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Climate Change Impact on Sustainable Agricultural Growth: Insights from Rural Areas

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Abstract: Agricultural production and advancement is significantly affected by climate change (CC), especially in drought-prone regions where farmers depend primarily on rainfall for their livelihoods. One of the main threats to the agricultural sector for decades has been global warming, and the sector is particularly susceptible to climatic circumstances. CC has become a crucial concern impeding sustainable development due to rapid changes in urbanization, industry, and agricultural systems. Food security, which is a worldwide concern, is another essential component connected to a country's economy and people's livelihoods. In view of these adverse consequences, the main objective of this study was to examine the impact of CC and food security on sustainable agricultural development in Pakistan. The study area was selected from twenty-four districts in two provinces of Pakistan (Khyber Pakhtunkhwa and Balochistan). Collectively, the current research offers possible solutions to the dilemmas described above, which could have a significant impact on improving efficiency and technological progress. To address these issues, we introduced a slack-based approach to quantify inefficiencies in overall agricultural production. In addition, this study further scrutinized the decomposition of specific variables. The results show that Pakistan has an agricultural inefficiency of 0.62 under CC and food security constraints, of which 0.29 is primarily attributable to food security limitations. In the end, this study will help policymakers to make appropriate decisions to minimize the impact of CC on sustainable agriculture growth and improve human living standards and food security.

Keywords: climate change; food security; atmosphere; sustainable agricultural growth; food safety

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1. Introduction

Asia is the world's most populated region, accounting for 4.5 billion people, which is almost 60% of the total global population [1]. Nearly 70% of the total population lives in rural areas, 75% of which is poor and most vulnerable to climate change (CC), especially in arid and semi-arid regions [2]. The population is projected to exceed 5.2 billion by 2050, making it difficult for Asia to meet food demand and ensure food security [3]. From this perspective, the region is most likely to be linked to population growth rates and more vulnerable to rising temperatures, droughts, floods, and sea level rise [4,5]. In Asia, the diversification of incomes of small and poor farmers and increasing urbanization are worrisome for agricultural output. Asia is home-based to one-third of the world's population and the majority of poor households, most of whom work in agriculture [1]. Due to the range of climate-dependent farming and cropping systems, we can expect multiple adverse CC outcomes in the agricultural sector. Increased flood and drought risks make agricultural yields particularly vulnerable to CC, as described in the IPCC's Sixth Assessment [6]. However, CC has severe implications for achieving various Sustainable

Development Goals (SDGs). The impacts of CC, such as rising temperatures, extreme weather events, and sea-level rise, which affect several SDGs including poverty eradication, zero hunger, clean water and sanitation, and sustainable cities and communities. CC exacerbates poverty by decreasing agricultural productivity, displacing communities, and increasing the frequency and intensity of natural disasters. Additionally, it poses a threat to food security, water resources, and overall human well-being. Therefore, understanding the CC impact on different SDGs is crucial in formulating effective strategies to mitigate CC and achieve sustainable development.

Despite the region's modest greenhouse gas (GHG) emissions, global warming is already adversely affecting agricultural production, the economy, and development [7–9]. For instance, the study reported by Gregorio and Ancog [10] shows that 3.11% (17.03 million tons) decrease in agricultural production in Asia because of a weakening in the workforce. CC has rapidly and increasingly become a dangerous issue in the world [11]. CC and related natural calamities are reforming production and reshaping farming growth, thus threatening growers' adaptability and income sustainability. The prevalence of CC across the world is overwhelming, and Pakistan is one of the countries with the most visible catastrophic repercussions. A quarter of Pakistan's population faces malnutrition, food insecurity, and CC, which means they cannot meet basic intake requirements. The quarantine policy has had an unprecedented adverse impact on Pakistan's already struggling food system, including supply chains. From 1998 to 2018, Pakistan sustained a total loss of USD 3.79 million because of CC. However, in May 2021, the Asian Development Bank (ADB) and the World Bank (WB) jointly released a study titled "Climate Risk Country Profile" for Pakistan, which estimated that CC could cost Pakistan up to USD 3.8 billion if temperatures rise by as much as 2.5 degrees Celsius over the next two decades. As a result, the long-term Global Climate Hazard Index study ranks Pakistan as the fifth most troubled country on Earth [12,13].

In recent years, the temperature has risen by 0.6–1.0 °C and precipitation has increased by 18–32%, which could dent agricultural productivity in countries such as Pakistan [14]. Many studies indicate that the situation may deteriorate more in the future, posing a significant issue for farming in Pakistan [15]. Problems related to CC affect both industrialized and poor countries. However, due to insufficient adaptive capacity, the impact is more serious and obvious in less developed countries [12,16,17]. While relief activities are the most effective way to address CC issues, they need significant financial resources and time. Adapting to changing climatic conditions is an excellent way to mitigate the risky effects of CC in the farming sector in developing countries such as Pakistan [18–20]. According to Pakistan's Sixth Population and Housing Census 2017, the country's population is expanding at a pace of 2.4 percent each year. This fast population growth is increasing the demand for agricultural products. The agriculture business in Pakistan has a significant impact on the country's economy, accounting for up to 18.9% of the country's yearly gross domestic product (GDP) and engaging 42.3 percent of the labor force [21]. However, agricultural development is crucial to the Pakistani economy and faces many problems. Disasters related to CC, such as floods and droughts, are major difficulties [21,22].

The imminent hazards associated with CC are real, but in the agricultural sector they are unpredictable; therefore, adaptation is not only an effective strategy but also mitigates the negative impact of eco-friendly risks [23]. Every civilization is adaptable, but an understanding of CC may have a significant influence, and adaptability is inextricably linked to the education system, availability of resources, and awareness. However, smallholder growers in Pakistan do not have access to these components. A bigger proportion of the population (29.5%) lives in poverty, limiting farmers' ability to address CC concerns [12]. Therefore, adaptation is challenging in developing countries with high awareness of CC, which is further exacerbated by poverty and low adaptation at the farm level [19,24–26].

However, the low technical and financial capacity of farmers and ineffective environmental policies limit present sustenance for CC adaptation [27]. Therefore, there is a need to develop targeted adaptation policies and understand the factors that influence growers' cognitive and adaptive responses [28,29]. Although farmers' adaptation efforts are linked

to social, ecological, and economic factors, CC awareness is crucial [30–32]. Therefore, it is critical to investigate how farmers perceive CC and how they respond to it. Furthermore, the style and degree of mitigation strategies used are critical to the prognosis [25,33]. Though farmers' perspectives and learning abilities under CC have been thoroughly investigated, additional investigation is still required to recognize the factors that influence adaptive behavior [12,19,26,34–36]. Current CC studies in Pakistan are restricted to CC influences and related forecasts of particular crop yields. Consequently, this study intends to close the knowledge gap in food security and CC's impact on Pakistan's sustainable agricultural growth.

According to Pakistan Statistics' Labor Force Survey (2017–2018), 39% of the labor force is employed in agriculture (30.2% men and 67.2% females). Pakistan's average yearly temperature has risen considerably during the last century. Temperatures in Pakistan's most populous areas are expected to rise by 0.6–1.0 °C by the end of the twenty-first century [37]. Consequently, it is critical to determine how food security and CC affect sustainable agricultural development, especially when Pakistan's agriculture industry is in transition and undergoing a slew of natural calamities. Abid et al. [38] investigated crop producers' adaptability to CC and its influence on productivity and agricultural growth. However, they only looked at adaption options for high-risk climatic circumstances. Therefore, other studies cannot assess whether the current adaptation strategies of Pakistani farmers are beneficial to agribusiness. To the best of the authors' knowledge, the current study aims to bridge this gap by focusing on the impact of climate change and food security on sustainable agricultural growth.

This paper is divided into five sections. After the introduction, Section 2 is the literature review. Section 3 presents the materials and methods. Section 4 describes the results and discussion, and finally, Section 5 outlines the conclusions and policy implications.

2. Literature Review and Theoretical Background

Theory of Change, Food Security, and Climate Change

Considering the understanding and skills of these activities, a theory of change lays out a path of influence in an attempt to achieve a logical set of outcomes or effects. In addition to the main research, the World Program on Agriculture and Food Security in a Changing Climate has produced many more products. These include peer-reviewed and unpublished work on the transformation of agri-food systems. Practitioners are applying the theory of change to create context-specific approaches to agricultural systems, using new findings from agricultural research in the context of development. The process of agricultural research for development requires multiple research activities whose outputs can encourage change or outcomes by changing the knowledge and habits of officials, extension workers, farmers, and development practitioners. The impact of these developments includes improved food security and reduced poverty. The linking of inputs, outputs, outcomes, and effects is often a more complex and evolving process. To solve issues with food security, CC, and agricultural growth, we offer this theory of change. In recent years, the increasing amount of carbon dioxide (CO_2) in the atmosphere has accelerated. The widespread usage of fossil fuels such as oil, coal, and gas may be the main cause of this growth. Another significant factor contributing to the atmospheric CO_2 rise during the past 100 years may be the depletion of carbon sinks caused by excessive land usage and deforestation. CC can alter the suitability of land for agriculture, resulting in more farmland being developed at higher latitudes while inhibiting agricultural expansion at lower latitudes. Crop yields are projected to increase in temperate regions but decline in tropical and seasonally dry regions, especially for food crops. However, the entire board is expected to be adversely affected due to CC. Many researchers have already investigated CC and food security using diverse tools and methodologies. Chen et al. [39], used a stochastic network data envelopment analysis (DEA) model to assess airline efficiency, accounting for both CO_2 emissions and flight delays. Mahdiloo et al. [40] used DEA to explore the static emission reduction efficiency of power producers' CO_2 emissions, including effective techniques of

rewarding eco-efficiency and penalizing the eco-inefficient behavior of power producers. Cecchini et al. [41] conducted an environmental efficiency analysis and estimated CO_2 abatement costs on a dairy farm in Umbria, Italy, using a slack-based model (SBM). The SBM was used to quantify marginal CO_2 abatement costs. Four farms were not CO_2 efficient, with reduction potentials ranging from 45.7% to 26.3% CO_2

Iftikhar et al. [42] used network DEA techniques to estimate the energy and CO_2 emission efficiencies of major global economies. Overall, it was found that 85% of energy consumption and 89% of CO_2 emissions were due to economic and distributional inefficiencies alone. Yang et al. [43] refined the zero-sum benefit DEA to analyze and optimize provincial CO_2 emission reduction choices and discovered that 12 provinces required greater emission reduction targets, while the remaining 18 provinces might achieve overall efficiency with lower target values. Li et al. [44] used a comprehensive hybrid life cycle assessment (LCA) model for numerous places in China to estimate the life cycle CO_2 emissions, energy consumption, and energy payback period of a 10 MW tower complex solar power plant in China. Whitmarsh et al. [45] conducted a large-scale survey globally to understand the usage of aviation by CC experts. They discovered that while CC researchers, particularly professors, flew more frequently than other researchers, they were also more likely to take actions to limit or counterbalance their traveling.

In addition to CC caused mostly by CO_2, food security has drawn the attention of academic circles owing to its relevance in preserving economic development and people's welfare. McKune et al. [46] proposed a gendered conceptual framework for understanding the CC effect on food security among livestock keepers, highlighting possible places of susceptibility and intervention points that should be included in global health programs to promote household food security. Bizikova et al. [47] investigated how agricultural interventions might improve food security and long-term development goals. Kansiime et al. [48] used data from an online survey of four hundred and forty-two respondents to evaluate the impact of the coronavirus disease 2019 (COVID-19) pandemic on family income and food security in two East African nations, Kenya and Uganda. The results showed that the food security and diet quality of respondents in both countries worsened during the COVID-19 pandemic compared to before. This was due to lost or reduced income, reduced access to markets due to travel restrictions, and low purchasing power. Farmers depend on the market, and restrictions directly affect their income, unlike wage earners who may have temporary remote working mechanisms. Across the countries studied, the number of food-insecure respondents increased by 38 percent in Kenya and by 44 percent in Uganda. Van et al. [49] suggested a wider outline to search the future of food and nutrition security, concentrating on plausible proxy pointers of food accessibility, food access, and food use. Badami and Ramankutty [50] examined different perspectives on whether urban agriculture makes a significant contribution to food security and poverty alleviation and assessed the impact of urban agriculture on urban food's potential to contribute to the safety and daily vegetable intake of the urban poor. Weather and environment are still important variables in agricultural output, even in the face of technological advancements such as better crop types and irrigation systems. Agriculture will be directly affected by increased levels of CO_2 in the atmosphere and the resulting CC. The two main issues hindering the spread of agriculture are CC and food security. However, combining these two components into a unified framework has not received sufficient consideration in earlier studies.

3. Material and Methods

3.1. Study Area and Data Collection

Khyber Pakhtunkhwa (KP) and Balochistan are both in Pakistan that have diverse topography. KP, formerly known as the North-West Frontier Province, is located in the northwestern part of Pakistan. It is known for its mountainous terrain, with the western part of the province being dominated by the Hindu Kush mountain range. On the other hand, Balochistan is located in the southwestern part of Pakistan. It is the largest province in terms of land area but is sparsely populated. Balochistan has a diverse landscape; both

provinces offer unique landscapes, rich natural resources, and cultural diversity. They are important for tourism and agriculture and have strategic significance due to their border regions. Twenty-four districts in two provinces of Pakistan (KP and Balochistan) (Figures 1 and 2) were selected as the study area for this survey. Research conducted in Pakistan, a developing country, may have more beneficial policy implications globally. In the selection of input–output variables, the fixed asset investment, planting area, labor force, machinery equipment, and fertilizer consumption of Pakistan's agricultural sector are used as inputs again, and the total agricultural output value of Pakistan is regarded as the ideal output. When agricultural production activities produce CO_2 emissions, it is considered to be a constraint of CC. This study uses agricultural disaster areas as a constraint on food security. Using these molds, the production technology can be clearly defined. It is worth noting that all data are from the National Bureau of Statistics (December 2022 assessment, from the National Bureau of Statistics of Pakistan). In addition, the lack of agricultural CO_2 emission data in the autonomous region forced us to choose the remaining 24 districts as the research field, and the study period is 2010–2020. Specifically, input descriptive data/output variables are provided in Table 1.

Table 1. Summary data of agricultural input/output variables.

Variables Names	Year	Mean	Standard Deviation
Investment in fixed assets (I, PKR 100 million)	2010	147.87	118.64
	2015	262.86	201.04
	2020	346.99	236.01
Labor force (L, 10^4 people)	2010	2411.77	1660.99
	2015	2200.37	1487.37
	2020	1977.90	1308.97
Seeded areas (S, 10^3 hectares)	2010	5015.73	3539.60
	2015	5115.47	3785.93
	2020	5381.59	4076.24
Machinery (M, 10^4 Kilowatts)	2010	2206.38	2305.30
	2015	2992.92	2886.79
	2020	3604.13	3296.88
Fertilizer consumption (F, 10^4 tons)	2010	153.75	128.53
	2015	179.41	146.84
	2020	194.28	153.98
CO_2 emissions (C, 10^4 tons)	2010	3.681	2.610
	2015	3.710	2.181
	2020	4.353	3.052
Value added (Y, PKR 100 million)	2010	1316.48	1009.81
	2015	2185.91	1648.17
	2020	3286.89	2333.91
Disaster areas (D, PKR 100 million)	2010	644.07	435.45
	2015	598.00	510.57
	2020	412.67	377.31

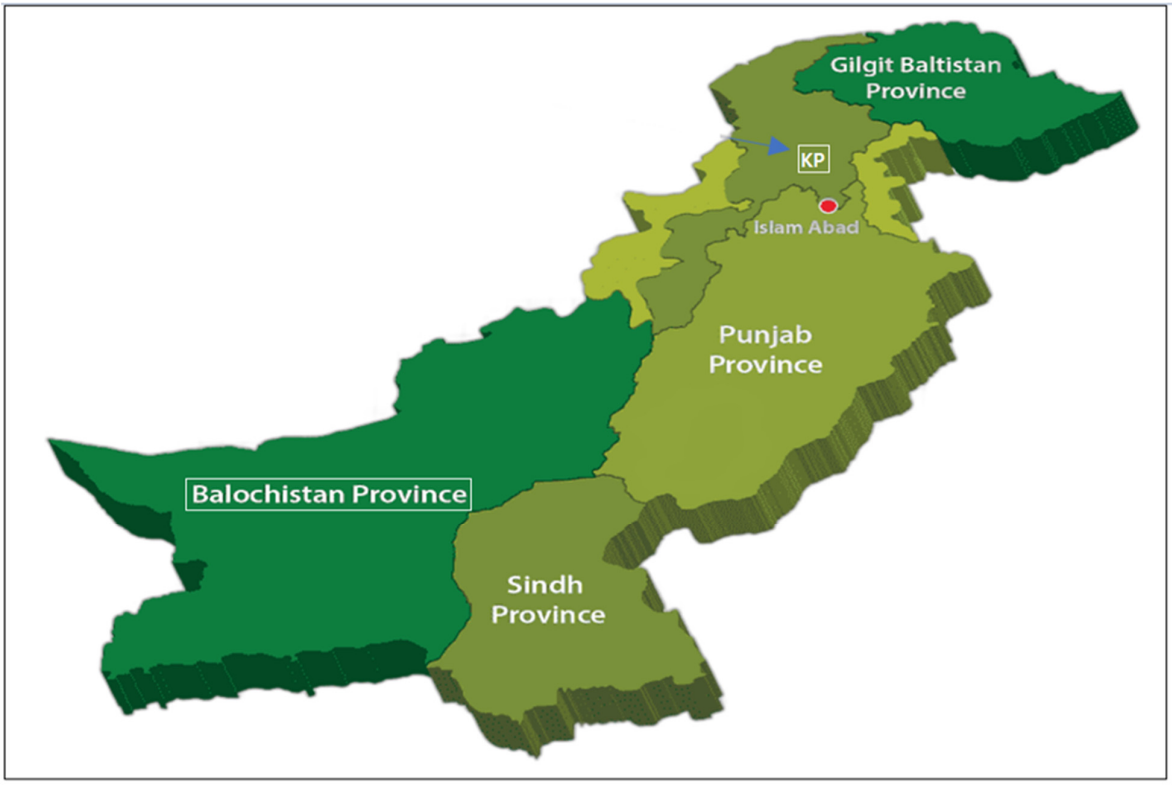


Figure 1. Map of the provinces.

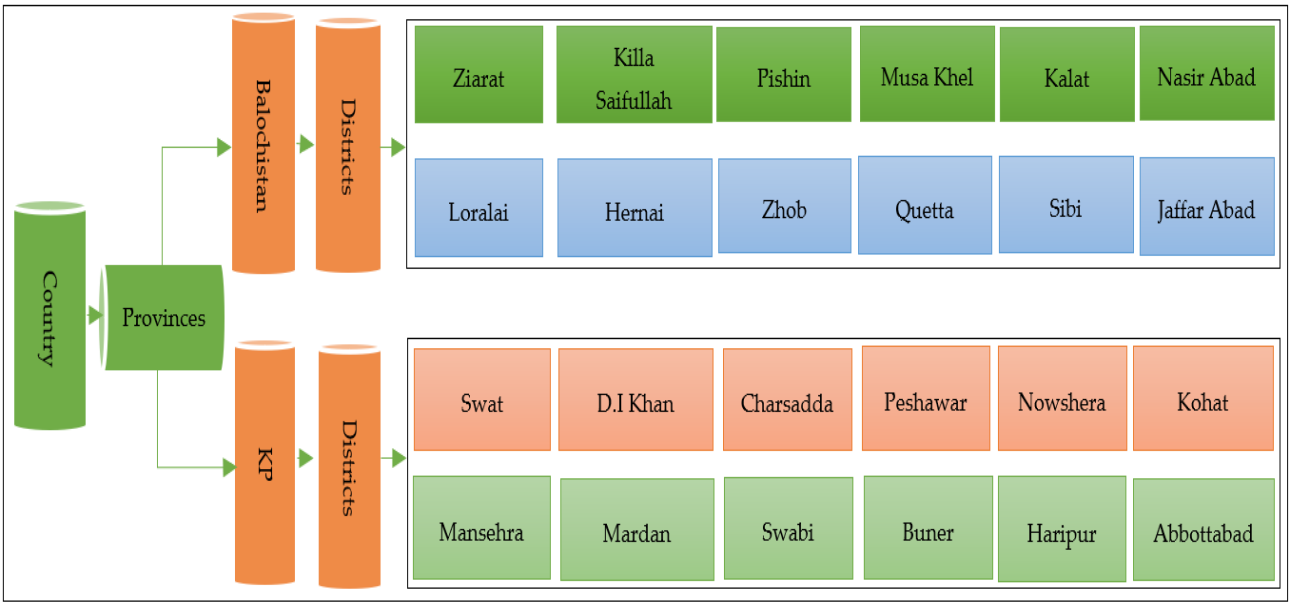


Figure 2. The provinces and districts of the study area.

3.2. Agricultural Production Technology

Agriculture technologies are the primary drivers of agricultural productivity across countries and stimulate agricultural expansion. In the past, technologies were selected and used to boost yields, efficiency, and profitability in farming. Agriculture, commerce, research and development, education, training, and guiding policies have all had a long-term impact on technology utilization, crop yields, and agricultural practices. However, the actual construction of the non-performing output analysis framework is the basis of the total factor productivity research. In recent years, with increasing emphasis on environ-

mental issues, pollutant emissions have been characterized as environmental constraints in several study frameworks. They have significant implications for technical efficiency and total factor productivity indicators. Among these reports, Färe et al. [51] and Färe et al. [52] first defined the mechanism of environmental production technology, which laid a theoretical foundation for the study of environmental efficiency including adverse output. Zhou et al. [53] measured CO_2 emissions for some countries. The environmental protection production technology is briefly defined as follows.

The environmental production technology analysis framework includes P input variables $x = (x_1, \ldots, x_p) \in R_P{}^+$ and Q output variables $y = (y_1, \ldots, y_q) \in R_Q{}^+$ for one decision-making unit (DMU) and R undesirable output variables $b = (b_1, \ldots, b_r) \in R_R{}^+$. In period t, the input, desirable output, and undesirable output variables of the DMU i are $\left(x_i{}^t, y_i{}^t, b_i{}^t\right)$. Under the evidence that all input–output variables meet significant disabilities; environmental production technology can be described as:

$$P^t\left(x^t\right) = \left\{\left(y^t, b^t\right) : \lambda X \le x_{ip}{}^t, \lambda Y \ge y_{iq}{}^t, \lambda B \le b_{ir}{}^t \forall p, q, r, \lambda \ge 0\right\} \tag{1}$$

where λ is a weight vector greater than or equal to 0, and x, y, and b are the variables that construct the production frontier's input, desired output, and undesired output, respectively. According to different constraints on the value λ, it can be explicitly characterized as variable returns to scale (VRS) and constant returns to scale (CRS).

3.3. Inefficiency of Agricultural Production

The ability to assure the attainment of increased production levels, efficiency, profit, and quality of products depends on the effectiveness of financial and economic operations of a financial entity in agriculture. The highest agricultural product output at the least living expenses and contracted labor is the criterion. Despite this, the basic DEA technique has been widely utilized in existing food safety and CC-related performance measurement analyses. However, the weakness of these studies is that they can only measure efficiency and productivity from the perspective of input or output and cannot consider the impact of all variables. It is therefore necessary to measure the performance of input and output variables more widely.

Fukuyama and Weber [54], Tone [55], and Tone et al. [56] proposed or improved the slack-based measurement (SBM) approach. This method completes the construction of the technology frontier by measuring the slack values of input variables and output variables. It is a non-radial measure of all variables; consequently, it is named a non-radial distance function [53]. When both input and output variables are redundant, the calculation outcomes using non-radial directional distance functions are different from traditional directional distance functions. This paper follows the distance function employed by Miao et al. [57]. The systematic technique is as follows:

$$\begin{aligned} &\overrightarrow{S}^t\left(x_i{}^t, y_i{}^t, b_i{}^t; g^x, g^y, g^b\right) = \tfrac{1}{3}\max\left(\tfrac{1}{P}\sum_{p=1}^{P}\frac{S_p{}^x}{g_p{}^x} + \tfrac{1}{Q}\sum_{q=1}^{Q}\frac{S_q{}^y}{g_q{}^y} + \tfrac{1}{R}\sum_{r=1}^{R}\frac{S_r{}^b}{g_r{}^b}\right) \\ &s.t. \lambda X + S_p{}^x = x_{ip}{}^t, \lambda Y - S_q{}^y = y_{iq}{}^t, \lambda B + S_r{}^b = b_{ir}{}^t; \\ &\forall p, q, r, \lambda \ge 0; S_p{}^x, S_q{}^y, S_r{}^b \ge 0 \end{aligned} \tag{2}$$

In Equation (2), $\left(x_i{}^t, y_i{}^t, b_i{}^t\right)$ signifies the input and output variables of DMU i in period t, $\left(g^x, g^y, g^b\right)$ signifies the direction vector of reducing input, rising desired output, and decreasing undesired output, respectively, and $\left(S_p{}^x, S_q{}^y, S_r{}^b\right)$ denotes slack variables for inputs, desirable outputs, and undesirable outputs, respectively. Using the additive structure to decompose all variables, the inefficiency value of each variable can be further obtained:

$$IE = \overrightarrow{S}^t = IE_x + IE_y + IE_b = \frac{1}{3P}\sum_{p=1}^{P}\frac{S_p{}^x}{g_p{}^x} + \frac{1}{3Q}\sum_{q=1}^{Q}\frac{S_q{}^y}{g_q{}^y} + \frac{1}{3R}\sum_{r=1}^{R}\frac{S_r{}^b}{g_r{}^b} \tag{3}$$

where $\frac{1}{3P}\sum_{p=1}^{P}\frac{S_p{}^x}{g_p{}^x}$ is the total of inefficiencies of the input variables, $\frac{1}{3Q}\sum_{q=1}^{Q}\frac{S_q{}^y}{g_q{}^y}$ is the sum of inefficiencies of the desired output variables, and $\frac{1}{3R}\sum_{r=1}^{R}\frac{S_r{}^b}{g_r{}^b}$ is the sum of inefficiencies of the undesirable output variables.

4. Empirical Results and Discussion

As shown in Table 1, on average, investment in fixed assets, planting area, machinery and equipment, fertilizer consumption, CO_2 emissions, and added value of agriculture continued to grow. In contrast, on average, labor and disaster areas have continued to decline over the past decade. Therefore, reducing agricultural CO_2 emissions should be a top priority for the Pakistani authorities. Using the previously defined slack-based model and selected variables, we calculated the inefficiency of the agricultural sector in 24 districts of Pakistan. In particular, we attribute overall inefficiency scores to individual variables due to variable-specific decompositions. The detailed analysis is as follows.

4.1. Variable-Specific Decomposition

As revealed in Table 2, the average inefficiency value for Pakistan's twenty-four districts during 2010–2020 is 0.62, while the inefficiency value associated with ideal output (GDP, Y) is 0.00. This shows that under the constraints of existing agricultural production technologies such as the total power of agricultural machinery, agricultural CO_2 emissions, and agricultural disaster-affected areas, the possibility of agricultural economic growth is relatively limited. Therefore, the government should choose to adjust the agricultural structure to ensure agricultural productivity instead of increasing factor inputs.

Table 2. Input/output inefficiencies in Pakistan's agricultural sector 2010–2020.

Province Name	District Name	*IE*	*I*	*L*	*S*	*M*	*F*	*Y*	*C*	*D*
KP	Swat	0.22	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.20
	Mansehra	0.60	0.07	0.00	0.00	0.06	0.05	0.00	0.00	0.42
	D.I. Khan	0.82	0.12	0.11	0.04	0.12	0.08	0.00	0.14	0.21
	Mardan	0.50	0.12	0.06	0.00	0.12	0.04	0.00	0.00	0.15
	Charsadda	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07
	Swabi	0.58	0.12	0.02	0.00	0.09	0.06	0.00	0.00	0.29
	Peshawar	0.69	0.07	0.01	0.00	0.02	0.05	0.00	0.07	0.46
	Buner	0.46	0.09	0.05	0.07	0.04	0.03	0.00	0.00	0.19
	Nowshera	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Haripur	0.85	0.08	0.07	0.01	0.03	0.05	0.00	0.00	0.62
	Kohat	0.40	0.01	0.02	0.00	0.03	0.00	0.00	0.00	0.33
	Abbottabad	0.88	0.09	0.07	0.04	0.07	0.07	0.00	0.04	0.48
Balochistan	Ziarat	0.68	0.06	0.04	0.00	0.04	0.06	0.00	0.00	0.48
	Loralai	0.79	0.11	0.08	0.04	0.08	0.05	0.00	0.14	0.30
	Killa Saifullah	0.70	0.09	0.08	0.04	0.08	0.07	0.00	0.00	0.34
	Hernai	0.91	0.11	0.09	0.06	0.09	0.09	0.00	0.00	0.46
	Pishin	0.59	0.10	0.10	0.01	0.02	0.07	0.00	0.00	0.29
	Zhob	0.58	0.12	0.11	0.01	0.06	0.04	0.00	0.00	0.24
	Musa Khel	0.81	0.11	0.08	0.00	0.06	0.08	0.00	0.00	0.48
	Quetta	0.88	0.10	0.07	0.05	0.08	0.08	0.00	0.25	0.25
	Kalat	0.52	0.10	0.03	0.00	0.05	0.08	0.00	0.02	0.24
	Sibi	0.44	0.02	0.01	0.00	0.01	0.01	0.00	0.01	0.37
	Nasir Abad	0.80	0.12	0.11	0.06	0.06	0.07	0.00	0.01	0.37
	Jaffar Abad	0.69	0.08	0.07	0.04	0.06	0.00	0.00	0.09	0.34
	Average	0.62	0.09	0.05	0.02	0.06	0.05	0.00	0.05	0.29

On average, the inefficiencies associated with the seeded area (S), the labor force (L), and fertilizer consumption (F) are 0.02, 0.05, and 0.05, respectively. In particular, fixed asset investment (I, 0.09) and machinery (M, 0.06) have higher inefficiency scores than other input variables. This means focusing on investment optimization and mechanical upgrades later on. As we distinguish between energy and non-energy inputs, the associated inefficiencies can be captured to provide relevant policy implications. It is worth noting that the contribution of the three variables related to energy consumption (M), GHG emissions (C), and disaster area (D) is 0.40, accounting for 65.6% of the whole inefficiency score (0.62). The inefficiency score associated with low output and disaster-related inefficiency (D, 0.29) is significantly higher than the inefficiency score associated with agricultural CO_2 emissions (0.05). This suggests that the potential increase in productivity in the affected areas (which could lead to a credible food security situation) outweighs the reduction in agricultural CO_2 emissions. It also shows that it is possible to reduce CO_2 emissions from the agriculture sector. Therefore, in the future, the Pakistani government should focus on improving the efficiency of agricultural investment, standardizing agricultural disaster prevention, and improving the overall technical efficiency of the agricultural economy.

Regionally, substantial variation exists among the twenty-four districts. High efficiency is observed for Nowshera. Compared to other districts, Nowshera has a more developed economy and can well coordinate machinery consumption, agricultural economic development, CC, and food security. On the other hand, the total output of the economy of Charsadda is not high, as the level of food security and CC can be streamlined along with economic development. The inefficiency level in Swat is generally low because of the relatively high pollutant emission intensity per unit area. Still, atmospheric environmental control is needed to ensure continuous growth in environmental productivity. Particularly, the districts of Northeast Pakistan (i.e., the overall IE observed for Swabi, Peshawar, and Buner are 0.58, 0.69, and 0.46, respectively), as Pakistan's main granary, have moderate agricultural inefficiency scores. Therefore, these areas can partly coordinate agricultural economic development, CC, and food security, although with more stress on food security. The sum of the static inefficiencies related to CC and food security variables (M, C, and F) in Haripur, Abbottabad, Quetta, Harnai, and Peshawar exceeds that of other areas of Pakistan. This is because other regions have more agricultural disaster areas. Therefore, in the later stage, local governments should address food security issues by preventing natural disasters.

4.2. Tempo-Wise Decomposition

Table 3 presents the change in average annual inefficiency of Pakistan's agricultural sector across 2010–2020. As implied in Table 3, the average inefficiency score in 2010 was 0.47, whereas it turned to 0.64 in 2020. Hence, the decline in agricultural production efficiency reached 36.2%, indicating that structural adjustments are required with the constraints of food security and CC. Notably, Nowshera has been the only district to locate itself at the frontier of agricultural production technology. Considering Pakistan's granary (i.e., Swabi, Peshawar, and Buner), Peshawar's inefficiency distinguishes itself, which should be focused on further.

Moreover, it is important to analyze further the regional pattern of the 24 districts. For the sake of brevity, we clustered the 24 districts from the two provinces in the Northwest (KP) and West (Balochistan) regions when analyzing the changing trend of inefficiency. Specifically, we considered the Northwestern and Western regions. The detailed results are presented in Figure 3.

Table 3. Average annual inefficiency of Pakistan's agricultural sector across 2010–2020.

Province	District Name	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
KP	Swat	0.00	0.00	0.00	0.09	0.69	0.92	0.47	0.05	0.00	0.00	0.00
	Mansehra	0.56	0.67	0.62	0.54	0.54	0.89	0.94	0.00	0.97	0.86	0.00
	D.I. Khan	0.87	0.89	0.74	0.86	0.81	0.83	0.85	0.74	0.83	0.77	0.74
	Mardan	0.50	0.39	0.67	0.35	0.14	0.44	0.60	0.62	0.63	0.67	0.64
	Charsadda	0.06	0.00	0.00	0.30	0.00	0.00	0.22	0.00	0.27	0.00	0.00
	Swabi	0.36	0.46	0.91	0.74	0.41	0.62	0.85	0.77	0.78	0.35	0.46
	Peshawar	0.00	0.47	0.84	0.85	0.57	0.74	0.88	0.88	0.88	0.84	0.80
	Buner	0.00	0.30	0.88	0.58	0.00	0.67	0.74	0.64	0.38	0.75	0.57
	Nowshera	0.00	0.00	0.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Haripur	0.79	0.69	0.74	0.89	0.85	0.91	0.84	0.80	0.92	0.91	0.86
	Kohat	0.20	0.59	0.81	0.26	0.57	0.84	0.63	0.36	0.00	0.52	0.00
	Abbottabad	0.80	0.86	0.91	0.85	0.91	0.88	0.94	0.86	0.87	0.93	0.87
Balochistan	Ziarat	0.45	0.00	0.66	0.87	0.78	0.49	0.87	0.76	0.83	0.92	0.86
	Loralai	0.74	0.74	0.58	0.71	0.78	0.74	0.83	0.85	0.77	0.85	0.85
	Killa Saifullah	0.00	0.00	0.90	0.94	0.79	0.81	0.91	0.89	0.88	0.92	0.84
	Hernai	0.86	0.90	0.86	0.89	0.86	0.91	0.93	0.94	0.94	0.87	0.98
	Pishin	0.54	0.45	0.50	0.00	0.75	0.66	0.66	0.67	0.62	0.82	0.76
	Zhob	0.53	0.58	0.00	0.00	0.75	0.58	0.66	0.74	0.48	0.71	0.79
	Musa Khel	0.83	0.65	0.77	0.66	0.89	0.90	0.93	0.89	0.78	0.80	0.76
	Quetta	0.86	0.84	0.55	0.87	0.90	0.86	0.86	0.90	0.93	0.85	0.90
	Kalat	0.56	0.77	0.65	0.43	0.60	0.50	0.00	0.58	0.49	0.33	0.88
	Sibi	0.37	0.00	0.00	0.36	0.68	0.00	0.29	0.00	0.84	0.85	0.96
	Nasir Abad	0.72	0.63	0.62	0.79	0.80	0.77	0.80	0.87	0.83	0.88	0.92
	Jaffar Abad	0.74	0.46	0.74	0.51	0.74	0.55	0.62	0.87	0.65	0.81	0.93
	Average	0.47	0.47	0.67	0.57	0.63	0.65	0.69	0.64	0.67	0.68	0.64

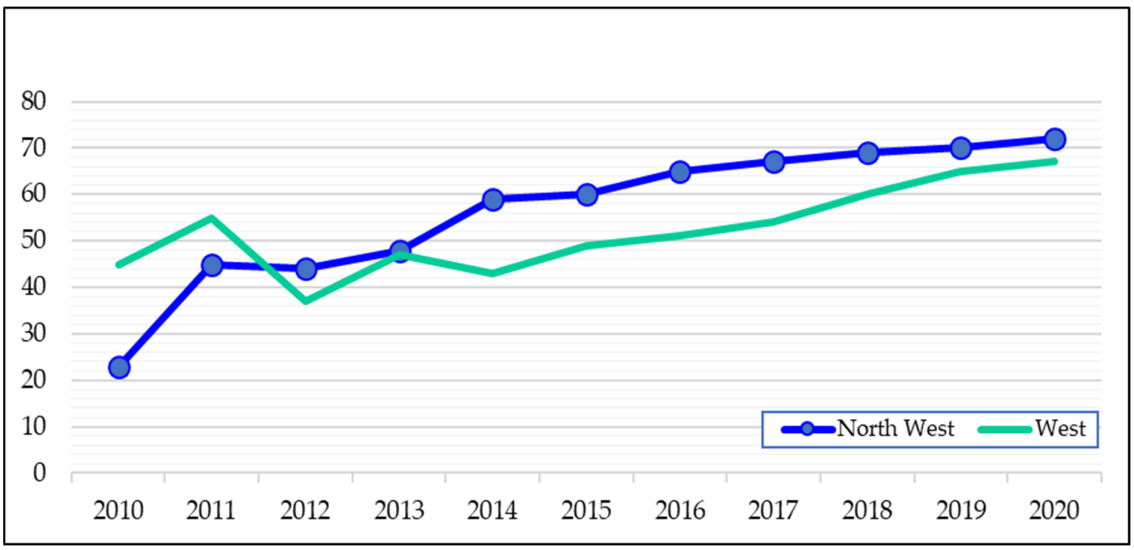


Figure 3. The changing trend of inefficiency score in the Northwest (KP) and West (Balochistan) regions during the study period (2010–2020).

Figure 3 shows that all Northwestern (KP) and Western regions (Balochistan) have inefficiency scores between 20 and 80. Overall, the higher inefficiency in 2020 than in 2010 can be attributed to these two regions. A sharp increase in the inefficiency score can be observed during the period 2012–2015, which may be related to the global financial crisis. This shows that food security and CC in Pakistan's agricultural sector are vulnerable to the global environment. In contrast, the Western region is self-sufficient. In 2019–2020 in particular, efficiency scores declined in both areas.

5. Conclusions, Policy Implications, and Limitations

5.1. Conclusions

Global climate patterns have changed due to increased human activity, especially in emerging countries. CC may pose several challenges in Asia, particularly in South Asian countries (e.g., Pakistan) owing to poor populations, terrain, and technology. Seasonal temperature rises can harm agricultural growth. This study introduces an agricultural production technology framework that modifies previously utilized methods by incorporating specific variable decompositions to assess the performance of the agricultural sector in Pakistan. Furthermore, unlike previous research, we also estimated the aggregation performance. Considering data availability, this study used panel data covering Pakistan's agricultural sector from 2010–2020. Non-parametric models allow multi-input and multi-output investigations from economic and environmental perspectives, where food safety and CC are combined. In particular, overall inefficiencies were decomposed into variable-specific inefficiencies from a resource-specific perspective.

Disaster areas accounted for 0.29 of the 0.62. In addition, the analysis shows that CO_2 emissions, which accounted for 0.05, cannot be ignored. Furthermore, total agricultural output relative to excess inputs and zero inefficiencies indicate the need for structural adjustment. From a regional point of view, Nowshera was a frontier district-level frontrunner in this decade (2010–2020), which should be the best example for other districts. Furthermore, regarding the breadbasket of Pakistan (i.e., Swabi, Peshawar, and Buner), the inefficiency scores of these three regions were 0.58, 0.69, and 0.46, respectively. Peshawar contributes much more to the inefficiency score than other regions, which can be attributed to CC and food security constraints. Therefore, all localities should pay more attention to agricultural CO_2 emission reduction and agricultural disaster prevention.

5.2. Policy Implications

In Pakistan, where production is very important, it is significantly affected by CC and natural disasters. As the main component of grains, wheat plays an important role in ensuring food security. At the same time, rape, as an important oil crop, is also a spring-sown crop. Therefore, production is directly related to the annual supply of grain and oil, and it is of great significance to promote the sustainable supply and price of important agricultural products, such as crops, and increase farmers' income. Considering the normalization of epidemic prevention and control and the prominent La Niña phenomenon in 2023, relevant departments should strengthen the understanding of the importance of early production and comprehensively promote the sowing of crops and increase food production, improve farmers' income, and ensure sustainable food production. The study has some shortcomings. First, due to funding constraints and concerns about the COVID-19 epidemic, only twenty-four districts in two Pakistani provinces (Khyber Pakhtunkhwa and Balochistan) were used in this study. Second, the data limited the extension of our results within some years and the ability to adjust for selection bias due to unobserved heterogeneity issues. Therefore, it is felt that future studies should use panel data to extend our study more accurately.

5.3. Future Directions

In future research, it would be important to include a larger number of districts from more provinces in Pakistan to increase the generalizability of the findings. This could help overcome the limitation of the current study's limited sample size. To overcome the funding constraints faced in the current study, future research could seek additional funding sources or collaborations to conduct a more comprehensive study. This could involve partnering with universities, research institutions, or other organizations that have access to resources. Given the concerns about the COVID-19 epidemic and its potential impact on data collection, future studies could explore strategies to mitigate these challenges. This could include adapting data collection methods, utilizing remote or online data collection

techniques, or implementing appropriate safety measures to ensure that data collection is not compromised.

To overcome the limitation of restricted data regarding the timeframe, future research could consider collecting data over a longer period to capture any potential trends or variations. This would allow for a more robust analysis of the research question and reduce the impact of any short-term fluctuations. To account for the issue of selection bias due to unobserved heterogeneity, future studies could employ advanced statistical techniques such as matching methods, instrumental variable analysis, or regression discontinuity designs. These methods can help minimize the influence of unobserved factors that might affect the study outcomes. Given the identified shortcomings, future research could focus on conducting follow-up studies to build upon the current findings. This could involve addressing the limitations stated and exploring additional research questions related to the topic. Follow-up studies could also consider incorporating qualitative research methods to gain a deeper understanding of the factors influencing the outcomes. Overall, by addressing these future directions, researchers can enhance the validity, generalizability, and impact of their study findings.

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Abbreviations

CC	Climate change	GHG	Greenhouse gas
ADB	Asian Development Bank	WB	World Bank
CO_2	Carbon dioxide	GDP	Gross domestic product
DEA	Data envelopment analysis	SBM	Slack-based model
LCA	Life cycle assessment	KP	Khyber Pakhtunkhwa
DMU	Decision-making unit	VRS	Variable returns to scale
CRS	Constant returns to scale	IPCC	Intergovernmental Panel on Climate Change
SDGs	Sustainable Development Goals		

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