





## Article

# Climate Trends and Wheat Yield in Punjab, Pakistan: Assessing the Change and Impact

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**Abstract:** Climate change has made weather patterns less predictable, making situations more challenging for farmers throughout the production process. This study investigates the impact of climatic variables (maximum and minimum temperature, rainfall, humidity at 8 AM and 5 PM) and fertilizer application on wheat production in Bahawalnagar district, a major wheat producing region of Punjab, Pakistan. The study utilizes the Mann–Kendall and multiple linear regression analysis to check climatic trends and identify the factors influencing wheat yield from 1991 to 2022. The study utilized a regression model to compare actual and predicted wheat yields. The results showed a decreasing trend in rainfall and an increasing trend in both maximum and minimum temperatures during the wheat growing season. Sen’s slope values for maximum temperature (0.037), minimum temperature (0.007), humidity at 8 AM (0.275), and humidity at 5 PM (0.167) indicate the direction and magnitude of trends. The regression model explained about 92% of the variance in the wheat yield. The regression analysis of humidity at both 8 AM ( $p = 0.001$ ) and 5 PM ( $p = 0.001$ ) shows a significant positive correlation with wheat yield. Fertilizer use exhibited a significant positive association with wheat yield ( $\beta = 9.58$ ). Fertilizer application for wheat crops increased from 112.4 kg/ha in 1991 to 284.3 kg/ha in 2021. The regression model identifies that the average wheat yield loss from 1991 to 2022 is approximately 0.1208 t/ha per year because of the influence of climatic factors. The study findings underscore the importance of the utilization of adaptive agricultural practices that can ensure food security and improve agricultural sustainability in the region.

**Keywords:** wheat production; fertilizer use; humidity; Mann–Kendall test; regression analysis



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## 1. Introduction

Climate change is the most pressing global environmental issue, with far-reaching implications that affect every aspect of human life. The issue is contradictory, as its consequences exceed the geographical boundaries of its origin [1]. Pakistan is expected to have a temperature increase that is above the average global increase. Temperature is expected to rise by 1.4–3.7 °C by the 2060s and by 6.0 °C by the 2090s [2]. Azmat et al. [3] identified Pakistan as a region highly affected by climate change, resulting in a significant impact on crop yield and subsequent food scarcity [4,5].

Wheat has a key role in human nutrition. It is an essential diet for more than 35% of the world’s population, accounting for 20% of daily protein and calorie intake. Wheat accounts for around 40–43% of the daily caloric and protein intake in North Africa and West Asia [6,7]. Pakistan falls in the list of top 10 wheat producing countries. Wheat is a major

staple food crop of Pakistan, dominating all crops in terms of area and production. Wheat accounts for 8.2% of the value added in agriculture and 1.9% of the GDP of Pakistan [8]. Approximately 80% of farmers cultivated wheat on about 8.95 million hectares, which accounts for around 40% of the country's total cultivated land during the winter (Rabi) season. Specifically, 6.62 million hectares (73.9%) of this wheat cultivation was carried out in the Punjab province [9]. Pakistan's day temperature has been experiencing a notable increase during March, April, and May, while the night temperature, specifically, increases in March, coinciding with the grain-filling phase of wheat [10]. Lawlor et al. [11] found that a 1 °C increase in temperature would decrease the reproductive phase by 6%, grain filling duration by 5%, and would proportionately influence grain yield and harvest index. According to Lobell et al. [12], a 1 °C increase in temperature will reduce the global wheat yield by 5.4%. Aggarwal et al. [13] predicted a 5.7% reduction in wheat yield in Pakistan for every 1 °C increase in temperature, while Chaudhry [14] predicted a fall of approximately 6% in wheat yield. Since 1930, the potential wheat production has decreased as a result of an increase in minimum temperature.

Climate change threatens future crop production by temperature shifts, changes in precipitation patterns, and more frequent extreme weather events. The agriculture sector is vulnerable to long-term trends and variations in weather conditions [15]. Identifying the relationships between climatic variables and crop yields is essential for predicting and understanding how long-term weather conditions will affect the growth of plants, as well as for developing appropriate adaptation strategies and responses to climate change [16,17]. In order to accurately identify the impact of climate change on agriculture, it is essential to develop a model that adequately represents the statistical correlation between climatic factors and crop production [18].

According to previous studies, the relationship between temperature and the yield of wheat is complex and can be affected by various genetic and environmental factors. Fluctuations in temperature have a direct impact on wheat physiology, affecting crucial growth stages and ultimately leading to a reduction in yield [19]. Djanaguiraman et al. [20] reported a positive correlation whereby increases in photosynthetic rates under certain temperatures boosted yield. At the same time, Ghafoor et al. [21] observed negative impacts under heat stress. Precipitation patterns have a major effect by supplying the essential water needed for the growth of wheat, but extreme precipitation levels can disrupt planting and exacerbate stress conditions [22]. Increased rainfall positively affects wheat yield by improving soil moisture and protein content of grains [23]; however, excessive rainfall can negatively impact wheat yield due to waterlogging and nutrient leaching [24]. Adequate humidity levels are essential for retaining soil moisture and facilitating nutrient uptake and growth [25]. Increased humidity enhances wheat yield by improving grain development [26]. Dogan et al. [27] highlighted a negative correlation between wheat yield and humidity, suggesting that higher humidity levels could adversely affect grain yield through increased susceptibility to diseases and a decrease in grain quality. Changing climatic conditions have an impact on the efficacy of mineral fertilizers. Their application may become ineffective in the case of unusual climatic conditions such as drought [28]. As climate change causes frequent droughts, ineffective mineral fertilizer application will likely become more prevalent [29,30]. Another study noted that high nitrogen fertilizer application can reduce the adverse effects of high temperature during the wheat grain filling stage [31]. These relationships show that along with climatic variables, fertilizer application must also be considered. Furthermore, it must be noted that excessive use of fertilizer has the potential to negatively impact the environment by increasing hazardous substances in the soil [32], which ultimately reduces yield [33]. Therefore, understanding the interactions between climatic variables, fertilizer application, and wheat yield is crucial to ensure optimal crop growth.

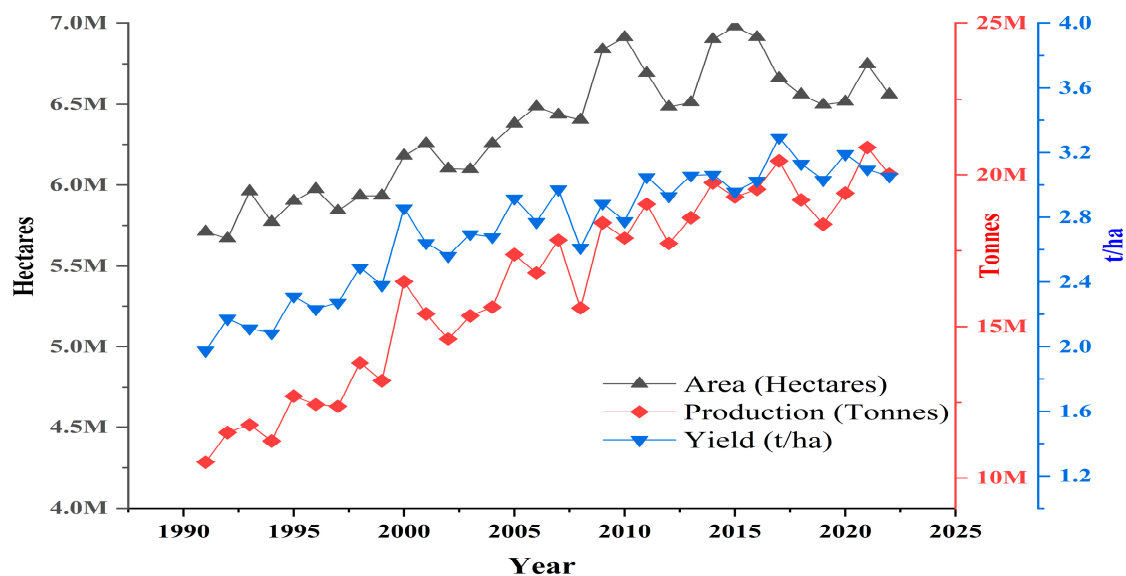
This study employs 32 years of data (1991–2022) on temperature (minimum and maximum), humidity (at 8 AM and 5 PM), rainfall, and fertilizer use to understand the climatic trends and the impact of these factors on wheat yield in Bahawalnagar district, a

major wheat producing region of Punjab, Pakistan. First, we applied the Mann–Kendall test to understand climatic trends during the wheat growing season in the study area. Then, we conducted a correlation analysis to examine the relationship between climatic variables, fertilizer use, and wheat yield. Furthermore, we performed multiple linear regression analyses to assess the impact of climatic variables and fertilizer use on wheat yield. The present study aimed to answer the following research questions: (1) what are the climatic trends in the study area during the wheat growing season over the past three decades? (2) How does fertilizer use affect crop yield as the observed climatic variables have changed over the past three decades?

## 2. Materials and Methods

Punjab, the most populated province, makes the most contribution to the country's overall agricultural production. Punjab is the second-largest province in the country, making up 25.9% of the total area and covering 20.63 million hectares. Punjab has 16.68 million hectares of total arable land, of which 5.87 million hectares were utilized over multiple crop cycles annually. Wheat was grown on 40% of the land in Punjab during the 2018–2019 farming season, while cotton covered 11.5% and rice occupied 12.8% of the total cultivated area [34].

Figure 1 provides a detailed summary of wheat production in Punjab from the cropping season of 1991 to 2022. Wheat was grown on 5.71 million hectares in 1991, producing 10.51 million tons at an average rate of 1.97 tons per hectare. The years 2000, 2005, 2007, 2015, and 2017 were very productive for wheat, with higher averages. The average wheat production reached its peak in the 2017 growing season at 3.29 t/ha. During the growing seasons of 1999, 2008, and 2018, there were notable decreases in wheat production. The decreased crop production in 1999, at 2.3 t/ha, was associated with severe weather conditions. In 2008, wheat production decreased to 2.61 t/ha compared to the previous year due to severe floods in various parts of Punjab province.

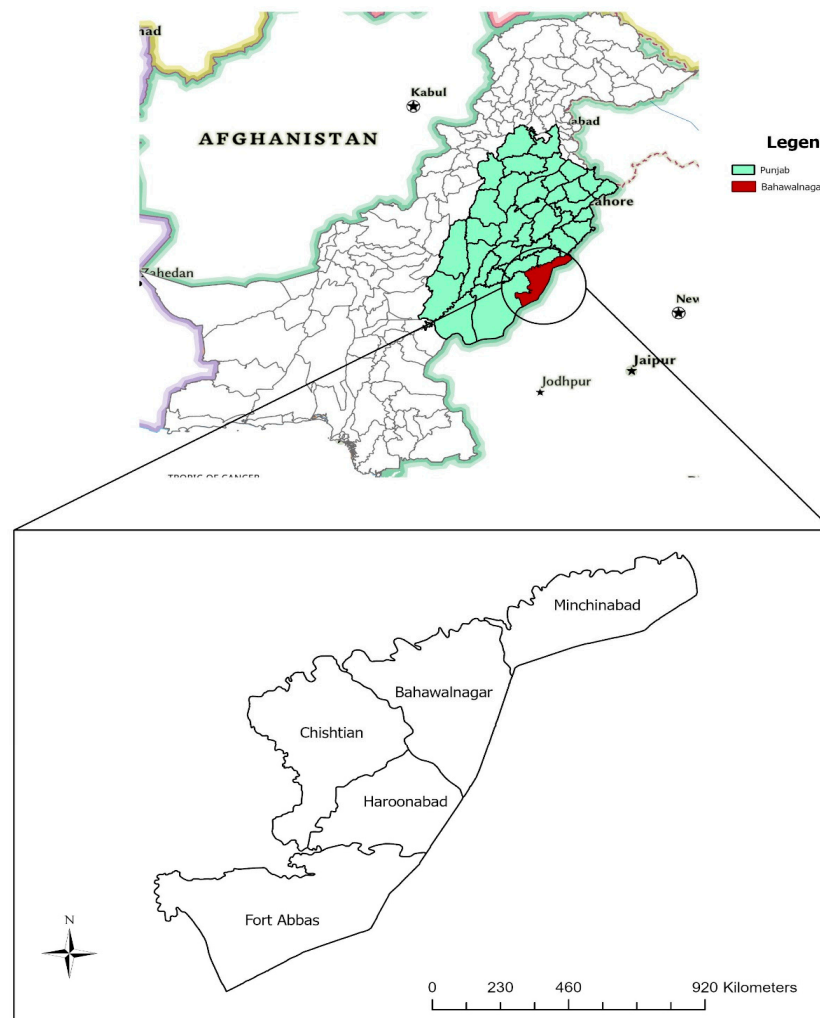


**Figure 1.** Area, production, and yield of wheat (t/ha) in Punjab Province (1991–2022). Source: Crop Reporting Service, Punjab, Pakistan [35].

Between 1950 and 2011, Pakistan witnessed one flood every three years, with approximately 21 extreme floods. The floods resulted in the loss of 8887 human lives and an indirect economic effect of USD 19 billion [36]. Pakistan saw its most severe flooding in history in 2008 and 2010, before the 2022 monsoon disaster. The massive 2010 floods claimed 1985 lives, cost USD 9.7 billion, and impacted 0.2 billion people in the country. The intangible economic losses remain unidentified [37]. The 2022 monsoon floods, as reported

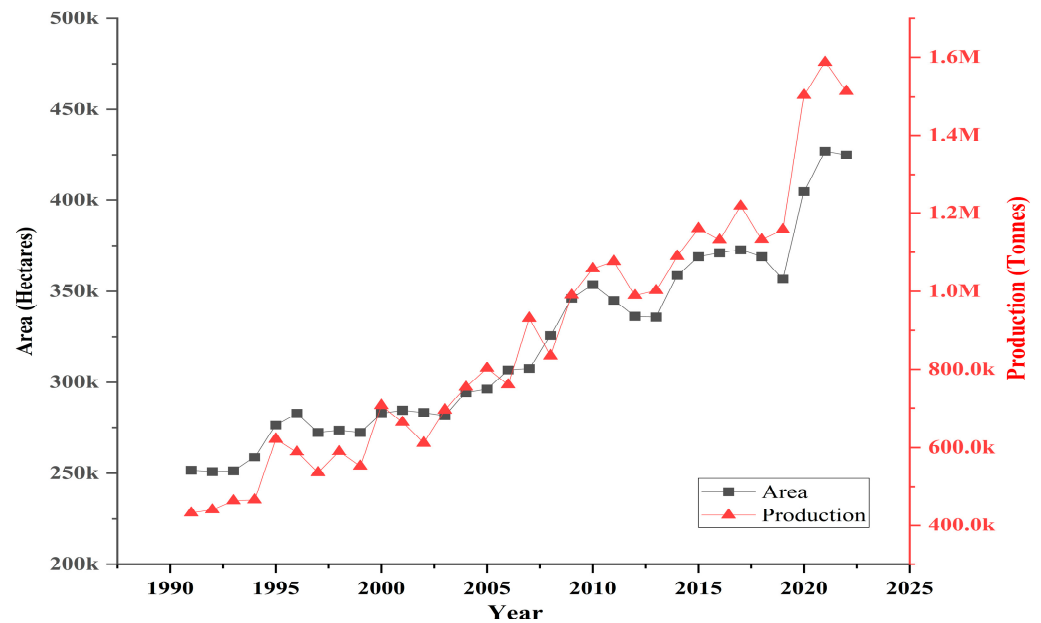
by the government of Pakistan [8], resulted in the death of a minimum of 1033 individuals, impacting 33 million people, and displacing 5.4 million individuals, with 72 districts being officially recognized as “calamity stricken”. Furthermore, the floods devastated 2 million acres of crops and orchards, as well as 2 million homes.

As shown in the Figure 2, the Bahawalnagar district is located in southern Punjab but is classified inside the cotton–wheat zone based on its agroclimatic conditions. Bahawalnagar is situated between latitudes  $20^{\circ}51'$  and  $30^{\circ}22'$  N and longitudes  $72^{\circ}17'$  to  $73^{\circ}58'$  E. Bahawalnagar district ranks first among the 36 districts of Punjab in terms of its contribution to the total acreage of agricultural land cultivated with wheat and its share in total wheat output in Punjab. Bahawalnagar district’s land cover is classified into various categories, with irrigated crops comprising the most significant area (66%). According to the Punjab Forest Department [38], Bahawalnagar has 971,209.4 acres of agricultural land. Most of the agricultural land in Bahawalnagar has been allocated to the cultivation of wheat and cotton. The district of Bahawalnagar has a mostly dry and hot temperature during the summer.



**Figure 2.** Map of the study area.

The wheat area shows a generally increasing trend from around 251,720 hectares in 1991 to approximately 424,929 hectares in 2022 (Figure 3). Similarly, wheat production exhibits variability, with peaks and troughs over the years. Despite fluctuations, there is an overall upward trend in wheat production, rising from 432,000 tons in 1991 to 1,514,000 tons in the growing season of 2022.



**Figure 3.** Area and production of wheat in Bahawalnagar (1991–2022). Source: Crop Reporting Service, Punjab, Pakistan [35].

Table 1 presents comprehensive data on fertilizer use for wheat crops from 1991 to 2022, detailing both national trends and regional figures for the Bahawalnagar district. Fertilizer usage for wheat crop shows upward trends, indicating an increase in national fertilizer use over time, reaching a peak of 2520.06 thousand nutrient tons in 2017 and then declining slightly. Fertilizer use for wheat crops in Bahawalnagar district has followed a similar upward trend over the years. In 1991, farmers applied an average of 112.46 kg of fertilizer per hectare to their wheat crops. This fertilizer use steadily climbed over the following years, reaching a peak of 284.39 kg/ha in 2021 [39]. The 20.05% increase in 2005 exemplifies these variations, likely due to a combination of factors like agricultural practices, economic conditions, and climatic variations influencing fertilizer use decisions at both national and regional levels.

**Table 1.** Fertilizer use in wheat production.

Year	Total Fertilizer Use in Country (000 Nutrient Tons)	Fertilizer Use kg/ha	Fertilizer Use in Bahawalnagar (000 Nutrient Tones)	% Change in Bahawalnagar
1991	889.71	112.4649	28.30966	----
1992	885.48	112.3991	28.20212	−0.38
1993	1009.38	121.612	30.56296	7.72
1994	1009.09	125.6024	32.53159	6.05
1995	1026.05	125.5875	34.71318	6.28
1996	1182.00	141.1175	39.91951	13.04
1997	1076.00	132.6921	36.13993	−10.46
1998	1186.00	141.9509	38.83401	6.94
1999	1171.65	142.3633	38.77398	−0.15
2000	1285.05	151.8433	42.95365	9.73
2001	1344.02	164.2855	46.73927	8.10
2002	1328.59	164.8784	46.70776	−0.07
2003	1369.87	170.5091	48.02684	2.75
2004	1461.5	177.8846	52.33594	8.23
2005	1847.0	220.9859	65.46405	20.05
2006	1902.1	225.1539	69.06784	5.22
2007	1835.8	214.0126	65.82338	−4.93
2008	1790.5	209.4152	68.22308	3.52

Table 1. Cont.

Year	Total Fertilizer Use in Country (000 Nutrient Tons)	Fertilizer Use kg/ha	Fertilizer Use in Bahawalnagar (000 Nutrient Tones)	% Change in Bahawalnagar
2009	1855.5	205.1183	70.97375	3.88
2010	2180.0	238.721	84.43632	15.94
2011	1966.38	220.9168	76.17202	−10.85
2012	1930.48	223.1769	75.05463	−1.49
2013	1810.6	209.0762	70.22795	−6.87
2014	2044.55	222.2579	79.78256	11.98
2015	2157.95	234.4578	86.53402	7.80
2016	1849.64	200.5247	74.41569	−16.28
2017	2520.06	280.8805	104.6908	28.92
2018	2381.68	270.7378	99.92425	−4.77
2019	2307.20	263.9817	94.22576	−6.05
2020	2274.29	262.0754	106.1665	11.25
2021	2504.05	284.3896	121.4209	12.56
2022	2500.73	272.7672	115.9068	−4.76

Source: authors' own attribution based on data provided by National Fertilizer Development Centre (NFDC).  
---- = data unavailable.

### 2.1. Data

Wheat, as a rabi crop, usually grows from November to April in Punjab, Pakistan. Therefore, from November to April (1991–2022), we computed the seasonal maximum and minimum temperatures, precipitation, and humidity levels in the morning and evening by averaging monthly climate variables. These variables were chosen based on their agronomic significance and their impact on wheat physiology and production. For example, temperature affects enzymatic reactions in plants, photosynthesis rates, and grain development [19,20]. Rainfall patterns directly influence water stress conditions in crops, affecting yield and quality [23]. Humidity levels impact evapotranspiration rates and the occurrence of plant diseases [27]. The variability in climatic conditions and wheat yield within the dataset introduces challenges in modeling and may restrict the applicability of the results beyond the specific study area. The secondary data were gathered from three main sources:

Climatic data: climatic data for the wheat growing season (1991–2022) were obtained from the Pakistan Meteorological Department.

Wheat production data: secondary data on wheat production from 1991 to 2022 were obtained from the Crop Reporting Service (CRS), a division of the Agriculture Department of the Government of Punjab that maintains agricultural statistics in the region.

Fertilizer use data: fertilizer offtake data for the wheat crop from 1991 to 2022 were collected from the National Fertilizer Development Centre (NFDC).

### 2.2. Data Analysis

The Mann–Kendall test was employed to analyze climatic patterns in the study area. The MK test is utilized to identify statistically significant decreasing or increasing patterns in long-term temporal data [40]. A multiple linear regression (MLR) model is applied to determine the impact of climatic factors and fertilizer use on wheat yield. Regression analysis is a statistical method used to estimate the relationships between a dependent variable (wheat yield) and one or more independent variables. The multiple regression model enables the prediction of an outcome utilizing information from several explanatory variables [41]. Lobell et al. [18] examined the correlation between wheat production and climatic patterns in Mexico. They utilized mechanistic and statistical models to demonstrate that a significant portion of the yield increase is caused by climatic shifts in northwest states, particularly the decrease in nighttime temperatures throughout the growing season. Tao et al. [42] conducted a study in China at the provincial level to analyze the relationship between climatic variables and crop yield, focusing on the effects of current climatic trends. The study revealed that the crop yields in China's main farming regions were closely

linked to the climatic conditions of the growing season, with a notable upward trend in the growing season temperatures.

### 3. Results

#### 3.1. Mann–Kendall Trend Test

The Mann–Kendall (MK) test was used to assess trends in climatic data for the wheat growing season (1991–2022). In the MK test, the  $S$  value identifies the increasing or decreasing trends in the climatic parameters, with a positive sign indicating an increasing trend and a negative indicates a decreasing trend. After analyzing the trends in rainfall, minimum, maximum temperature, and humidity at 8 AM and 5 PM from 1991 to 2022 and comparing it with a significance level of 0.05, results show that annual rainfall is decreasing, with a negative  $S$  value of  $-4$ , a Kendall's Tau of  $-0.008$ , and a non-significant  $p$ -value of 0.961 (Table 2).

**Table 2.** The results of the MK test and Sen's estimate for wheat growing season in Bahawalnagar (1991–2022).

Climatic Parameters	S	( $\tau$ )	$p$ -Value	Var(S)	Z	Result
Rainfall (mm)	$-4$	$-0.008$	0.961	3800.6	$-0.008$	$H_0 \downarrow$
Maximum temp. ( $^{\circ}\text{C}$ )	98	0.198	0.116	3800.6	0.037	$H_0 \uparrow$
Minimum temp. ( $^{\circ}\text{C}$ )	61	0.123	0.330	3799.6	0.007	$H_0 \uparrow$
Humidity 8 AM (%)	212	0.430	0.001	3769	0.275	$H_a \uparrow$
Humidity 5 PM (%)	126	0.256	0.042	3796.6	0.167	$H_a \uparrow$

Test statistic =  $S$ , the variance of  $S = \text{Var}(S)$ , Sen's slope =  $Z$ , Kendall tau =  $\tau$ , test results = increasing ( $\uparrow$ ) or decreasing ( $\downarrow$ ), alpha = 0.05 The alpha level is set at 0.05, the chosen significance level,  $H_0$  = there is no trend in the series,  $H_a$  = there is a trend in the series. Source: authors' own attribution based on data provided by the Metrological Department Pakistan.

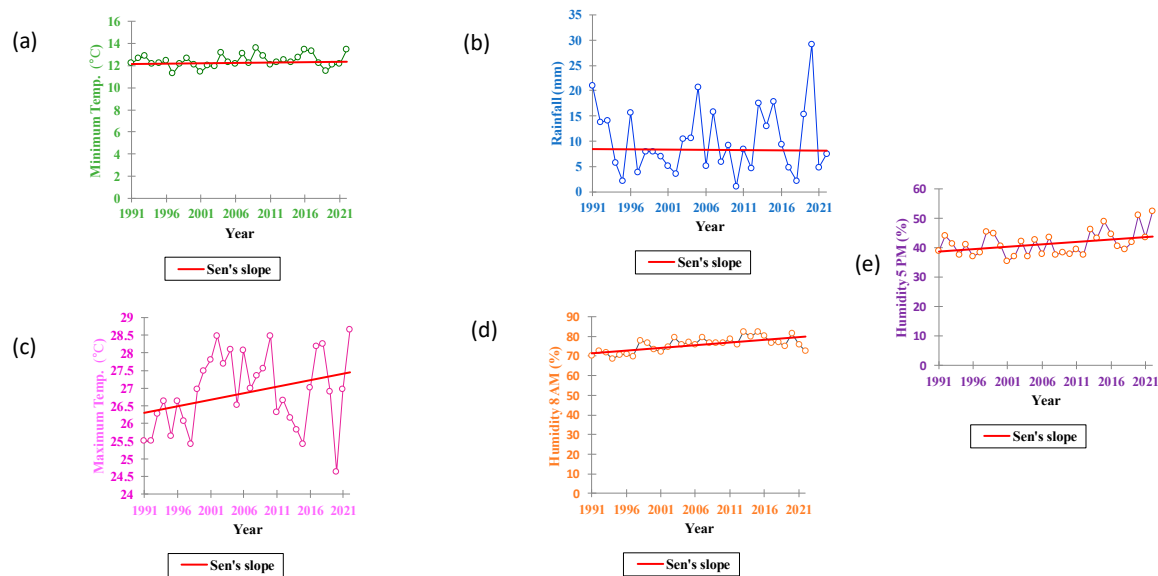
The maximum temperature showed increasing trends, with a positive  $S$  value of 98 and  $\tau$  of 0.198. Similarly, minimum temperature also highlights increasing trends, with positive  $S$  of 61, Kendall's Tau of 0.123, and  $\text{Var}(S)$  of 3799.6. The seasonal maximum and minimum temperatures both exhibit a positive trend, but their respective  $p$ -values (0.116 and 0.330) are non-significant; this shows that both trends are not increasing significantly. A study conducted by the World Food Program found that the average annual temperature in Pakistan increased by around  $0.07^{\circ}\text{C}$  every decade from 1960 to 2018 [43]. The World Bank and Asian Development Bank conducted similar research indicating that the average temperature of Pakistan increased by around  $0.47^{\circ}\text{C}$  between 1960 and 2007 [44].

However, in contrast, the Mann–Kendall test for humidity at both 8 AM and 5 PM highlights significant increasing trends. The humidity level at 8 AM was found to have an  $S$  value of 212 and a Kendall tau ( $\tau$ ) of 0.430. This led to the rejection of the null hypothesis, showing a significant increasing trend in humidity with a  $p$ -value of 0.001. Similar results can be observed for humidity at 5 PM, where a noticeable increasing trend in humidity is indicated by an  $S$  value of 126 and a Tau coefficient of 0.256, which again leads to the rejection of the null hypothesis  $H_0$  with a significant  $p$ -value of 0.042 (Table 2).

#### 3.2. Sen's Slope Estimator

Sen's slope values provide useful insights into the direction and magnitude of trends in climatic parameters, allowing us to understand long-term patterns and changes in environmental conditions. Sen's slope, derived from the MK test, provides a measure of the magnitude of the trend observed in the respective climatic parameters over the given time period (Figure 4). In this context, a negative Sen's slope value, such as for annual rainfall ( $-0.008$ ), suggests a slight downward trend, although not statistically significant, indicating a minor decrease in rainfall over time. Conversely, positive Sen's slope values, like those for maximum temperature (0.037), minimum temperature (0.007), humidity at 8 AM (0.275), and humidity at 5 PM (0.167), indicate increasing trends. These positive slopes indicate

a gradual rise in temperature and humidity levels, with higher values indicating steeper upward trends (Figure 4).



**Figure 4.** Sen's slope for climatic parameters during the wheat growing season in Bahawalnagar (1990–2022). Source: authors' own attribution based on data provided by the Metrological Department Pakistan. (a–e) Sen's slope.

### 3.3. Regression Analysis

Table 3 provides a summary of the wheat yield and various climatic variables over a 32-year period. The mean yield is approximately 2.834 t/ha, with a standard deviation of 0.594, indicating a moderate degree of variability in yields across the years. Rainfall shows substantial variability, with a mean of 10.047 mm, ranging from 1.000 mm to 29.250 mm, indicating considerable variability in precipitation levels. Minimum and maximum temperatures exhibit less variability compared to rainfall, with mean values of 12.422 °C and 26.887 °C, respectively. Humidity at 8 AM and 5 PM also demonstrate moderate variability, with mean values of 75.818 and 41.536, respectively, during the growing seasons of wheat crop over the years (Table 3). The fertilizer application rates for the wheat crop in Bahawalnagar range from 0.112 to 0.195 t/ha, with an average of 0.195 tons per hectare.

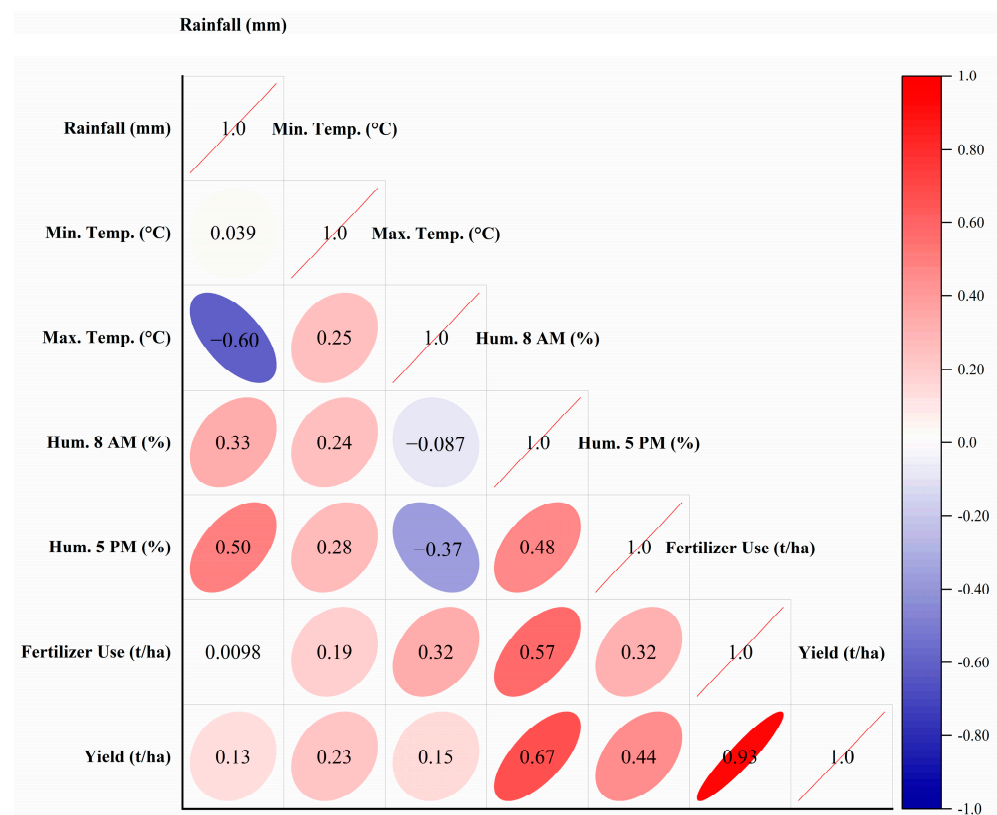
**Table 3.** Summary statistics from regression analysis of factors impacting wheat yield (1991–2022).

Variable	Observations	Minimum	Maximum	Mean	Std. Deviation
Yield (t/ha)	32	1.838	3.983	2.834	0.594
Rainfall (mm)	32	1.000	29.250	10.047	6.574
Min. temp. (°C)	32	11.317	13.617	12.422	0.581
Max. temp. (°C)	32	24.633	28.667	26.887	1.066
Hum. 8 AM (%)	32	68.667	82.500	75.818	3.717
Hum. 5 PM (%)	32	35.333	52.500	41.536	4.212
Fertilizer use (t/ha)	32	0.112	0.284	0.195	0.054

Source: authors' own attribution based on data from the Metrological Department and Agriculture Department.

The correlation matrix, which ranges in value from  $-1$  to  $1$ , offers a numerical summary of the associations between the variables. A negative correlation signifies an inverse relationship, whereas a positive correlation depicts a direct relationship. Figure 5 shows that humidity at 8 AM ( $0.674$ ,  $p \leq 0.0001$ ) and humidity at 5 PM ( $0.441$ ,  $p = 0.012$ ) exhibit the strongest positive correlations, suggesting that higher humidity levels are associated with higher wheat yields. Rainfall ( $0.135$ ), minimum temperature ( $0.233$ ), and maximum temperature ( $0.146$ ) also show positive correlations with yield, although weaker ones.

A correlation coefficient of 0.935 ( $p \leq 0.0001$ ) indicates a significant positive association between increased fertilizer use and higher yield of wheat.



**Figure 5.** Correlation matrix presenting the relationship between different variables; each cell shows the Pearson correlation coefficient between variables, 1 indicating a stronger positive correlation, and  $-1$  indicating a stronger negative correlation. The color intensity and the size of the ellipse in each cell indicate the strength of the correlation, with red representing positive and blue denoting negative correlations. Source: authors' own attribution based on data from the Metrological Department and Agriculture Department.

The regression analysis for the variable “Yield” indicates that the model has an excellent goodness of fit (Table 4). With 32 observations and 25 degrees of freedom, the model explains approximately 92% of the variance in the yield data, as indicated by the  $R^2$  value. The adjusted  $R^2$  of 0.901 indicates that over 90.1% of the variance in yield is explained by the independent variables, taking into account the number of predictors in the model. The mean squared error (MSE) is 0.035, and the root mean squared error (RMSE) is 0.187, indicating the average deviation of the observed values from the predicted values by the model. The ANOVA indicates that the regression model is statistically significant ( $F = 48.242$ ,  $p < 0.001$ ), indicating that at least one independent variable strongly predicts wheat yield (Table 4).

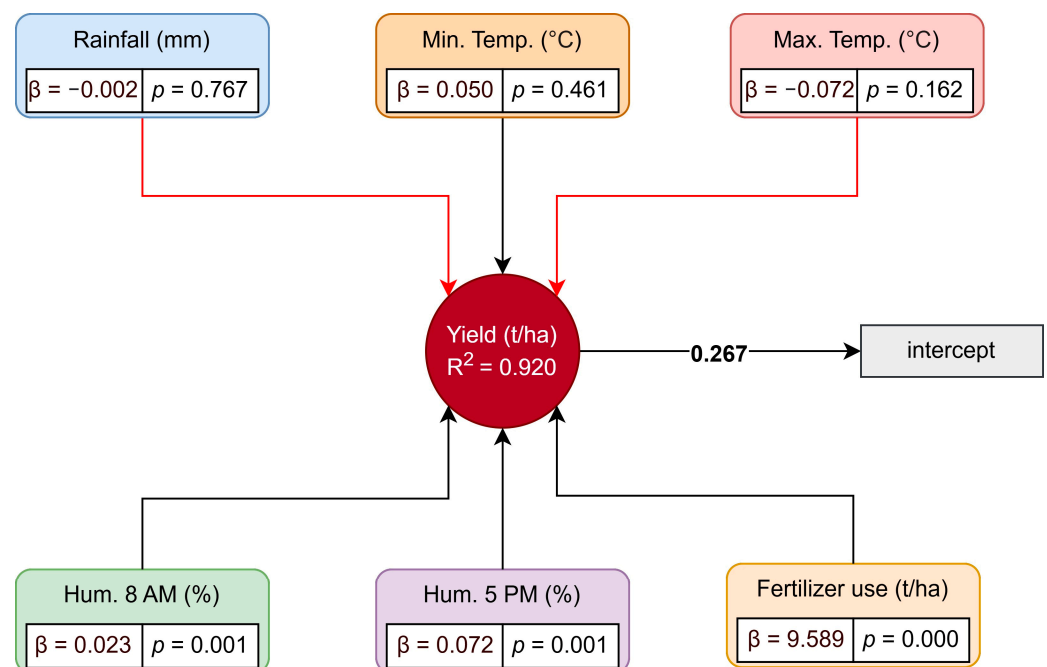
**Table 4.** Regression of variable yield: goodness-of-fit statistics.

Observations	DF	$R^2$	Adjusted $R^2$	MSE	RMSE	ANOVA (F)	$p$
32	26	0.920	0.901	0.035	0.187	48.242	0.000

DF = degrees of freedom,  $R^2$  = R-squared (coefficient of determination), Adjusted  $R^2$  = adjusted R-squared (model accuracy), MSE = mean square error, RMSE = root mean square error, ANOVA (F) = analysis of variance (F-statistic),  $p$  =  $p$ -value.

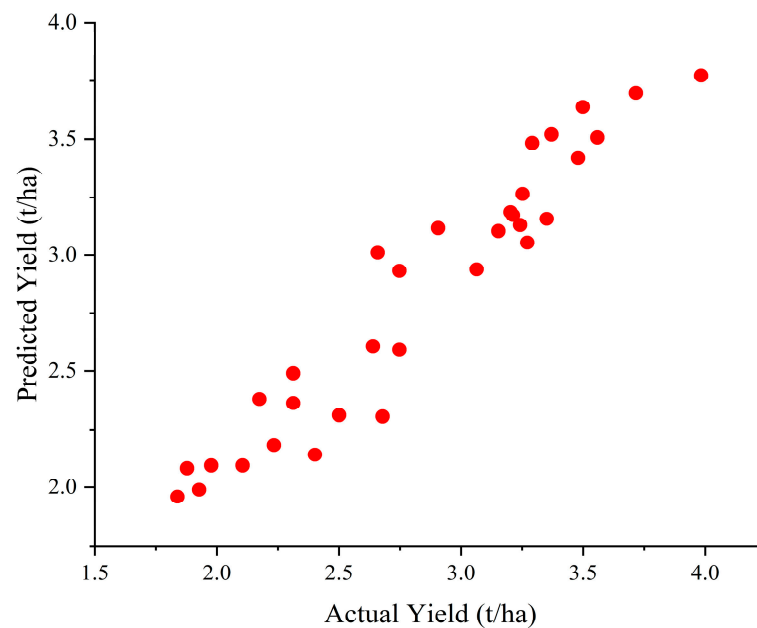
The model parameters provide insights into the relationship between wheat yield and the various climatic factors considered (Figure 6). In our findings, the intercept value (0.267)

represents the expected wheat yield when all predictor variables are equal to zero. The high intercept value can be attributed to factors such as residual soil fertility or irrigation, which contribute to a baseline yield even in the absence of the measured variables. The coefficients for humidity at 8 AM and 5 PM are 0.023 (0.001) and 0.007 (0.001), respectively. These positive coefficients suggest that for every unit increase in humidity at 8 AM and 5 PM, the wheat yield is expected to increase by 0.023 and 0.007 tons per hectare, respectively, holding other variables constant. Studies have shown that adequate soil moisture, which can be affected by the level of humidity in the atmosphere, is essential for optimal wheat growth and yield. Bramley et al. [45] emphasize the significance of soil moisture, influenced by climatic factors such as humidity, as the main factor affecting the potential crop production in wheat and barley fields. The coefficient for rainfall is  $-0.002$  ( $p = 0.767$ ) which indicates that for every unit increase in rainfall, the wheat yield is expected to decline by 0.002 t/ha, holding other variables constant. However, the correlation was non-significant. Hochman et al. [46] found that the wheat yield potential in southern Australia has dropped because of decreased rainfall. On the other hand, increased precipitation at the post-anthesis stage increases the risk of disease and insect attacks in wheat crop [47]. Increased rainfall leads to waterlogging, which delays harvesting and results in seed sprouting in the field [48]. The coefficient (0.050,  $p = 0.461$ ) of minimum temperature shows a non-significant positive relation with wheat yield. Previous research indicates that an increase in temperature decreases the photosynthetic process in wheat plants and accelerates leaf senescence [49]. It alters the water dynamics in wheat, leading to a decrease in water-use efficiency in wheat crops [50]. The coefficient for fertilizer use (t/ha) is 9.589, indicating a strong positive association with wheat yield ( $p$ -value  $< 0.0001$ ), highlighting the importance of fertilizer application in enhancing crop productivity. A meta-analysis [33] conducted on the effect of chemical nitrogen fertilizer application on wheat output in Africa and China revealed that the appropriate use of nitrogen fertilizer leads to a substantial improvement in wheat production. This effect is particularly important for food security, as it allows for more production on the same amount of land.



**Figure 6.** The partial least square (PLS) path diagram represents the relation between independent variables (climatic factors, fertilizer use) and dependent variable (wheat yield). The red line indicates a negative relation,  $\beta$  = coefficient value,  $p$  = level significance, which is set at the level of 0.05. Fertilizer unit is taken as t/ha for regression model. Source: authors' own attribution based on data from the Metrological Department and Agriculture Department.

We forecasted the decrease in wheat yield caused by climate patterns using selected predictor variables from 1991 to 2022 (Figure 7). The projected wheat yield losses consider the impact of the different factors incorporated in the regression model. Figure 6 presents observations from 1991 to 2022, including the actual yield and predicted yield values. For each year, the observed yield represents the actual outcome, while the predicted yield is the value estimated by the regression model. For example, in 1991, the observed yield was 1.838 t/ha, while the predicted yield was 1.958 t/ha. In 2003, the observed yield was 2.639 t/ha, while the predicted yield was 2.607 t/ha. For the year 2010, the observed yield was 3.212 t/ha, whereas the predicted yield was 3.172 t/ha. In 2015, the observed yield was 3.370 t/ha, and the predicted yield was 3.520 t/ha. The average wheat yield loss from 1991 to 2022 is approximately 0.1208 t/ha per year, indicating an underestimation by the model and influence of climatic and agronomic factors.



**Figure 7.** Actual vs. estimated wheat yield (t/ha) over the study period (1991–2022). Source: authors' own attribution based on data from the Metrological Department and Agriculture Department.

#### 4. Discussion

Precipitation patterns have changed significantly in recent decades. Overall, Pakistan has experienced a slight rise in precipitation over the past century. However, the Mann–Kendall test indicated a non-significant decreasing trend in rainfall which aligned with the findings of Salma et al. [51], who reported rainfall patterns in different areas of Pakistan over three decades (1976 to 2005). Their study found that several locations, including Dir, Gilgit, Kakul, Muzaffarabad, Islamabad, Lahore, Kalat, Khuzdar, Bahawalpur, Khanpur, Hyderabad, Jewani, and Nawabshah, experienced a decrease in average rainfall with a non-significant trend. Minimum and maximum temperatures during the wheat growing season showed non-significant positive trends, consistent with previous findings. For example, Hughes and Balling [52] reported a non-significant average increase of 0.07 °C per decade in minimum temperature at non-urban stations in South Africa. Similarly, Kruger and Shongwe [53] found a non-significant positive trend of 0.07 °C per decade in mean annual maximum temperature for South African urban stations.

Humidity levels during morning and evening indicate notable upward trends during the wheat growing season. This study contrasts with the findings of Oguntunde et al. [54], that RH remained relatively stable, but coincided with the research of Xiao et al. [55] in northeastern China, which showed similar patterns.

The results of the regression model identified the effects of climatic parameters and fertilizer use on wheat yield. Among the different variables, humidity in the morning

shows significant positive effects on wheat yield. Higher humidity in the morning can create favorable conditions for dew formation on wheat leaves. Dew can provide moisture to the plant, contributing to its hydration and potentially reducing water stress, particularly in arid regions or during dry spells [56]. The presence of morning humidity has a moderating effect on microclimate temperatures and helps in maintaining ideal moisture levels. This, in turn, prevents plant stress while enhancing physiological activities such as photosynthesis and stomatal conductance [57]. Furthermore, morning humidity can reduce the temperature fluctuations between night and day, which tend to stress plants and can affect grain filling—a critical phase for determining wheat yield [58]. By stabilizing temperatures, morning humidity supports the efficient continuation of metabolic processes crucial for optimal yield accumulation. This effect is particularly beneficial during the grain-filling stage, where consistent and optimal conditions can significantly impact final yields. The positive impact of humidity on wheat indicates the importance of microclimate management through conservation tillage and mulching. By regulating soil moisture and temperatures, these methods mitigate the adverse impacts of diurnal fluctuations on plants [57]. Rainfall showed a non-significant negative relation with wheat yield (Figure 4). Irregular rainfall impacts wheat productivity during the harvesting season, resulting in food insecurity in the country [59]. High rainfall can have both positive and negative impacts on wheat yield, depending on the timing and intensity of precipitation. While adequate moisture is essential for the germination, growth, and development of wheat plants, excessively high rainfall, especially during critical growth stages such as flowering and grain filling, can lead to waterlogging, nutrient leaching, and increased susceptibility to diseases such as root rot and fungal pathogens. These conditions can inhibit root development, stunt plant growth, and ultimately reduce yield [24]. Minimum temperature shows a non-significant negative relationship with wheat yield (Figure 6), while maximum temperature shows a non-significant positive relationship with wheat. These results are in contrast with previous studies, such as that by Wang et al. [60], which identified a significant positive correlation between minimum temperature and yield and a significant negative correlation between maximum temperature and wheat yield. In our results, the non-significant relationships of minimum and maximum temperatures with wheat yield can be attributed to the use of regional climatic adaptive wheat varieties that can resist temperature stress [61]. Our findings are consistent with previous studies indicating a positive correlation between fertilizer application and wheat yield [62]. For example, Youssef et al. [63] demonstrated that the application of organic manure and biofertilizers resulted in increased wheat yield. Similarly, Hawkesford [64] emphasized that the application of nitrogen not only increases the amount of grain produced but also enhances the crop's ability to absorb nitrogen. Likewise, Abedi et al. [65] further explained that appropriate levels of nitrogen can enhance the protein and gluten content of wheat, which is essential for the quality of the grain. He et al. [66] documented a significant correlation between soil quality improvement due to organic fertilizer use and increases in wheat yield, underscoring the sustainability aspect of fertilizer application. Nitrogen is essential for plant growth, and fertilizers replenish these nutrients in the soil [67]. Hlisnikovský et al. [28] found that specific fertilization treatments could mitigate the effects of less favorable weather conditions, resulting in a consistent yield over a period of time. This study suggests that fertilizer application can act as a tool for adapting to climate change and maintaining the yield of wheat. However, long-term solutions require a combination of strategies, including sustainable fertilizer use and development of climate-resilient wheat varieties. Continuous research and data collection are essential for refining models and adapting agricultural strategies to ensure long-term sustainability under evolving climate impacts.

## 5. Conclusions

This study analyzed climatic trends in Bahawalnagar, a major wheat producing region of Punjab, Pakistan, from 1991 to 2022, to assess the impact of climate and fertilizer use on wheat production.

The Mann–Kendall (MK) analysis revealed a decreasing trend in rainfall and increasing trends in both minimum and maximum temperatures during the wheat growing season. Additionally, humidity levels in the morning (8 AM) and evening (5 PM) showed an increasing trend.

The regression analysis of wheat yield and climatic variables over 32 years in Punjab, Pakistan, revealed the influence of climate on agricultural productivity. Wheat yields exhibited significant variation, ranging from 1.97 t/ha to 3.29 t/ha, but variations in rainfall patterns highlighted the challenges caused by uncertain climatic conditions. The study found that humidity levels at 8 AM and 5 PM were positively correlated with the yield of wheat. In contrast, rainfall and minimum temperature reveal a negative association with wheat yield. The positive correlation between fertilizer use and wheat production highlights the importance of fertilizer application in increasing crop productivity. Data limitations precluded the inclusion of important factors such as soil properties, crop varieties, and pest attacks. This omission might introduce bias and provide an incomplete understanding of the determinants of wheat yield.

The linear regression approach might not fully capture the non-linear responses of wheat yield to climatic changes. Future studies should consider including additional variables, applying advanced modeling techniques, and extending the geographical scope to enhance the model's validity and applicability. To maintain wheat yields in the context of shifting climatic circumstances, it is essential to employ adaptive agricultural practices that improve water efficiency, mitigate temperature stress, and optimize moisture levels. Further research and advancements in technology are required to develop crop types and implement management strategies that can endure severe weather conditions in Punjab, Pakistan. This is critical for ensuring food security and agricultural sustainability in the region.

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