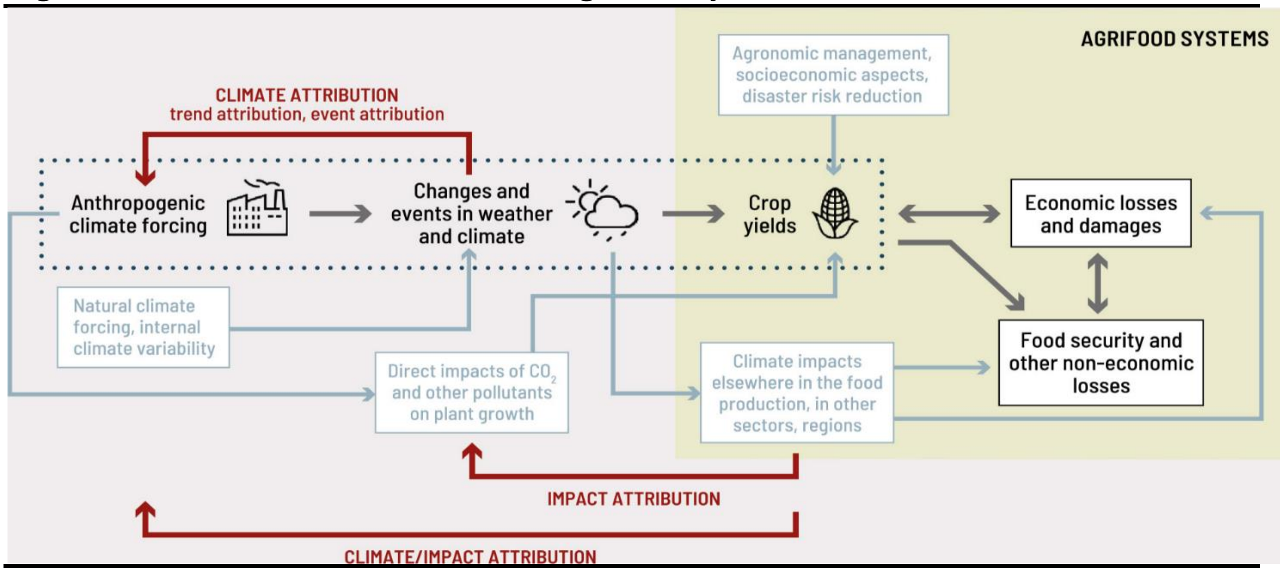


Source: Climate Watch, 2025.

Climate Change

Climate variation is the most critical issue in Pakistan, and it has undergone changes during the past. few years as well as the climate of the whole region of South Asia with considerable impact on environment and inhabitants. Along with the rise in heat, the Himalayas glaciers are melting rapidly and are affecting main rivers of Pakistan, sometimes producing water scarcity and sometimes bringing heavy floods Maqbool and Shah (2018). Pakistan ranked fifth among the countries with extreme weather due to climate change since 1999. The variation in climate is producing frequent and severe impacts across physical, ecological, and social systems, with recent syntheses confirming that continuing current emission trajectories will significantly increase the risks of extreme heat, sea-level rise, and compound climate events (IPCC, 2023; Hultgren et al., 2025; Global budget 2025; Friedlingstein et al., 2025; UNEP, 2024; Chen, et al. 2025). Latest peerreviewed studies highlight that, while nature-based and technological mitigation options can play a crucial role in reducing atmospheric CO_2, their effectiveness depends on strong land-use governance, rapid deployment at scale, and robust safeguards to prevent adverse social or biodiversity effects (Bai et al., 2022; Nature Climate Change expert reviews, 2024; PCC, 2023; UNEP, 2024; Global Carbon Project, 2025). The interconnected process of climate variation and impact of disasters on agrifood systems are shown in Figure 2.

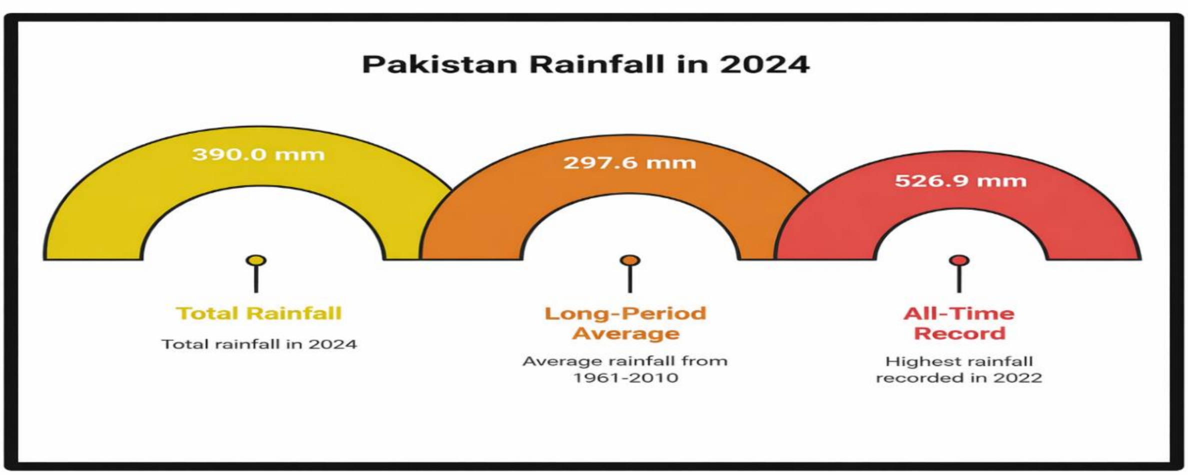
Figure 2: How do climate attributes and agri-food systems interact?



Source: Global Cabon Project, 2025.

As per the State of Pakistan Climate Report, (2024), Pakistan recorded a total rainfall of 390.0 mm, which was 31 percent higher and it broke the last 49 years (1961-2010) average record of 297.6 mm. The year 2024 was the warmest with average mean temperature reaching 23.52°C. This was above average of 22.80°C recorded during 1961-1990. The monthly distribution of rainfall in 2024 is shown in Figure 3, shows climate-driven challenges experienced and Pakistan in 2024.

Figure 3: Rainfall fluctuation in Pakistan



Source: The author own drawing using Napkin Software and State of Pakistan Climate in 2024

Natural Disasters

Pakistan is vulnerable to several natural disasters such as earthquakes, floods, cyclones, scarcities and heat waves. The most common and most ubiquitous are floods. Although earthquakes may inflict great destruction, riverine floods are devastating and cause heavy damage in Sindh and Punjab provinces every year due to monsoon rains. Awan, 2015; Zahid & Shafqat, 2020). Between 1980-2024, Pakistan faced 224 devastating natural disaster incidents. Among them, floods were the most horrible event in terms of human and economic loss as well as making a vast population homeless due to destruction of their houses. With 109 incidents of different types of floods displaced more than 100 million people and inflicted a total economic loss of US$ 36.4 billion (World Bank. (2016). Table 1 shows the detail of human and financial losses suffered by Pakistan during last 34 years due to climate change-related disasters.

Table 1: Summary of Natural Disasters, Human and Financial losses (1980–2024)

Types of disasters	Sub-Type of disasters	Incidences	Deaths	Population affected	Economic losses (in 000 US$)
Drought	Drought	2	220	6,880,912	247,000
Total (Drought)	—	2	220	6,880,912	247,000
Earthquake	Ground Movement	30	75,124	7,420,276	5,345,500
Total (Earthquake)	—	30	75,124	7,420,276	5,345,500
Epidemic	Bacterial Disease	2	105	10,028	—
	Parasitic Disease	1	0	—	5,000
	Viral Disease	4	130	59,066	—
	Infectious Disease (General)	5	131	—	371
Total (Epidemic)	—	12	366	69,094	5,371
Extreme Temperature	Cold Wave	3	18	—	—
	Heat Wave	13	2,741	80,574	18,000
Total (Extreme Temperature)	—	16	2,759	80,574	18,000
Floods	Flash Floods	28	3,630	22,114,353	10,184,118
	Riverine Floods	42	6,329	34,967,357	9,727,030
	General Floods	39	5,059	43,694,593	16,510,230
Total (Floods)	—	109	15,018	100,776,303	36,421,378
Mass Movement	Avalanche	13	580	4,460	—
	Landslide	9	222	29,707	18,000
	Mudslide	2	16	12	—
	Rockfall	1	13	—	—
Mass Movement total	—	25	831	34,179	18,000
Storms	Convective Storm	18	514	1,019,806	—
	Tropical Cyclone	5	1,106	2,189,940	1,710,936
	Storm (General)	7	223	3,123	—
Total (Storms)	—	30	1,843	3,212,869	1,710,936

Note: Damages reported in thousands of US dollars (000 US$).

Source: Fiscal Risk Statement (March 2025).

Agriculture sector

Agriculture sector is divided into three sub sectors: Crops, Livestock, Fisheries and Forests. As per 7th Census, 2024, the share of Livestock in agriculture is 63.6%, crops 32.6%, Fisheries and Forestry is 3.6%. Now we discuss different indicators of agricultural sector to understand their importance (Pakistan Bureau of Statistics, 2024).

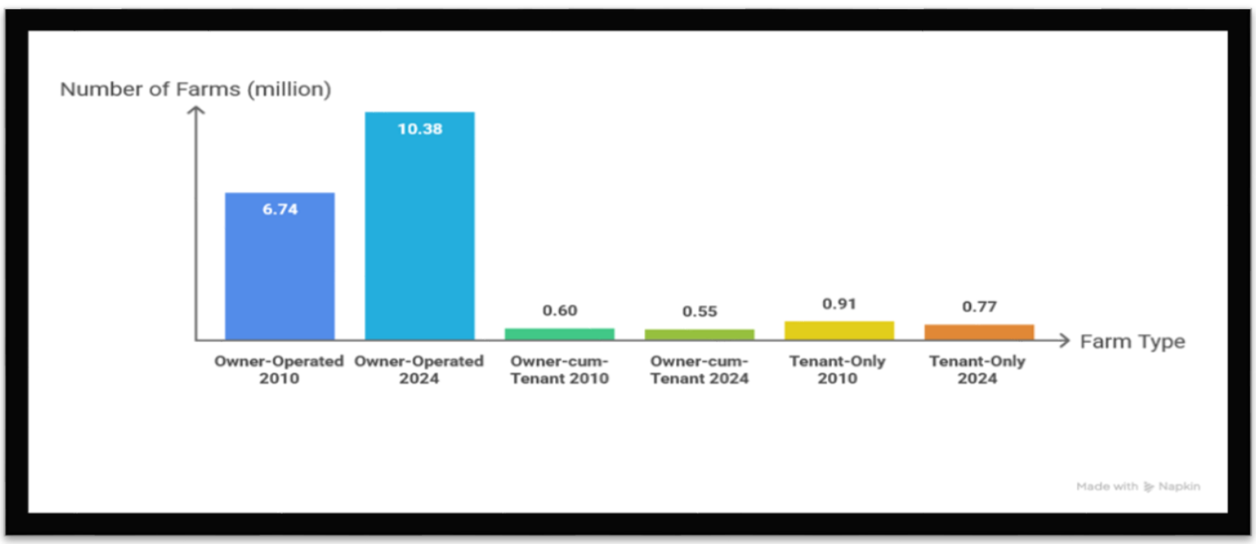
Size of Agricultural households

The agriculture sector is a large segment of the Pakistani economy and its shares in GDP is 24%, bigger than Industrial sector (18%) and smaller than service sector (58%). Around 20 million people are attached to this sector, and they are known as agriculture households. Out of total 19,799,443 agricultural households, 98.5% (19,501,431) are male head of HHs and 1.5% (298,012) are female heads (Pakistan Bureau of Statistics, 2024). This distribution highlights a significant gender disparity among agricultural households.

Farm ownership pattern

The number of crop land holding households is 11,701,584, who own or manage cropland. In 2024, Pakistan had nearly 11.7 million total farms, a significant rise from 8.26 million in 2010. Most farms are managed by owners (about 10.38 million), compared to 6.74 million in 2010, pinpointing a positive strong transition toward farm ownership. Owner-cum-tenant farms reduced to 0.55 million from 0.60 million, and tenant-only farms also declined to 0.77 million in 2024 from 0.91 million in 2010, indicating a sharp fall in tenancy-based farming (Pakistan Bureau of Statistics, 2024). This was shifting trend from land ownership from tenant farming, which is a healthy sign. The ownership structure and farming patterns are presented in Figure 4.

Figure 4: Farm ownership patterns in Pakistan (2010-2024)



Cultivated Area and farming trends

Pakistan's agricultural landscape has undergone notable structural and compositional changes over the period 2010–2024. The total farm area expanded from about 52.9 million acres in 2010 to nearly 59.3 million acres in 2024, while cultivated land also increased from roughly 42.6 million to 52.8 million acres. Despite this expansion, the average farm size declined from 6.4 to 5.1 acres, and cultivated land per farm fell from 5.2 to 4.5 acres, reflecting increasing fragmentation of holdings. Punjab remained the dominant province, accounting for approximately 5.05 million farms with 31.04 million acres of farm area and 29.6 million acres under cultivation (Pakistan Bureau of Statistics, 2024). In terms of water use, irrigated agriculture became increasingly prominent, with total irrigated area reaching about 45.9 million acres in 2024. Canal irrigation expanded substantially, while rain-fed cultivation contracted sharply, indicating a growing reliance on controlled water sources**.** Concurrently, the total cropped area rose markedly to 82.8 million acres. Table 2 shows land use, cropping trends.

Table 2: Land Use, Cropping Pattern, and Irrigation in Pakistan (2010–2024)

Category	2010	2024	Key Observation
Total Farm Area (million acres)	52.9	59.3	Expansion of farm area
Cultivated Area (million acres)	42.6	52.8	Increased land under cultivation
Average Farm Size (acres)	6.4	5.1	Declining average farm size
Cultivated Land per Farm (acres)	5.2	4.5	Land fragmentation
Total Cropped Area (million acres)	67.9	82.8	Intensification of farming
Irrigated Area (million acres)	—	45.9	Dominance of irrigated farming
Rain-fed Area (million acres)	8.4	4.9	Sharp decline in non-irrigated land

Source: Pakistan Bureau of Statistics, 2025.

Livestock contribution in Agriculture

Livestock is a large subsector of Pakistan's agriculture sector, and it covers animal population comprising sheep, goats, cattle, buffaloes, camels, horses, mules, and asses. In 2024, total livestock population peaked at 251.3 million. Punjab province possesses the largest share of 104 million animals. Baluchistan province with 47.9 million total animals out of 18.8 million sheep, 22.9 million Goats and 0.772 million Camels due to having arid terrain and pastoral landscape (Pakistan Bureau of Statistics (2024).

The above empirical evidence reflects how climate change and natural disasters are affecting Pakistan's agriculture sector. The fall and rise of the production in agriculture cause adverse fluctuations in Pakistan's GDP growth because agriculture sector's share is 24 percent. There is an urgent need to conduct deeper research to understand climate change phenomena and its severe impact. Hence, the primary objective of this study is to examine the influence of CO_2 emissions, climate change and natural disasters on agriculture production in Pakistan. To explore these objectives, we have constructed the following research questions to identify direct and indirect relationships among these variables.

- How do CO_2 releases and climate change affect agricultural production in Pakistan?
- How natural disasters affect crop yield and overall agricultural production in Pakistan?
- How is GDP growth affected due to climate change and natural disasters and how it can be sustained without compromising environmental quality.
- What types of mitigating strategies can be adopted to minimize the effects of climate change and natural disasters on human lives and agriculture production.

By exploring these research questions, this study will add new piece of knowledge on CO_2 emissions, climate change and natural disasters, besides developing understanding the causes and impact of these three variables on Pakistan's agriculture production. The study's findings add new insights into the ecological and Environmental Economics and enhance the understanding of scholars and policymakers about the importance of Pakistan's agrarian economy and enable them to devise resilience strategies to control climate change, natural disasters and CO_2 emissions to achieve UN' s Sustainable Development goals #13, which urges to "take immediate action to reduce the impacts of climate change."

Literature Review

Theoretical Underpinning

The theory of Anthropogenic Global Warming (AGW) argues that the influential driver of contemporary climate change is the rapid increase in greenhouse gas emissions originating from human economic activity, particularly fossil-fuel combustion, industrial production, and land-use change. Empirical attribution studies increasingly show that natural climatic forcings, such as solar variability and volcanic activity, are insignificant to explain the scale and consistency of observed global warming since the mid-twentieth century (IPCC, 2021; Ribes et al., 2021). However, critics of AGW highlight uncertainties related to climate sensitivity estimates and the magnitude of feedback mechanisms, especially those associated with water vapor and cloud dynamics. Despite these debates, model–observation comparisons show that temperature trends align closely with projections incorporating anthropogenic forcing, particularly when aerosol cooling effects are measured for, strengthening the empirical credibility of the theory (Hausfather et al., 2020).

If we study this theory in Pakistan-specific perspective, it offers a robust explanatory framework for understanding the country's growing exposure to climate extremes, despite its relatively small contribution to global emissions. Empirical studies link anthropogenic warming to intensified heatwaves, erratic monsoon patterns, accelerated glacial melt in the Hindu Kush–Karakoram–Himalaya region, and increased flood risk — all of which have been observed with increasing frequency in Pakistan over recent many decades (Philip et al., 2022). Attribution research further suggests that flood events in South Asia have been significantly augmented by human-induced warming, underscoring the uneven global distribution of climate impacts. While AGW does not deny the role of regional climatic variability, it provides a scientifically grounded basis for interpreting Pakistan's climate vulnerability as part of a broader global process driven by anthropogenic emissions, thereby reinforcing the need for both mitigation at the global level and adaptation at the national level.

Another theory which directly relates to this research is *Adaptive management theory* developed by Tunio et al. (2024) and refined by Taylor and Schlenker (2021) is a paradigm that explains how complex systems can be managed in a process that is responsive to the changes in climate and natural disasters. This is a natural resource management approach that highly regards the importance of the continuing learning process, flexibility and adaptability in response to change and uncertainty. The basic concept is that the managers will put the policies and initiatives in place and then at the end evaluate the system and changes that have been ocurred in the light of feedback. It recognizes that human systems and ecosystems are dynamic and that management plans need to be modified on a regular basis to manage it.

Empirical Analysis and Hypothesis Development

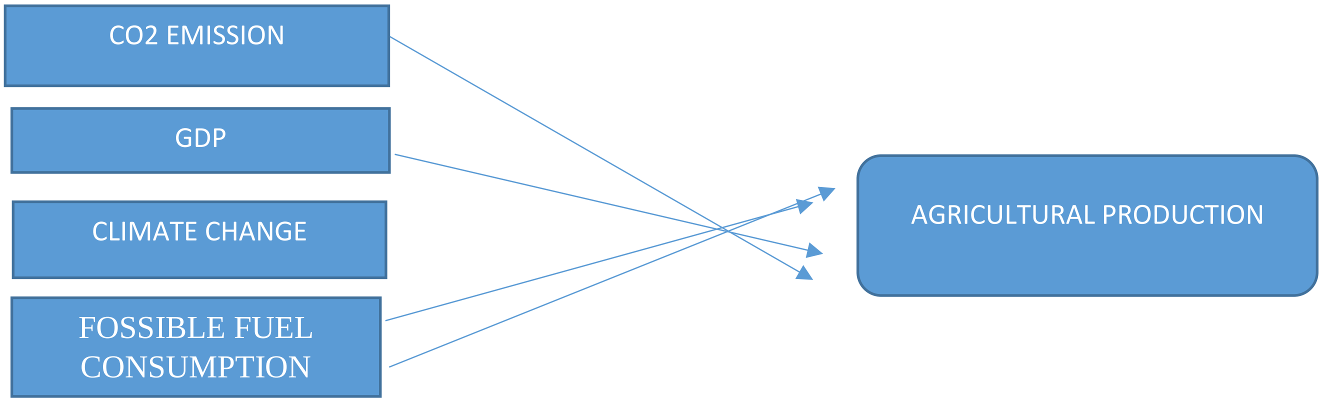
Academic scholars consistently urge that climate change poses a serious threat to Pakistan's agricultural systems. Awan (2015) found that increasing drought conditions in Punjab province of Pakistan reduced crop yields and altered seasonal crop dynamics, highlighting the sensitivity of crop production to climatic variability. A study by Awan, (2015) further corroborated these concerns, indicating that rising temperatures and extreme weather incidences negatively affect agricultural output, suggesting that temperature increases can suppress crop yields. Another seminal study conducted by Ramsey (1969) and Sarwar et al. (2014) identified agriculture's relationship with carbon emissions and found significant asymmetric impacts of CO_2 emissions on agricultural output, underscoring the complex interplay between productivity and environmental footprints. These findings confirm that rising CO_2 concentrations, while potentially increasing photosynthesis, also change crop nutrient quality and exacerbate heat stress, ultimately affecting agricultural production.

The natural disaster, especially flooding, has been studied extensively in relation to agricultural losses. The disastrous 2022 floods, which inundated millions of hectares of fertile land, demonstrated the vulnerability of Pakistan's agrarian economy to extreme weather. An integrated satellite-based assessment revealed that 1.1 million hectares of cropland were inundated in Sindh alone. The severity of these events is increasingly being attributed to climate change; for example, a World Weather Attribution study reported that monsoon rainfall in recent extreme events was up to 15 % heavier due to global warming, intensifying flood impacts on agriculture and human settlements (Li & Raza, 2019; Awan & Aslam, 2015) probed irrigated agriculture in Punjab and Sindh and found that farmers perceive significant climate variability but face constraints in adaptation due to socio-economic and institutional limitations, highlighting gaps in resilience and climate-smart investment. Similarly, Awan (2013)emphasize that rising temperatures, water security issues, and heat waves are altering cropping patterns and water availability, with broader socioeconomic impacts on rural livelihoods. Hydrological stress—closely tied to climate change—is another critical dimension affecting agriculture. Based on literature and objectives of the study, we proposed the following hypotheses.

H_0; CO_2 emission negatively correlates with Agricultural Production.
H_1: CO_2 Emission positively correlates with Agricultural Production.
H_0: Climate change negatively affects agricultural production.
H_1: Climate Change positively affects agricultural production.
H_0: Natural disasters negatively influence agricultural production.
H_1: Natural disasters positively influence agricultural production.
Ho: Fossil fuel consumption negatively correlates with agriculture production
H_1: Fossil fuel consumption positively correlates with agriculture production.

The conceptual model has been constructed based on variables and hypotheses of the study to identify statistical relationships between independent and dependent variables**.** The sketch of the model is displayed in Figure 5.

Figure 5: Research Model



Methodology

The objective of this research is to assess the impact of CO_2 releases along with climate variation and natural disasters on the agriculture production in Pakistan. This study explores the effects of increase in CO_2 on environment, which is characterized by higher temperatures, modified rain regimes, and more frequent extreme weather resulting in the destruction of the harvests and food inaccessibility due to heat waves, floods, and scarcities. The study used 25 year data spanning from 2000 to 2024 sourced from World Bank's World Development Indicators, Asian Development Bank, Pakistan Economic Survey, the State Bank of Pakistan and Pakistan Bureau of Statistics. Agriculture production serves as a dependent variable while CO2 emissions, Fossil fuel consumption, climate change and natural disasters acted as independent variables. Various econometric techniques such as descriptive statistics, correlation matrix, ADF unit root test, bound test, ARDL approach and error correction model were used to identify statistical link between variables. Through descriptive statistics we understand, means, mode, central tendency and normal distribution of data among variables. Correlation matrix is used to identify the direction of a pair of variables whether they move in the positive or opposite directions. ADF unit root test was employed to check stationarity among variables, and if there are stationery at different levels then we can use ARDL model, which enables us to estimate long-term relationship between independent and dependent variables. To identify model robustness and various issues relating to data and error terms we used different diagnostic tests to disclose multicollinearity, heteroscedasticity, serial correlation and normal distribution of data. We constructed an econometric model showing statistical relationships among variables. The model is explained as follows:

$Y = Bo + B1\ X_1 + B_2 + B_3 + B_4 + \ldots\ldots\ e$

Where?

Y = Agriculture Production

X1 = CO_2 Emission.

X2 = Climate change.

X3 = GDP

X4: Fossil fuel consumption

E = error term

Bo = constant

B1, B2, B3 are slope parameters.

Results

Descriptive analysis

The outcomes of descriptive statistics are given in Table 3.

Table 3: Descriptive statistics results

	AGRI	CLCH	CO2	FFC	GDP
Mean	22.44584	287.8497	4.712399	61.55902	2.691581
Median	22.32833	298.8375	4.751900	60.79000	2.805047
Maximum	25.38714	322.1997	5.658682	67.06111	5.202456
Minimum	19.93795	220.0556	3.396900	57.62000	0.110981
Std. Dev.	1.298054	29.99331	0.731457	2.786334	1.536225
Skewness	-0.023444	-0.765898	-0.339428	0.549380	0.001384
Kurtosis	2.760784	2.483102	1.905254	2.170823	1.918813
Jarque-Bera	0.061899	2.722485	1.728453	1.973757	1.217680
Probability	0.969525	0.256342	0.421377	0.372738	0.543982
Sum	561.1460	7196.243	117.8100	1538.976	67.28952
Sum Sq. Dev.	40.43865	21590.37	12.84071	186.3278	56.63966
Observations	25	25	25	25	25

The findings of descriptive analysis show that all variables' mean and median values are quite close to one another, suggesting that the statistics are well-balanced and devoid of notable outliers. The results indicate that climate change (CLCH) shows strong variability, indicating significant swings in climate-related metrics. The fact that CO_2 releases and fossil fuel consumption (FF) are more steady than other variables is further supported by standard deviation statistics. Most variables show rough symmetrical distribution apart from climate change, which has mild negative skewness. The skewness values remain close to zero. Additionally, all variables had kurtosis values less than 3, implying platykurtic distributions, which contain fewer extreme values. Furthermore, all variables displayed a normal distribution as evidenced by the Jarque-Bera test where the probability values exceeded the 0.05 threshold. In conclusion, the dataset is normally distribution and as such further econometric analysis can be carried out.

Correlation Analysis

Correlation matrix is widely used by researchers to identify nature of correlation between variables, implying when one variable increase or decreases, the other variables also follow the same direction. The results of correlation matrix are presented in Table 4.

Table 4: Correlation Matrix outcomes

	AGRI	CLCH	CO2	FFC	GDP
AGRI	1				
CLCH	-0.340049268570481	1			
CO2	-0.1884548119606732	0.5604457640736815	1		
FFC	-0.2270289079963537	0.6111695665903664	0.8209364282695869	1	
GDP	-0.3261712463462631	0.3544937040797041	0.2823259766964048	0.2801925454233413	1

Climate change (0.34), CO_2 releases (0.19), fossil fuel consumption (0.22) and GDP (0.32) were all weakly positively correlated with agricultural production (AGRI), meaning that while these factors do exert some effect on agriculture, their interactions were not significant. Climate change (CLCH) has a moderate positive correlation with CO_2 releases (0.56) and fossil fuel consumption (0.61), which means that higher fossil fuel use is significantly linked to higher CO_2 releases and stronger climate change effects. Considering that fossil fuels as a major driver of Emission, the correlation between CO_2 emission and fossil fuel consumption is large (0.82). GDP is positively moderately correlated with all other variables, but most strongly correlated with CO_2 emission (0.28) and climate change (0.35).

Unit root tests

These tests are used to check stationarity among variables. The outcomes of these tests are presented in Table 5.

Table 5: Unit Root tests results

Results of ADF and PP Tests				
variables	**ADF**		**PP**	
	Level	1st Difference	Level	1st Difference
AGRI	0.0952	0.0350	0.0952	0.0389
CO2	0.5032	0.0000	0.3813	0.0000
GDP	0.0040	0.0000	0.0040	0.0000
FFC	0.9139	0.0469	0.9337	0.0003
CLCH	0.0033	0.0062	0.0031	0.0000

All the values are probability values.

The outcomes of the ADF and PP unit root tests suggest that the variables have different orders of integration. In the case of the integration of FF, CO2, and AGRI, these variables are of order one, is to say, 1(1): these variables are non-stationary at level but become stationary after first differencing. In contrast, the GDP and CLCH systems are stationary at level and of order zero, one (0). For these reasons, the Autoregressive Distributed Lag (ARDL) bounds testing approach can be used to estimate short-and-long-term relationship among variables.

Bound Test

This tool provides unbiased long-run estimates of small samples and helps address issues of endogeneity through appropriate lag structures. The results of Bound test are presented in Table 6.

Table 6: ARDL Bounds Test for Long-Run Cointegration

Null Hypothesis: No cointegration
Sample Size (Asymptotic): *n* = 1000

Test Statistic	**Value**	**Significance Level**	**I(0) Lower Bound**	**I(1) Upper Bound**
F-statistic	**8.6087**	10%	2.20	3.29
		5%	2.56	3.29
		2.5%	2.88	3.29
		1%	3.29	3.29
Number of Regressors (K) 4				

The findings of Bound test show that the variables have a long-term relationship. The upper critical limits values are all traditional significance levels (3.09 at 10%, 3.49 at 5%, 3.87 at 2%, and 4.37 at 1%), are much lower than the computed F-statistics of 8.61. The null hypothesis that postulates no long-term link between explanatory and explained variables is rejected if the test statistics are more than 1(1) critical values. This suggests that, despite potential short-term volatility, the study's variables have a stable long-term equilibrium relationship because they are cointegrated.

ARDL Long-run results & Hypotheses testing

The Autoregressive Distributed Lag (ARDL) model is widely used in econometric analysis because it is the most suited for identifying long-run relationships among variables, even when they are integrated of different orders, i.e., I (0) and I (1). Contrary to traditional cointegration methods, the ARDL approach does require that all variables must be integrated at the same level, making it particularly useful in applied research with limited time-series observations. These characteristics make the ARDL framework a robust and flexible tool for analyzing economic, financial, and environmental relationships, especially in developing-country like Pakistan where data constraints are common (Pesaran et al., 2001; Narayan, 2005). The ARDL model long-term estimated results are presented in Table 7.

Table 7: ARDL Long-Run Estimation Results

Variable	Coefficient	Std. Error	t-Statistic	Prob.
CLCH	-0.0418	0.0165	-2.5374	0.0318
CO_2	1.4717	0.6621	2.2226	0.0533
FFC	0.0332	0.1595	0.2080	0.0399
GDP	-0.6067	0.1737	-3.4921	0.0068
C (Constant)	27.0500	6.1500	4.3984	0.0017

*****Agriculture production is dependent variable.
Source: Author own calculation using E-View software.

The estimated long-run Cointegration Equation is as follows:

$$EC = AGRI - (-0.0418\,CLCH + 1.4717\,CO_2 + 0.0332\,FF - 0.6067\,GDP + 27.0500)$$

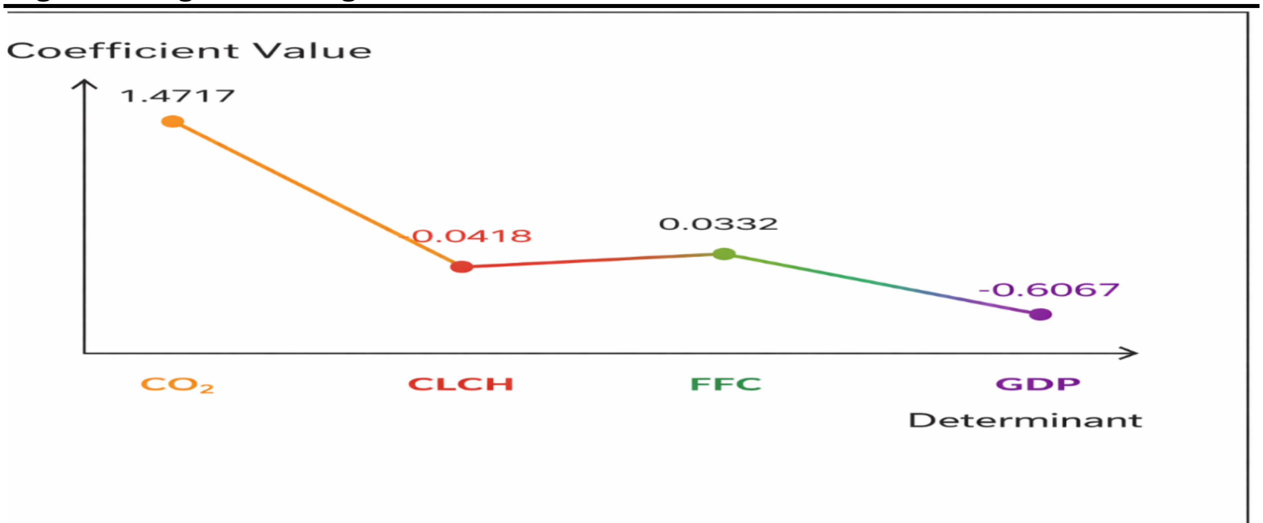
According to the ARDL long-term findings shown in Table 8, agricultural production (AGRI) is affected by climate change (CLCH), carbon deoxidate releases (CO_2), fossil fuel consumption (FFC), and GDP. CO_2 releases have a positive coefficient (1.4717) and are weakly significant at the 10% level (p=0.0533), indicating that in the long run, higher releases may initially be associated with agricultural expansion, possibly due to industrial and mechanized farming, but that over time, the environmental costs could outweigh the benefits. This finding is in line with the prediction of *Environmental Kuznets Curve Hypothesis*. Hence, first null hypothesis (Ho) is rejected, and alternate hypothesis (H_1) is confirmed by empirical evidence. However, Climate change (CLCH) has a negative and statistically significant effect on agriculture production (coefficient = -0.0418, p = 0.0318), indicating that adverse climate changes decrease agricultural output. Therefore, second null hypothesis (Ho) is confirmed by empirical evidence. The small but substantial positive effect of fossil fuel consumption (FFC) (0.0332, p=0.3999) on agriculture output do not support null hypothesis (Ho), which states that fossil fuel consumption has no relationship with agriculture output. Hnece, alternate hypothesis (H_1) is confirmed. However, GDP has a significant negative effect (-0.6067, p=0.0068), which may reflect that as the economy grows, resources shift away from agriculture to industry and services sectors, reducing agricultural contribution in GDP. These findings support *Environmental Kuznets Curve (EKC) hypothesis*, which postulates that GDP growth has adverse effect on the environment at initial stage. The constant term (27.05, p=0.0017) is significant, including the presence of other structural factors sustaining agricultural output. The results of hypotheses testing are exhibited in Table 8**.**

Table 8: Results of Hypotheses testing

Variables	Effect Direction	Statistical Significance	Hypothesis Result	Explanation
CLCH	Negative	Significant (5%)	Ho: Supported	Climate stress reduces productivity
CO_2	Positive	Weakly significant (10%)	H_1: Supported	Industrialization boosts agriculture initially
FFC	Positive	Significant (5%)	H_1: Supported	Mechanization raises output in long-run
GDP	Negative	Highly significant (1%)	Ho: Supported	Structural shift away from agriculture

These long-term results are displayed in Figure 6 for further elucidation.

Figure 6: Regression long-term trends



Error Correction Model

This Model (ECM) is widely employed in empirical analysis to identify the short-run dynamics of a system while ensuring consistency in its long-run equilibrium relationship. When variables are cointegrated, deviations from long-run equilibrium may be taken place in the short run; this model includes an error-correction term which denotes the speed at which these deviations are corrected over time. This permits scholars to differentiate between short-term adjustments and long-term causal links among variables, reflecting a more realistic representation of economic behavior. In fact, the ECM is a valuable tool, which is commonly used in time-series analysis for understanding both equilibrium restoration and quick interactions among variables as suggested by Engle & Granger, (1987) and Banerjee et al. (1993). The outcomes of ECM are presented in Table 9.

Table 9: Error Correction Regression results

Variable: D(AGRI)				
Selected Model: ARDL (1, 2, 2, 2, 2)				
Case 4: Un-restricted Constant and Restricted Trend				
Date: 08/23/25 Time: 03:46				
Sample: 2000 2024				
Included observations: twenty-three				
ECM Regression				
Case 4: Un-restricted Constant and Restricted Trend				
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
C	-11.47746	0.762362	-15.05514	0.0000
D (CO2)	0.629478	0.158629	3.968247	0.0041
D (CO2 (-1))	-1.451083	0.173170	-8.379511	0.0000
D(CLCH)	-0.005255	0.002188	-2.402131	0.0430
D (CLCH (-1))	-0.007460	0.002311	-3.227817	0.0121
D(FF)	0.424312	0.053775	7.890472	0.0000
D (FF (-1))	-0.095888	0.044933	-2.134001	0.0654
D(GDP)	0.044305	0.032368	1.368781	0.2083
D (GDP (-1))	0.455089	0.046154	9.860279	0.0000
CointEq (-1) *	-0.242564	0.015989	-15.17025	0.0000

Source: The author owns calculation using E-view software

The consequences of the Error Correction Model for agricultural output (AGRI) show short-term dynamics. The error correction term (CointEq (-1)) is negative and significant (-0.242564, p=0.0000), confirming a long-run equilibrium from the previous period that is corrected annually in the short-run, even though their lagged effect (D (CO_2 (-1))) is negative and significant (-1.451083, p=0.0000), indicating mixed short-run dynamics. Agriculture production is positively affected by CO_2 releases (0.629478, p=0.0041). Additionally, agriculture production is significantly affected by climate variation (CLCH) in both its immediate (-0.005255, p=0.0430) and lagged (-0.007460, p=0.0121) forms, underscoring its detrimental effect. GDP growth (D (GDP)) has a large positive and considerable effect on agriculture production; however, it is negligible in the short term (0.044305, p=0.0000). Overall, the results indicate that economic growth and environmental factors (such as climate variation and CO_2 releases) have a considerable effect on agricultural output. Fusil fuel consumption has also positive impact on agriculture output in the short term.

Variance Inflation Factors

This technique is used to identify the issue of multicollinearity among variables. The estimated findings are presented in Table 10.

Table 10: Variance Inflation Factors Outcomes			
Date: 08/09/25 Time: 09:40			
Sample: 2000 2024			
Included observations: twenty-five			
Variables	**Coefficient Variance**	**Uncentered VIF**	**Centered VIF**
CLCH	0.000134	166.3375	1.715835
CO2	0.411502	138.6075	3.133436
FF	0.030914	1740.183	3.415827
GDP	0.034458	4.858193	1.157354
C	64.54770	956.9303	NA

Source: The author owns calculations using E-view software**.**

According to the Variance Inflation Factor (VIF) test findings, multicollinearity is not a significant problem in the regression model, and it shows that all variables in the model have VIF values below the recognized cutoff of 10. In particular, the VIF values for CLCH, GDP, CO_2, and FF are 1.71, 1.15, 3.13, and 3.41, respectively. Despite the extremely high uncentered VIF values, they are not observed as problem since the centered VIF values are the common metric used to evaluate multicollinearity. Thus, there is no detrimental multicollinearity in the model, and the predicted coefficients are valid for further analysis.

Diagnostic test for Regression Model

To ensure the reliability of the estimated model, a series of post-estimation diagnostic tests were performed, including serial correlation, heteroskedasticity, and normality checks. The Breusch–Godfrey Serial Correlation LM test indicates that the null hypothesis of no serial correlation up to two lags cannot be rejected, as the probability values for both the F-statistic ($p = 0.7660$) and the Chi-square statistic ($p = 0.6389$) exceed the 5% significance level. This result confirms that the residuals are not serially correlated, implying that the dynamic structure of the model is correctly specified and the estimated coefficients are efficient. Similarly, the Breusch–Pagan–Godfrey test for heteroskedasticity provides strong evidence in favor of homoscedastic residuals. The reported probability values for the F-statistic ($p = 0.2864$), Obs*R^2 ($p = 0.2565$), and scaled explained sum of squares ($p = 0.6183$) are all statistically insignificant. These findings indicate that the variance of the error term remains constant across observations, ensuring the validity of standard errors and hypothesis testing. The summary of serial correlation and Heteroskedasticity tests are summarized in Table 11.

Table 11: Summary of Serial Correlation and Heteroskedasticity Tests

Diagnostic Test	Statistic	Value	Probability	Decision
Breusch–Godfrey Serial Correlation LM Test	F-statistic	0.2717	0.7660	No serial correlation
	Obs*R-squared	0.8967	0.6387	No serial correlation
Breusch–Pagan–Godfrey Heteroskedasticity Test	F-statistic	1.3499	0.2864	Homoskedastic residuals
	Obs*R-squared	5.3148	0.2565	Homoskedastic residuals
	Scaled explained SS	2.6485	0.6183	Homoskedastic residuals

Source: Author’s own calculations using EViews.

Discussion

Key findings

The objectives of this research were to examine the impacts of CO2 emissions, climate change, natural disasters, industrialisation, and GDP growth on agricultural production in Pakistan using 24 years of data sourced from the World Bank’s World Development Indicators, Pakistan Bureau of Statistics, Pakistan Economic Survey, State Bank of Pakistan and Agriculture Department of Pakistan. Agricultural production served as the dependent variable, while the independent variables included CO2 emissions, climate change, natural disasters, industrialisation, and GDP growth. The ARDL modelling approach was employed to predict the relationship between these variables. Diagnostic tests were applied to assess the model's robustness. The empirical findings predict that rising CO2 emissions and climate change manifested through higher temperature, irregular rainfall patterns, scarcities, and floods negatively affect crop yields, livestock productivity and overall food safety (Gornall et al., 2010; Awan, 2013; Sarwar, Awan, & Kalsoom, 2014; Abbas, 2022; Areeja et al., 2022; Ali & Mujahid, 2024; Friedlingstein et al., 2025). Natural disasters such as floods and heatwaves further exacerbate the vulnerability of agricultural production, which is already constrained by limited resources and outdated farming practices (Awan & Yaqoob, 2023; Global Carbon Project). (2025). The results further confirmed that Pakistan’s agricultural output is sensitive to environmental changes, making it one of the most climate-vulnerable countries in the world. If left unaddressed, these factors will continue to threaten not only agricultural production but also the rural population and food security (Arora, 2019; Tunio, Li, & Khan, 2024).

Theoretical Implications

The ARDL long-run findings are significant when interpreted against the backdrop of Pakistan’s climate-sensitive agricultural system, which remains heavily dependent on rainfall during the monsoon season, glacial meltwater streams originating from the Hindu-Kush range of the Himalayas, and smallholder farming practices combined in an integrated manner. In the same vein, the significant and negative relationship of agricultural production loss in Pakistan during climatic change can provide valid empirical support for the validity of the Anthropogenic Global Warming (AGW) theory because the latter holds that anthropogenic global warming has the capacity to impugn natural production patterns, and the negative finding of the Climate change provides strong empirical support for the AGW paradigm. In Pakistan, rising temperatures, erratic monsoon patterns, increased frequency of floods and droughts, and rising glacial melting have directly undermined crop yields, soil fertility, and water availability. The ARDL result confirms that climate change is not a transitory shock but a structural constraint on agricultural productivity, thereby validating the second null hypothesis and reinforcing AGW's claim that anthropogenic emissions impose long-term economic and ecological costs on vulnerable agrarian economies such as Pakistan.

The positive but weakly significant result for CO_2 emissions captures the process-stage characteristic of this aspect in particular in the context of agricultural modernization in Pakistan. With respect to the AGW theory, in the immediate to medium term in particular, higher emissions correlate with higher mechanization, fertilizers, tube-well irrigation, and even post-harvest handling. The implications are higher agricultural outputs in the process, in keeping with the AGW theory as well as the Environmental Kuznets Curve (EKC) hypothesis, which posit that higher economic development in early stages could imply environmental degradation until unsustainable ecological thresholds are breached. With respect to fossil fuels, the positive significant value in particular captures the higher dependence in the context of agricultural outputs in Pakistan, in particular, that emphasizes the rejection of the null hypothesis in this context as much as AGW theory implications, in that fossil fuels heighten vulnerability to climate change in the context of heightened greenhouse gas emissions. Similarly, the sharp impact of the coefficient of GDPPCP indicates the structural change in the broader economic landscape of Pakistan over the years. The impact has continuously favored the development of the industrial and services sectors over the agrarian sector. Within the specific framework of the study, the applicability of the adaptive management theory is very pertinent. The constant term underscores the impacts of traditional knowledge and coping mechanisms that continue to support the output of the agrarian sector even as the challenges mount. Under the logic of the adaptive management theory, the impacts are attributable to the failure to adapt through strategies like climate-smart agriculture and efficient climatic governance. The highlights continued the vulnerability of the agrarian sector in the long-term impacts as predicted by the AGW paradigm.

Conclusion

The study concludes that urgent policy interventions are required including the acceptance of climate resilient farming techniques, efficient water management system in disaster preparedness and the promotion of maintainable agricultural practices. Strengthening institutional frameworks and encouraging farmers' adaptation strategies can mitigate the adverse effects. Addressing CO2 releases through renewable energy adoption and green technologies used play a useful role in reducing environmental footprints and enhancing agriculture production. This research demonstrates that CO2 releases, climate change and natural disasters have a significant adverse effect s on agricultural production in Pakistan. The results confirm that without timely intervention, climate change will continue to undermine food safety and economic stability in Pakistan. Therefore, addressing CO2 Emission, adapting to climate variability are improving disaster resilience and are crucial for sustained agriculture output. The study suggests the adoption of efficient water management system, following climate change-resilient strategies, capacity building and farmers awareness are crucial to reduce the effects of environmental degradation.

The study's results offer important practical implications for policymakers, agricultural planners, and environmental institutions in Pakistan. The finding highlights the need for immediate policy action to promote climate-resilient farming methods, improve water-use efficiency, and strengthen disaster management systems to safeguard agricultural output. Encouraging the adoption of renewable energy and environmentally friendly technologies can help cut carbon emissions while supporting sustainable agricultural productivity. Moreover, strengthening institutional capacity, increasing farmer awareness, and supporting adaptive strategies at the farm level can reduce vulnerability to climate-related shocks and contribute to long-term food security and economic stability.

Despite providing valuable insights, this study is not without limitations. For instance, the study relies on aggregate-level data, which may not fully capture regional differences in climate impacts and adaptive capacity across Pakistan's diverse agro-ecological zones. In addition, this research focuses on selected environmental and climatic indicators, potentially ignoring other socio-economic and technological factors that influence agricultural production. Future research may address these limitations by using disaggregated data, incorporating farm-level adaptation techniques, and identifying the role of institutional effectiveness in greater depth.

References

- Abbas, S. (2022). Climate change and major crop production: Evidence from Pakistan. *Environmental Science and Pollution Research, 29*(4), 5406–5414. https://doi.org/10.1007/s11356-021-16041-4
- Acevedo, M., Pixley, K., Zinyengere, N., Meng, S., Tufan, H., & Cichy, K. (2020). A scoping review of adoption of climate-resilient crops by small-scale producers in low- and middle-income countries. *Nature Plants, 6*(10), 1231–1241. https://doi.org/10.1038/s41477-020-00783-z
- Ali, S., Shah, A. A., Ghimire, A., & Tariq, M. A. U. R. (2022). Investigating the nexus between CO_2 emissions, agricultural land, crop, and livestock production in Pakistan. *Frontiers in Environmental Science, 10*, 1014660. https://doi.org/10.3389/fenvs.2022.1014660
- Ali, S. R., & Mujahid, N. (2024). Sectoral carbon dioxide emissions and environmental sustainability in Pakistan. *Environmental and Sustainability Indicators, 23*, 100448. https://doi.org/10.1016/j.indic.2024.100448
- Arora, N. K. (2019). Impact of climate change on agriculture production and its sustainable solutions. *Environmental Sustainability, 2*(2), 95–96. https://doi.org/10.1007/s42398-019-00078-w
- Awan, A. G. (2013). Environmental challenges to South Asian countries. *Asian Accounting and Auditing Advancement, 3*(1), 84–103.
- Awan, A. G. (2015). Relationship between environment and sustainable economic development: A theoretical approach to environmental problems. *International Journal of Asian Social Sciences, 3*(3), 741–761.
- Awan, A. G., & Aslam, A. (2015). Impact of agriculture productivity on economic growth: A case study of Pakistan. *Global Journal of Management and Social Sciences, 1*(1), 57–71.
- Awan, A. G., & Yaqoob, R. (2023). Economic value of introducing technology to improve productivity: An ARDL approach. *Innovation and Green Development, 2*(3), 1–8.
- Bai, Y. L., Yang, Z., & Wang, G. (2022). Impact of climate change on agricultural productivity: A combination of spatial Durbin model and entropy approaches. *International Journal of Climate Change Strategies and Management*. https://doi.org/10.1108/IJCCSM-02-2022-0016
- Banerjee, A., Dolado, J., Galbraith, J. W., & Hendry, D. F. (1993). *Co-integration, error correction, and the econometric analysis of non-stationary data*. Oxford University Press.
- Chen, Y., Wang, D., Zhang, L., et al. (2025). World Heritage documents reveal persistent gaps between climate awareness and local action. *Nature Climate Change, 15*, 1293–1299. https://doi.org/10.1038/s41558-025-02461-4
- Engle, R. F., & Granger, C. W. J. (1987). Co-integration and error correction: Representation, estimation, and testing. *Econometrica, 55*(2), 251–276.

- Friedlingstein, P., et al. (2025). *Global Carbon Budget 2025 (preliminary)*. Global Carbon Project / *Earth System Science Data* (preprint). https://essd.copernicus.org/preprints/essd-2025-659/ESSD
- Gujarati, D. N., & Porter, D. C. (2009). *Basic econometrics* (5th ed.). McGraw-Hill.
- Hausfather, Z., Drake, H. F., Abbott, T., & Schmidt, G. A. (2020). Evaluating the performance of past climate model projections. *Geophysical Research Letters, 47*(1), e2019GL085378. https://doi.org/10.1029/2019GL08537
- Hultgren, A., et al. (2025). *Climate change impacts on global agriculture accounting for adaptation*. Zenodo. https://doi.org/10.5281/zenodo.14511339
- Iftikhar, H., Khan, M., & Żywiołek, J. (2024). Modeling and forecasting carbon dioxide emission in Pakistan using a hybrid combination of regression and time-series models. *Heliyon, 10*(13), e33148. https://doi.org/10.1016/j.heliyon.2024.e33148
- Intergovernmental Panel on Climate Change (IPCC). (2023). *Climate change 2023: Synthesis report*. IPCC. https://www.ipcc.ch/report/ar6/syr/
- Lin, B., & Raza, M. Y. (2019). Analysis of energy-related CO_2 emissions in Pakistan. *Journal of Cleaner Production, 219*, 981–993. https://doi.org/10.1016/j.jclepro.2019.02.112
- Maqbool, F., & Shah, S. (2018). Assessing the economic impact of climate change in Pakistan: A review of the literature. *Environmental Science & Policy, 89*, 46–53. https://doi.org/10.1016/j.envsci.2018.07.007
- Narayan, P. K. (2005). The saving and investment nexus for China: Evidence from cointegration tests. *Applied Economics, 37*(17), 1979–1990.
- Nature Climate Change. (2024). Expert review: The science underlying nature-based climate solutions. *Nature Climate Change, 14*(4). https://doi.org/10.1038/s41558-024-01960-0
- Ozdemir, D. (2022). The impact of climate change on agricultural productivity in Asian countries: A heterogeneous panel data approach. *Environmental Science and Pollution Research, 29*(6), 8205–8217. https://doi.org/10.1007/s11356-021-16291-2
- Pakistan Bureau of Statistics. (2024). *7th agriculture census*. https://www.pbs.gov.pk/agriculture-census/
- Pesaran, M. H., Shin, Y., & Smith, R. J. (2001). Bounds testing approaches to the analysis of level relationships. *Journal of Applied Econometrics, 16*(3), 289–326.
- Philip, S. Y., Kew, S. F., van Oldenborgh, G. J., et al. (2022). Rapid attribution analysis of the extraordinary heat wave on the Pacific coast of the US and Canada in June 2021. *Earth System Dynamics, 13*, 1689–1713. https://doi.org/10.5194/esd-13-1689-2022
- Ramsey, J. B. (1969). Tests for specification errors in classical linear least-squares regression analysis. *Journal of the Royal Statistical Society: Series B (Methodological), 31*(2), 350–371.
- Raza, M. Y., Tang, Q., & Wang, P. (2023). Agriculture-related energy consumption, food policy, and CO_2 emission reduction: New insights from Pakistan. *Frontiers in Environmental Science, 10*. https://doi.org/10.3389/fenvs.2022.1099813
- Taylor, C. A., & Schlenker, W. (2021). Environmental drivers of agricultural productivity growth: CO_2 fertilization of US field crops. *NBER Working Paper No. 29320*. https://www.nber.org/papers/w29320
- Tunio, R. A., Li, D., & Khan, N. (2024). Maximizing farm resilience: The effect of climate-smart agricultural adoption practices on food performance amid adverse weather events. *Frontiers in Sustainable Food Systems*. https://doi.org/10.3389/fsufs.2024.1423702
- United Nations Environment Programme. (2024). *Emissions Gap Report 2024: It is climate crunch time—It's time to level up*. UNEP. https://www.unep.org/resources/emissions-gap-report-2024
- World Bank. (2016). *Climate change and disaster risk management in Pakistan: A review of the evidence*. World Bank Publications.
- Zahid, M., & Shafqat, A. (2020). The impact of climate change on economic growth in Pakistan: A sectoral analysis. *Journal of Environmental Management, 262*, 110319. https://doi.org/10.1016/j.jenvman.2020.110319