Carbon Neutrality, Irrigation Practices and Sustainable Agriculture: Insights from Rice-Wheat Farming in Pakistan

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Abstract

Climate change poses significant challenges for agricultural policies concerning the rice-wheat farming system in Pakistan. Given the country's mounting population pressure, the area under-cultivation of rice and wheat is shrinking. Because intensive farming practices and excess use of fertilizer only maximize short-term yield, it ultimately compromises long-term soil productivity. The study explores the relationship between surface water management practices in rice and wheat farming systems by assessing the opportunities for enhancing water governance to support small-scale farmers. The research study employed the formula for economical water use efficiency to quantify water use efficiency. After that, to ensure the adequacy of the data for time series analysis, the Levin-Lin-Chu unit root test was conducted to assess the stationarity and panel cointegration. Consequently, the study proceeded to model the relationship among the variables using the Autoregressive Regressive Distributive Lag (ARDL) model. The results identify that integrating organic farming practices into the rice and wheat belt could reduce greenhouse gas (GHG) emissions and improve water use efficiency. Modernizing gravity-fed irrigation systems with improved monitoring mechanisms and trained and educated staff can withstand climatic stress and boost water use efficiency by ensuring long-term sustainability in rice and wheat crop zones.

Keywords: GHG Emission, Water, Efficiency, Irrigation, Agriculture, Crop, ARDL.

Introduction

Climate change is causing havoc worldwide; mainly, agricultural climate policies are at risk due to their complex, short-term, and cyclical nature, which is a leading cause of contradictions between different interests. The rice-wheat farming systems in South Asia are a central two agricultural cropping arrangement. As a major staple crop currently in the Indo-Genetic plains, more than 13.5 million hectares of land are under cultivation of these crops (Henery & Tysiachniouk, 2018; Turubanova et al., 2018).

In Pakistan, rice-wheat production is paramount in food supply, and these crops share in national income. However, due to climatic stress, the cropping arrangements output is under potential environmental threat. As the nation grapples with increasing water scarcity and environmental concerns, there is a growing imperative to adopt sustainable practices and technological interventions to ensure the resilience and long-term viability of this critical agricultural system. Balancing economic imperatives with environmental considerations emerges as a key aspect in the

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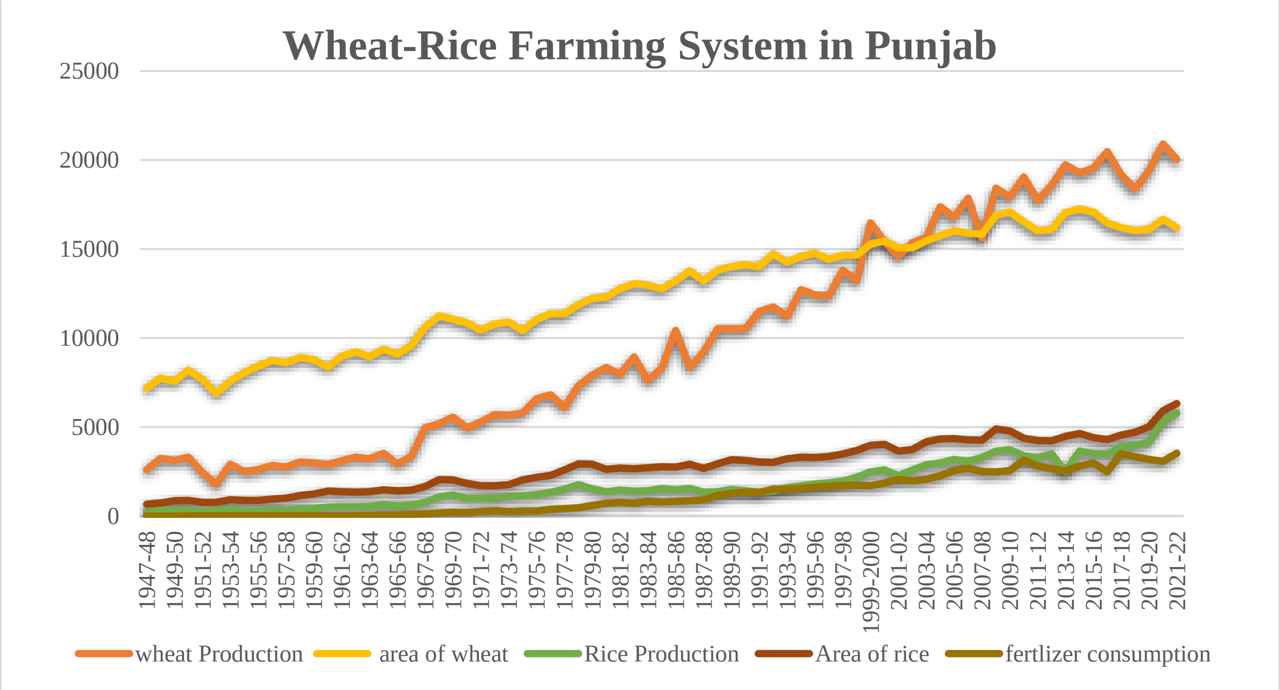
evolving dynamics of the rice-wheat production situation in Pakistan. The rice and wheat cropping arrangement is the mainstay of cereal production in Pakistan, especially in Punjab and Sindh.

Due to the impacts of climate change, Pakistan's agrarian economy faces declining crop yields, particularly the impact of rice in rice pr. Influenced by distinct environmental demands, the rice-wheat system undergoes periodic soil condition conversions. Within Pakistan, 52 % of Rice is cultivated in Punjab, and 38 % is grown in Sindh out of total rice cultivation, whereas 75.47 % of Pakistan’s wheat is grown in Punjab and then it followed by Sindh, 22 %, Khyber-Pakhtunkhwa 8 %, and 3 % in Balochistan ((Economic Survey of Pakistan, 2022; USDA, 2022). Regional rice and wheat cultivation disparities, predominantly in Punjab and Sindh, shape the agricultural landscape. Rising temperatures, water scarcity, floods, and pests decrease rice production. Acknowledging the water-food-carbon nexus, the policy focus on livelihood, food security, and socioeconomic inequalities often eclipses irrigation-climate policies, emphasizing the critical need for a balanced approach to resource allocation for sustainable agriculture (Akbar et al., 2023; Mustafa, Abro, & Awan, 2021; Ali et al., 2022; Brown et al., 2021; Tang, 2020; Xiang et al., 2022).

Figure 1: Graphical depiction of wheat-rice farming system marginal rate return of Punjab



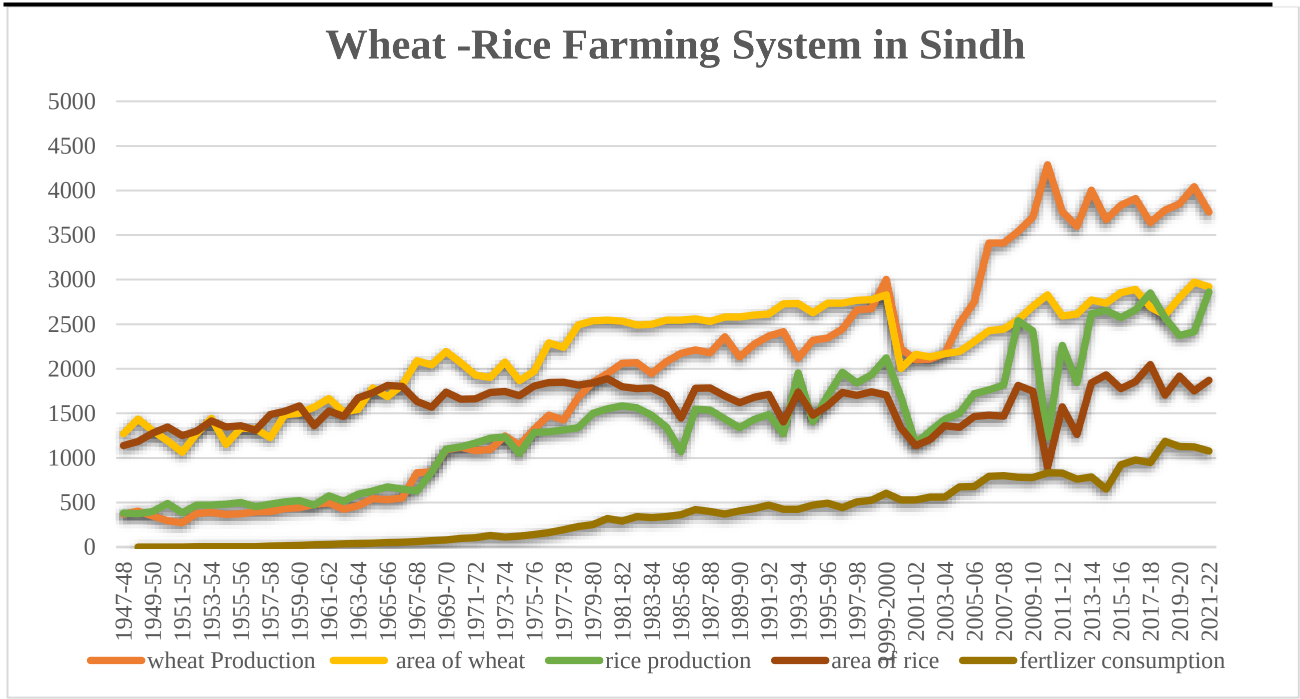
Wheat-Rice Farming Systems in Punjab

Graph 1 depicts the Wheat-Rice farming system in Punjab, revealing a concerning decline in wheat cultivation since 2002. Conversely, rice cultivation has marginally increased, but the growth is diminishing. Despite fluctuations, the wheat crop has substantially increased production over the years. However, very sluggish growth is seen concerning rice, mainly depicting Influencing factors, including land fragmentation, population pressure, reduced canal water availability, and increased fertilizer usage in Punjab (Mason, N. 2021).

Wheat-Rice Farming Systems in Sindh

Figure 2 below rates Sindh's Wheat- rice framing system, indicating a significant increase in wheat yield per acre and a decline in land expansion. A similar trend is observed for rice cultivation, with a negative expansion rate around 2014-15. Productivity relies on various inputs and factors, emphasizing the importance of irrigation methods, fertilizer usage, and socio-economic considerations (Ali et al., 2022; Sehgal & Robotka, 2020).

Figure 2: Graphical depiction of wheat-rice farming system marginal rate return of Sindh



The declining rice and wheat cultivation due to population pressure and urbanization prompts heavy nitrogen fertilizer use, affecting soil organic matter. Efficient canal water use is crucial amid growing scarcity and cost. Climate change exacerbates risks, emphasizing the need for sustainable water management within provinces. Therefore, intra-provincial water management becomes pivotal, considering crop water requirements, infrastructure, pricing policies, and technology adoption. Mainly when the rice and wheat area is more prone and vulnerable due to extreme seasonal variation as the temperature in wheat zones (Punjab-Sindh) varies substantially. Since 2010, farmers in the agricultural zones of Pakistan, which are mainly comprised of arid and semi-arid regions, have taken practical measures to counter the existing environmental threats (Singh et al., 2023; Uppal et al., 2019; Khan et al., 2020; Srinivasarao et al., 2017; Khan, 2016; Saharawat et al., 2009; Hobbs & Rajbhandari, 1998). Therefore, these progressing environmental challenges have underscored the importance of adapting surface water management, which is crucial for fostering sustainable water consumption at the farm level, particularly to bolster the environmental stability of crop production. Besides environmental challenges, the prevailing intricacies in intra-provincial water management necessitate a holistic consideration of resource allocation to navigate the challenges of extreme weather conditions in arid regions. Subsequently, the emerging pattern of water-food-carbon-nexus stresses the profound interdependencies of water, energy, and food systems.

Against this background, the notwithstanding point is that none of the prior studies are available on this nexus. This research study investigates the nexus application of carbon neutrality and irrigation practices within Pakistan's rice-wheat farming systems. Therefore, the study is necessary to address the aggravating effect of farm emissions on water governance, consumption, and its relationship with the required supply of food to meet the population's demand. Over the years, small farmers have become vulnerable due to anomalies in the water distribution system at the farm level in Sindh and Punjab. (Uppal et al., 2019; Khan et al., 2020; Wang et al., 2022; Rasul, 2014 ; Middleton et al., 2015; Hanchett et al., 2014; Lele et al., 2013; Serageldin, 2001; Serageldin, 1995; Serageldin, 1999).

Literature Review

The literature review has carefully studied the relationship between environmental and socio-economic variation impact on water usage and greenhouse-gasses (GHG) emission impacts on different regions along with various natural conditions to accelerate the development of a sustainable food-carbon-water nexus. Particularly when the different countries have different farming systems and cropping arrangements. The theory of natural resource production emphasizes the efficient use of water in agriculture systems. In 1776, for the first time, the French economist Turgot argued that each one per cent increase in natural resource input anticipates a proportional decrease in production due to a diminishing marginal rate of return.

FAO (2006) ultimately evolved the concept of the water-carbon-food-nexus and reinstated the importance of optimizing the use of resources for sustainable agriculture. Since the staple cropping system in South Asia plays a critical role in regional food security, but climate challenges pose risks to its sustainability (Huang et al., 2015; Piao et al., 2010; Steinfeld et al., 2006; Zarei, 2020; Biggs et al., 2015; Karnib, 2017; Bazilian et al., 2011).

Allan (1998) presented the concept of virtual water, which refers to the overall water volume embedded in agricultural products. He proposed that regions facing water scarcity should import water-intensive agricultural goods. A water footprint is a prevalent tool for assessing water management, representing the volume of freshwater utilized throughout the supply chain to produce a specific product. The water footprint is typically expressed as the water volume per product unit.

Dawadi and Ahmad (2012) conducted a study to assess the effects of climate variability and climate change on the Colorado River's flow and its implications for water resources management. The researchers developed a specific system dynamics model for the Colorado River Basin, analyzing monthly data from 1970 to 2035. The study has employed 16 global climate models (GCM) to evaluate three emission scenarios to measure the simulated changes in stream flow at Lake Mead levels. The study's results projected that, on average, 0.84 C temperature will increase between 2012 and 2035 with varying degrees of precipitation due to the variation in emission scenarios. However, despite the slight increase in rainfall, a 3 % reduction in rainfall was observed during the projected time of the study. This decline has significant implications for water supply to the basin states, affecting water availability and reliability. Given the limited availability of freshwater resources, the study outcomes provide critical insights for long-term planning and effective water resource management in the Colorado River Basin. Indeed, it is necessary to evaluate the agricultural water footprints, and virtual water flows to assess the effective management of local water resources and gain insight into the connection between local water usage and the global market.

Casolani. Et al. (2016) examined the water-carbon nexus footprints of durum wheat cultivation in Italy from 2012-2015. The results of the regression analysis exhibit that in the south of the country, low water consumption, below 500 m3 ha-1, was found for wheat cultivation. Contrary to this, higher water consumption was observed in the northern and central parts of the country. Notably, surface water usage and carbon footprint trends for crops were opposite concerning the agricultural land in the south of the country and Adriatic region. The carbon footprint (CF) follows a similar pattern, with the highest value found in northern Italy (2462 kg CO2 ha−1) and a ratio of 1.30 between the northern and central-north regions.

Additionally, future population growth is projected to increase water demand. Agricultural activities contribute approximately 35 per cent of total greenhouse gas emissions, with carbon emissions being a significant factor. Considering these indicators, it is crucial to address water resource management and carbon emission sources to enhance the environmental sustainability of Italian durum wheat production. Policy recommendations should prioritize these aspects.

F. A. O. (2016). There is a pressing need to revise the conventional irrigation methods used in the rice-wheat farming system while also implementing nature-based resource adaptation technologies to enhance yield per hectare. With this goal in mind, the study conducted under the Collaborative Research Project (CRP) on integrated soil water-nutrient management for sustainable rice and wheat cropping arrangements in Asia aimed to assess the impact of nominated innovative crop establishment methods on crop yields, as well as their effects on nitrogen use efficiency (NUE) and water use efficiency (WUE) in these regions. In this regard, the efficient allocation of resources plays a central role in integrating and disseminating innovative tools and techniques. Conservation agriculture aims to optimize the utilization of land, labour, and natural resources to increase food production and feed millions of people.

Hoekstra (2017) provides a concise overview of Water Footprint Assessment (WFA) progress, utilizing the CropWat model, split into two periods: 2000-2011 and a projected period from 2011-2021. It highlights the rising significance of WFA, recognizing that water consumption is a pivotal driver of water pollution and scarcity, moving beyond traditional "supply" and "demand" management approaches. WFA integrates supply-chain thinking into water management, involving stakeholders such as consumers, companies, and investors to address water-related challenges. In epitome, the study has identified four key areas where water footprints are essential to be discussed:

- Global water trade and management
- Recognition of finite freshwater resources
- Inclusion of supply to achieve sustainable water use
- Adaptation of a comprehensive water integration approach covering both green and blue water consumption

Siyal et al. (2021) investigated the complex water-carbon-food nexus relationship within the irrigated agriculture system in Pakistan by examining water usage in the crop and energy sectors. Also, it measured the subsequent associated carbon footprints of it. The study used the methodology of comparative analysis between gravity-fed and tubewell irrigation (pumped water) by evaluating the required amount of energy and its environmental consequences. The primary data of input is collected from farm-field surveys: the number of tube wells for irrigation and how much energy they consume per hectare, besides crop water requirement, and the available canal water data for the same number of farms for the two years, 2016-2017. The survey results also helped to identify hotspot districts where high energy use and carbon footprints are focal points. In this study, energy footprints (EFs) and carbon footprints (CFs) are major irrigated cash crops in Pakistan. The study's results revealed that the gravity-fed canal irrigation system is more climate resilient and can reduce carbon footprints.

Bhatt et al. (2021) explored the meta-analysis of the literature from 2000-2015 critically assesses the sustainability of the rice-wheat (R-W), mainly cropping systems in South Asia, focusing on northwest Indo-Gangetic Plains (IGPs). The analysis results disclosed that crop productivity has decreased over the years because of intensive and frequent use of fertilizers, besides land degradation that has become a generic phenomenon across South Asia. The proposed solution included the integration of resource conservation technologies (RCTs), reduction in tillage, residual management, and crop diversification. This intervention can effectively reduce carbon footprints and address sustainability concerns due to the intensive use of farm inputs for higher yield kg per hectare.

Novoa et al. (2023) investigated evaluating agricultural water footprints in central Chile during 2017-2018, besides virtual water flows for 21 critical country crops within four prominent river basins. The outcomes disclosed the significant changes in water usage, characterized by increased grey and green water footprints in the south-central basins. Meanwhile, a surge was found in blue water consumption within the central zone in the south-central basin. Moreover, the study highlighted a substantial annual surge of 44 per cent of virtual water footprints (VWF), which primarily channel towards destinations in North America, Europe, and Asia. These findings illuminate evolving water dynamics in a commodity-exporting nation grappling with scarcity issues because they underscore the urgency of enhanced water management policy adjustment.

The reviewed studies show that carbon and GHG emissions are crucial to address, though they have some limitations. The other variables, including canal water or surface (freshwater) irrigation contamination, are essential to consider carefully considering environmental impact.

Primarily reviewed research studies (Khedwal et al., 2023; Hennig et al.,2023; Siyal & Gerbens-2022; Pathak. et al., 2022; Harlan & Hennig, 2022**;** Majeed et al., 2021; Bhatt & Singh, 2018; Zhang et al., 2018; Thanawong et al., 2014; Kukal et al., 2014; Pattara & Cichelli, 2012; Weidema et al., 2008; Allan, 2003; Timsina & Connor, 2001), have identified the issue prominently. Various modelling tools, techniques, and approaches have already been used to identify this research gap in water use efficiency purely scientifically. However, regarding the implementation policy, a substantial disparity exists about mitigating carbon footprints within the context of the carbon-water-food nexus. Subsequently, it hinders the understanding of greenhouse gas emissions sources in agriculture and their relationship with input efficiency from socio-economic and environmental standpoints. This research study pioneers an innovative approach that amalgamates socio-economic and environmental considerations by enhancing water use efficiency and striving for carbon neutrality through contracting to bridge the critical policy and practice divide.

Methodology

Theoretical Foundation

The study's methodology is based on a multifaceted approach drawn on rich tap stray of the theoretical frameworks.

It also considered environmental aspects, sustainability challenges, systematic issues of the food supply, and resource management. In epitome, this research framework serves as the conceptual basis for guiding or understanding the interplay between carbon neutrality, irrigation practices, and sustainable agriculture in the long and short term, particularly concerning providing a multifaceted lens to explore the unique challenges posed by population growth and resource pressure in Sindh and Punjab, two of the central provinces in Pakistan.

Conceptual Framework

The study's conceptual foundation is engrained in the Cobb- Douglas production function (Cobb, & Douglas, 1928).

$Y = F(A, L, K, W)$…………………………………………………………………………eq (1)

The form of the Cobb-Douglas production function is as follows:

$Y = A * (L^\wedge\alpha) * (K^\wedge\beta) * (W^\wedge\gamma)$……………………………………………………eq (2)

Where:

- Y represents the output, such as crop yield.
- A denotes total factor productivity (TFP), encompassing technological advancements and other contributing factors.
- L stands for land (fixed).
- K signifies capital input.
- W represents water input.
- α, β, and γ are output elasticities that delineate the influence of labor, capital, and water, respectively.

The Water Use Efficiency (WUE)

After establishing the functional form of the study, the water use efficiency is calculated by using the water use efficiency formula, to quantify Water Use Efficiency (WUE). It can be defined as the ratio of output to water input, indicating the effectiveness of water utilization in the production process. Crop Water Use Efficiency (WUEc) is a critical metric that quantifies the yield of marketable crops per unit of water consumed by the crop. It can be expressed mathematically as.

$\mathrm{W} = (\mathrm{Y} / \mathrm{A}) / [(\mathrm{L}^\wedge\alpha) * (\mathrm{K}^\wedge\beta)]$……………………………………………………eq(3)

$\mathrm{WUEc} = \mathrm{Y/ET}$ or WR…………………………………………………………… eq (4)

For this study

$\mathrm{WUE} = \mathrm{Y} / \mathrm{WR}$…………………………………………………………………eq (5)

To integrate water, and use efficiency as the dependent variable in our model, the Cobb-Douglas production function can be rearranged to express WUE in terms of other inputs:

$\mathrm{EWUE} = \mathrm{f}(\mathrm{Y}, \mathrm{A}, \mathrm{W}, \mathrm{K})$……………………………………………………………...eq (6)

$\mathrm{EWUE}^3 = \mathrm{Yield\ (kg/ha)} / \mathrm{Water\ Applied\ (m3/ha)}$eq ……..…………………………eq (7)

The employed methodology of the study has leveraged the key indicators which include temperature, rainfall, and agriculture inputs to get an understanding of how these input factors influence water use efficiency (WUE)[4], (Zwart & Bastiaanssen, 2004; Sadras et al., 2011). Since the heart of water consumption lies in the water requirement (WR), a dynamic equation number (7) is influenced by crop type, soil moisture, fertilizer, and temperature. Because the water requirement (WR) directly impacts both the crop yield and evapotranspiration. Moreover, soil content and moisture, plant population density, and rate of precipitation patterns all play a centric role in optimizing water usage (Hashim et al., 2021; Tang, 2020). To get deep insight into the water use efficiency and its relationship with carbon neutrality in the context of staple crops in Pakistan, the study's theoretical framework employs a combination of non-parametric and parametric estimation techniques (Henry & Tysiachniouk, 2018; Subash et al., 2015; Shin et al., 2014; Asteriou & Hall, 2011; Odhiambo, 2010; Khan, 2009; Meena et al., 2009; Narayan, 2005).

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[3] Economic Water Use Efficiency.

[4] Notably, WUEc (crop-specific) and WUEf (field-level) offer distinct perspectives on water usage, encompassing different components like evapotranspiration and irrigation.

Unit Root Test

Utilizing the Levin-Chu panel unit root test ((Levin et al., 2002; Im et al., 2003) for cross-sectional dependence, before regression analysis of the panel ARDL model, serves to assess the null hypothesis of a unit root test against the alternative hypothesis of stationarity. The robust tool is based upon the Augmented Dickey fuller (ADF), test which demonstrates the advantages to address serial correlation. Since the Levin-Chu test excels in handling serial correlation and heteroskedasticity. In epitome, the test is pivotal for evaluating time series stationarity.

$\Delta Y - it = \alpha_i + \delta Y_{it} - 1 + \Sigma\beta_{(i\Delta X_{it})} + \varepsilon_{it}$ ………………………………….. eq (8)

where:

- $\Delta Y - it =$ the first difference of the dependent variable Y for the Province (Sindh & Punjab) in Year t.
- $\alpha_i =$ the Province(Punjab & Sindh)specific intercept.
- $\delta =$ the coefficient assigned to the lagged dependent variable, $WUE_{it} - 1$.
- $\Sigma\beta_{(i\Delta X_{it})}$ the sum of the coefficients on the first differences of the independent variables X_{it} for Pr
  Year t.
- $\varepsilon_{it} =$ the error term.

To test unit root (stationarity) in the individual series and the first differences of the series, The LLC test statistic is calculated as the t-statistic of the ρ_i coefficient, and the null hypothesis is that

$Ho = \alpha_i \ (\rho i = 1)$……………………………………………………..…………… eq (9)

Against the alternative of stationarity

$H1{:}\ \alpha_i < 0 \ (\rho i < 1)$……………………………………………………..……………eq(10)

Hence, if the individual series display a unit root, as indicated by the test statistic being lower than the critical value, the null hypothesis is rejected, and it can be concluded that the individual series are stationary.

Panel Cointegration Test

The ARDL approach proves to be particularly effective in addressing the challenge of multiple structural breaks within the data, which often poses difficulties in time-series analysis. Some empirical studies, such as Hossain et al. (2020) and Chen et al. (2022), have utilized ARDL to analyze the determinants of water use efficiency and estimate the impact of climate variation on crop water use efficiency.

In this study, an equation developed by the researchers is employed for this purpose. ((Pedroni 2004; Galetti, & Pedroni 1994; Kao, 1999) is used for panel ARDL with EWUE as the dependent variable.

Equation For Long Run Panel Cointegration

$$ewueijt = \beta o + \beta 1T1ijt + \beta 2T2ijt + \beta 3Pijt + \beta 4\,Pdit + \beta 5\,Git + \beta 6Eit + \beta 7Fit + \beta 8Ait + \beta 9wijt + \beta 10WPit + \varepsilon it. \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad eq(11)$$

where:

The dependent variable.

1. EWUEijt = the economic water use efficiency for province i and year t,
   The Independent variables
2. T1ijt = Maximum mean temperature in province i, year t in j season
3. T2ijt = Minimum mean temperature in province i, year t in j season
4. Pijt = Average amount of rainfall in province i year t in j season.
5. Pdit = the total amount of fertilizer applied in province i, year t.
6. Git = the government expenditure in province iyear t.

7. Fit = Fertilizer consumption in i province i , t year
8. Eit = Primary School enrollment in province im year t
9. Aijt = Area of the crop in the province i, year t
10. Wijt = water withdrawal in the province i in year t, and j season j
11. WPit = water prices in the province i in year t and crop j
12. ε_it is the error term.

The equation for the short-run Panel ARDL (Autoregressive Distributed Lag) model, can be presented as follows:

$\Delta WUEijt = \beta 0 + \beta 1\Delta T1ijt + \beta 2\Delta T2ijt + \beta 3\Delta Pijt + \beta 4\Delta Pdit + \beta 5\Delta Git + \beta 6\Delta Fit + \beta 7\Delta Eit + \beta 8\Delta Aijt + \beta 9\Delta CWijt + \beta 10\Delta WPit + \varepsilon ijt$…………………...eq (12)

In the above equation:

1. ΔEWUEijt represents the change in water use efficiency for province i and year t, which serves as the dependent variable.
2. ΔT1ijt represents the change in the maximum mean temperature in province i, year t, during season j.
3. ΔT2ijt represents the change in the minimum mean temperature in province i, year t, during season j.
4. ΔPijt represents the change in the average amount of rainfall in province i, year t, during season j.
5. ΔPdit represents the change in the total amount of fertilizer applied in province i, year t.
6. ΔGit represents the change in government expenditure in province i, year t.
7. ΔFit represents the change in fertilizer consumption in province i, year t.
8. ΔEit represents the change in primary school enrollment in province i, year t.
9. ΔAijt represents the change in the area of the crop in province i, year t.
10. ΔCWijt represents the change in water withdrawal in province i during year t and season j.
11. ΔWPit represents the change in water prices in province i during year t and crop j.
12. εijt represents the error term.

In this equation, T1, T2, P, Pd, G, F E, A, W, and WP are the independent variables that affect the water use efficiency of wheat (EWUEw) and the water use efficiency of rice (EWUWr).

Results

Table 1: Unit Root Test

	Rice			Wheat		
Variables	Level	1st difference	Decision	Level	1st difference	Decision
EWUE	-0.02 (0.51)	-3.69 (0.00) ***	I(I)	0.00(0.50)	-7.9(0.00) ***	I(I)
T1	-1.62(0.05) *	-6.95(0.00) ***	I (0)	-1.8(0.00) ***	-5.8(0.00) ***	I (0)
T2	-1.45(0.07) *	-6.07 (0.00) ***	I (0)	-2.0(0.00) ***	-6.6(0.0 0) ***	I (0)
p	-0.07(0.47)	-7.10 (0.00) ***	I(I)	-5.2(0.00) ***	-6.5(0.00) ***	I (0)
E	-1.66(0.05) *	-8.50 (0.00) ***	I(I)	-1.7(0.00) ***	-8.5(0.00) ***	I (0)
A	0.56 (0.71)	-6.01(0.00) ***	I(I)	-0.37(0.35)	-7.05(0.00) ***	I (I)
PD	-0.83(0.20)	-1.28(0.00) ***	I(I)	-0.8(0.20)	-1.3(0.00) ***	I (I)
F	-1.08(0.14)	-3.85 (0.00) ***	I(I)	-1.1(0.10)	-3.9(0.00) ***	I (I)
WP	-0.10(0.46)	-6.37 (0.00) ***	I(I)	1.5(0.90)	-4.3(0.00) ***	I (I)
CW	-2.43(0.01) *	-6.87(0.00) ***	I (0)	-0.7(0.2)	-6.3(0.00) ***	I (I)
GE	-0.25(0.40)	-2.02(0.02) *	I(I)	-0.2(0.40)	-2.0(0.00) ***	I (I)

Note: Probability values are in parenthesis, starik *shows the level of significance, (0.01) 10%*, (0.001) 5%**, (0.000) 1%***.

Table 1 presents the outcomes of the Levin-Chu unit root test conducted on various variables. The results reveal the significance of water use efficiency for rice (EWUEr) and wheat (EWUEw) in the integrated order (1st difference). Maximum temperature (T1) and Minimum temperature (T2) exhibit significance at both the level and integrated order. Regarding wheat, the average precipitation rate (P) and primary school enrollment demonstrate significance at both levels as well as the integrated order (Yilanci, and Pata, 2020).

Contrary to other variables such as the area under rice and wheat cultivation (A); population density (PD), fertilizer consumption (F), abiana rate (WP), canal water withdrawal during Rabbi (Wheat) and Kharif (Rice) cropping seasons, additionally, the government expenditure on infrastructural development (GE), exhibits significant results at the integrated order (1^{st} difference). According to these findings, it can be concluded that these variables are stationary as per the examined results of the series of the study, which postulates that the variables are stationary in the long run over the years from (1976 to 2022).

Table 2: Log-length criteria of regression

VAR Lag Order Selection Criteria for Rice

Lag	LogL	LR	FPE	AIC	SC	HQ
0	-3930.39	NA	1.81E+23	87.60863	87.94194	87.74304
1	-2929.14	1713.25	9.90E+14	68.55864	72.89164*	70.30596*
2	-2747.98	261.6727*	5.06e+14*	67.73290*	76.0656	71.09314

VAR Lag Order Selection Criteria for Wheat

Lag	LogL	LR	FPE	AIC	SC	HQ
0	-4699	NA	1.87E+40	123.9473	124.2846	124.0821
1	-3942.26	1274.507	1.05E+33	107.2173	111.2654*	108.8351*
2	-3811.39	182.521	9.71E+32	106.9577	114.7166	110.0586
3	-3636.52	193.2858	4.01E+32	105.5399	117.0096	110.1237
4	-3452.14	150.4095*	2.53e+32*	103.8722*	119.0526	109.939

In this study, the panel ARDL approach is employed to estimate the regression equation. To determine the suitable lag order for the variables, diagnostic tests such as the Akaike Information Criterion (AIC) or the Schwarz Bayesian Criterion (BIC) are utilized. These tests assist in selecting the optimal lag order for the analysis.

Table 3: Panel Cointegration Test Results: Long-Run Cointegration

	Wheat		Rice	
Variable	Coefficient	Prob.*	Coefficient	Prob.*
T1	-0.04(-2.88)	0.010*	0.0157(38.16)	0.00***
T2	0.03(2.95)	0.01*	-0.0277(49.11)	0.00***
P	0.00(3.20)	0.00***	0.0003(17.49	0.00***
PD	0.00 (6.87)	0.00***	-0.0006(-47.16)	0.00***
A	-0.00(-3.47)	0.00***	0.0002(72.59)	0.00***
GE1	-0.00(-5.87)	0.00***	0.0000(-18.34)	0.00***
F	-0.00(-1.27)	0.22	-0.0001(-82.16)	0.00***
E	0.00(1.38)	0.18	0.0000(1.23)	0.23
CW	0.01(2.84)	0.01	0.0029(25.75)	0.00***

WP	0.00(2.42)	0.02*	0.0009(60.06)	0.00***
COINTEQ01	-0.76(-3.00)	0.00**	-0.66(-3.704)	0.05*

Note. t-values are in parenthesis stark *shows the level of significance, (0.01) 10%*, (0.001) 5%**, (0.000) 1%***.

The above given table 3 depicts the results of long run cointegration of several factors separately, that are being examined for their significance concerning water use efficiency (EWUE) about wheat and rice area under cultivation.

The results disclosed that maximum temperatures (T1), show a negative correlation with wheat crop area, this indicates if the maximum temperature decreases the efficiency of water use for wheat crops increases. Conversely, if the minimum temperature (T 2) increases further it decreases the rice yield kg per acre. The population density (PD), coefficient value shows a negative correlation with rice area, but a positive correlation with wheat cropped area. It implies that higher population density has a detrimental effect on rice water use efficiency but a positive effect on wheat water uses efficiency the area under the cultivation of wheat shows a negative but significant relationship, whereas rice shows a positive and significant relationship with the respective water use efficiencies of the crops. (Anjum, 2019). These findings are similar to many other studies results which postulates that in rice production zones temperature and availability of water have been the prime reason of decrease in the area under the crop cultivation. Because the floods in 2010, 2012, and in 2015 caused substantial damages with notable crop losses mainly in Punjab and Sindh (Bokhari et al., 2017; Kiani & Iqbal, 2018).

The negative association between government expenditure on infrastructure development and the water use efficiency in wheat and rice crops could be attributed to the weakening and aging infrastructure in the respective zones. The lack of crop-water resources management integration practices further compounds the issue. The outdated infrastructure may result in water losses, inefficient distribution, and inadequate water management, leading to lower water use efficiency in agricultural activities. Additionally, the absence of comprehensive IWRM practices limits the ability to optimize water allocation, conservation, and utilization, thereby hindering improvements in water use efficiency in sample crop cultivation. Thereby the result is exhibiting a negative relationship with water use efficiency, (Gaydon et al., 2017; Ishfaq, et al., 2020; Kaur & Sharma, 2022).

In contrast, school enrollment did not show any significant effect on water use efficiency. Canal water withdrawal during the rabi season exhibited a positive relationship with water use efficiency for wheat, but a negative trend for rice, with both values being statistically significant. Water prices (abiana prices) for rice and wheat showed a positive trend, suggesting that higher prices were associated with increased water use efficiency. Water prices in Punjab and Sindh primarily depend on surface water supplies and developed aquifers, since long time a flat rate water pricing approach is being applied in two of the provinces. Irrespective, of inter-seasonal variation, the revenue generation in Punjab and Sindh is inappropriate to cover the operational and management cost, even not sufficient to meet recurring expenditure. The results are completely aligned with the ground realities because water prices can conserve water supplies in the long term (Hassan et al., 2021). Conjunctive use irrigation method is an effective tool to reduce variation in prices besides limiting the groundwater abstraction (Schuck & Green, 2002; Ahmad, et al., 2004).

The cointegration values (ECT), which measure the speed of adjustment, indicated a negative and moderate trend. The values of -0.76 for wheat and -0.66 for rice implied that approximately 76% and 66% of the unconventionality from long-term equilibrium, respectively, would be corrected in the short term. Overall, these findings shed light on the complex relationships between various factors: WUEw and WUEr cultivation. They provide valuable insights for policymakers and stakeholders involved in water resource management and agricultural practices, highlighting the need for targeted interventions to improve water use efficiency and sustainable crop production, (Zafeiriou et al. 2023; Yurtkuran, 2021; Khan et al., 2020; Abbas, 2020; Bildirici, 2014).

Table 4: Short Run Panel Cointegration Results

	Wheat		Rice	
Variable	Coefficient	Prob.*	Coefficient	Prob.*
D (WUE (-1))	-0.07(-0.27)	0.79	0.18(0.94)	0.36
D(T1)	0.02(2.66)	0.01*	-0.01(-2.24)	0.03*
D(T1(-1))	0.02(1.03)	0.31	0.00(-3.11)	0.01*
D(T2)	-0.02(-1.56)	0.03*	-0.02(-7.57)	0.00**
D(T2(-1))	-0.01(-2.60)	0.06*	0.01(2.34)	0.03*
D(P)	0.01(-3.32)	0.05*	0.00(2.18)	0.04*
D (P (-1))	0.00(-0.37)	0.72	0.00(3.51)	0.00**
D(PD)	0.01(0.68)	0.53	0.00(-0.65)	0.52
D (PD (-1))	0.02(2.83)	0.01*	-0.01(-1.47)	0.16
D(A)	0.01(6.40)	0.00**	0.00(-5.55)	0.00**
D (A (-1))	0.00(3.95)	0.05*	0.00(-0.69)	0.58
D(GE1)	0.00(3.40)	0.00**	0.002(3.29)	0.00**
D(GE1(-1))	0.07(7.42)	0.00**	0.00(0.22)	0.83
D(F)	0.00(1.25)	0.22	0.00(0.89)	0.38
D (F (-1))	0.00(1.11)	0.28	0.00(-0.85)	0.41
D(E)	0.00(-1.00)	0.33	0.00(1.89)	0.37
D (E (-1))	0.00(1.00)	0.33	0.00(1.00)	0.33
D(CW)	0.02(4.59)	0.00***	0.001 (4.65)	0.00**
D (CW (-1))	0.00(0.01)	0.99	0.00(-0.79)	0.38
D(WP)	0.00(0.45)	0.65	-0.0002(-3.16)	0.01*
D (WP (-1))	0.00(0.93)	0.36	0.000(0.90)	0.38
C	-0.63(-0.98)	0.34	0.07(24.30)	0.00**

Note. t-values are in parenthesis stark *shows the level of significance, (0.01) 10%*, (0.001) 5%**, (0.000) 1%***.

Table 3 presented above provides insights into the relationship between various factors and water use efficiency (WUE) for wheat and rice crops in the short run.

Maximum temperature (T1) is found to be significant for both crops, but it has a negative impact on rice. The results reveal that the maximum temperature (T1) coefficient value is found to be significant for both crops. However, it is showing a negative impact on rice and a positive impact on the water use efficiency of the wheat crop. In summer, extreme temperature decreases rice yield kg per hectare and, ultimately, revenue losses. Therefore, it explores that a further decrease in minimum temperature leads to decreased water use efficiency. However, it has detrimental effects on rice crop productivity because (T2) has shown a negative relationship with both the crops about water use efficiency in the short run. The results postulate that higher maximum temperatures adversely affect the crops' water use efficiency. Conversely, the average annual precipitation rate impacts these two crops differently. (Brack, et al., 2015; Gill, et al., 2011).

Population pressure plays a significant role in water use efficiency; as population pressure mounted, it aggravated crop productivity, where land is a critical variable. As per this study analysis, population density negatively correlates with crop water use efficiency, which signifies scarce resources. The area under rice crop cultivation has also shown a declining trend, though it depicts a significant trend for the current year. Any variation in cultivating the rice area can potentially affect the efficiency of rice water use in the short run. (Carrijo, et al., 2017). The results are similar to previous studies (Shafeeque et al., A. 2023; Kumbhar et al., 2018), showing that almost more than half of the country's rice crop area has decreased.

Government expenditure (GE) shows a positive trend for two crops; it reveals that increased investment in infrastructure positively influences water use efficiency in the short run. Apart from this, canal water irrigation (CW) in both seasons, the rabi and kharif, exhibit a positive trend for the current year, indicating that canal water availability has a positive impact on water use efficiency for both crops (Bajpai & Kaushal, 2020). Besides that, variables such as primary school enrollment (E), fertilizer consumption (F), and water prices (abiana rates) for wheat and rice are not showing any significant relationship or trend with water use efficiency. Overall, these findings highlight the complex dynamics influencing water use efficiency in wheat and rice cultivation in the short run, as these results emphasize the need for targeted strategies and policies to address climate factors, population growth, infrastructure investment, and water availability to enhance water use efficiency and ensure sustainable agricultural practices, (Gaydon et al., 2021; Devkota, et al., 2015)

In essence, controlling the overarching use of fertilizer and fossil fuels for farm operations can be beneficial. Since it can increase crop productivity in the long term. Moreover, proper land use and land cover management and the adoption of technological advancements can contribute to sustainable water management practices

Conclusion

Rising temperatures, ageing irrigation infrastructure, and inefficient water management farm practices in the face of mounting population pressure are the key challenges to expanding wheat and rice crop areas. Mainly to ensure water use efficiency in Punjab and Sindh**,** the government expenditure on infrastructure development lacks direction and fails to prioritize cropping areas effectively. Additionally, there needs to be more targeted investment for disseminating technical knowledge at the primary school level in the country. Therefore, farmers must be more mindful of the carbon emissions associated with inefficient rice-wheat farming practices, especially regarding excessive fertilizer usage. This issue is further exacerbated by the shrinking cultivation area due to an increase in population density, making farm inputs the sole means of achieving higher yields of kg per acre in Punjab and Sindh. This evidence suggests that the gravity-fed irrigation system (canal water) can become a potential opportunity to mitigate the impact of greenhouse gas emissions with proper education and trained irrigation staff. Energy reduction is still possible by integrating nature-based solutions within the agricultural sector. However, the only constraint is inadequate water pricing policies in Punjab and Sindh, which must be more uniform and cover operational and maintenance costs. The provinces must help with operational and management costs and expenditures on IWRM. For this reason, there is a dire need to establish interconnectivity between revenue and expenditure on canal water provision in the provinces.

Therefore, at the policy level, it is crucial to integrate carbon-neutral agriculture and irrigation systems to achieve sustainable agricultural growth in the long term by considering the broader perspective and agenda of the country. Currently, providing food for millions of people in Punjab and Sindh is a great challenge, and the problem has become intricate due to continuous flooding since 2010.

This integration requires a deep understanding of the interlinkages and interconnections among water, food, and carbon nexus. By adopting carbon-neutral pathways, provincial and national policymakers can effectively direct their policies towards promoting sustainable and resilient nature-based agricultural practices during rice-wheat farm field operations.

In conclusion the study's results emphasize the need for implementing community-based approaches that integrate the water-food-carbon (WFC) nexus. These approaches must aim to restore natural ecosystems, ensure sustainable food and water supply, and address the degradation of natural resources. Therefore, further research is crucial in this area. Additionally, improving intra-provincial water management through effective allocation systems and adopting integrated water conservation measures can enhance water resource efficiency and facilitate a transition towards carbon neutrality in staple crop production. These measures offer significant benefits to policymakers, researchers, and stakeholders involved in Pakistan's agricultural sector, because due to population pressure further expansion in area is a challenge and demands higher inputs.

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