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Assessing climate change-induced food security risks for rural communities in South Punjab, Pakistan

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Abstract. This study examined the impact of climatic variability on food security in rural communities across three key districts in South Punjab, Pakistan. A mixed-methods approach was employed, combining Geographic Information System (GIS) techniques to map food security zones and socioeconomic data to compute a food security index. Primary data were collected from 399 respondents through a field survey using a disproportionate stratified random sampling technique in selected union councils of Bahawalpur, Rahim Yar Khan, and Rajanpur districts. Climate data from 1991 to 2021 were analyzed using multiple linear regression analysis. Advanced statistical methods, including categorical principal component analysis, global Moran's I, and Anselin local Moran's I, were utilized to identify spatial clusters of food security. The analysis revealed regional disparities: Bahawalpur demonstrated high food security, Rajanpur exhibited severe food insecurity, and Rahim Yar Khan showed mixed results. The study found that expanding agricultural crop areas improved food availability, although climatic factors had a complex impact on the yields. Higher temperatures decreased wheat production in Rajanpur but enhanced yields in Bahawalpur and Rahim Yar Khan. Non-linear Principal Component Analysis identified key factors, such as livelihoods, asset accessibility, and desertification, which explained 46% of the variation in food security. These results underscore the need for adaptive strategies, including the use of advanced technologies and improved irrigation, to mitigate the effects of climate change and support agriculture in South Punjab.

Keywords: Climate variations, Agriculture, Food Security Index (FSI), Non-Linear Principal Component Analysis (NLPCA), Agricultural adaptation, GIS.

1. Introduction

Climate change is a concerning phenomenon rapidly occurring in the 21st century (Naz et al. 2022), and its Impacts can be seen thoroughly in every sector of life (Khan et al., 2024). Climate change vulnerabilities have impacted all sectors of the economy, but agriculture has been the most severely affected. It imposes several hurdles to agricultural methods, rural lives, food security, and the environment (Sargani et al., 2023). Climate change is having a detrimental impact on the livelihoods and food security of millions of farmers worldwide. Furthermore, future estimates of climate change lead to a warmer trend, typified by frequent intense heatwaves, floods, erratic patterns of rainfall, droughts, diseases, and insect/pest infestation illness (Tilahun et al., 2025). Additionally, changes in rainfall patterns and temperature are leading to long-term droughts (Badji et al., 2023) and floods (Yevdokimov et al., 2021), which directly affect food production (Gregory et al., 2005a). This rising climatic sensitivity of food production and agronomic threats are posing a significant impact on food security (Howden et al., 2007; Tariq et al., 2014). In addition, the Food and Agriculture Organization (FAO) reaffirmed the impacts of these climatic factors on food security across the globe (FAO, 2020). So, climate variation seriously influences global food security (Tariq et al., 2014; Kogo et al., 2021; Molotoks et al., 2021; Abbas et al., 2022a). Diversifying livelihoods is critical to addressing climate risk (Sargani et al., 2023) Achieving food security for all sustainable agricultural systems is essential to achieving the Sustainable Development Goals (SDGs) (Varzakas & Smaoui, 2024). Subsequently, this rising concern for food security is a significant threat multiplier (Shirazi et al., 2020) for sustainable development. In this context, agricultural activities are essential for maintaining food security in developing countries (Pawlak & Kołodziejczak, 2020). Agricultural output is a major source of income for rural sustainable development, and it is essential to adapt to changing environmental conditions. There is increasing rural poverty due to reducing livelihoods due to climate induced hazards. Farmers are extremely concerned about adapting to the changing climate in order to maintain sustainable livelihoods (Kuang & Liao, 2020). The survival of rural communities depends on achieving sustainable development in the face of climate change's threats (Usman et al., 2024)

Globally and in all regions except Northern America and Europe, the incidence of food insecurity is consistently higher in rural areas than in urban areas, however the prevalence in peri-urban areas varies by region (UNICEF, 2024). Food security was first defined as "availability at all times of adequate world food supplies of basic foodstuffs to sustain a steady expansion of food consumption and to offset fluctuations in production and prices" during the 1974 World Food Summit (United Nations, 1975). However, in 1983, the FAO reiterated the concept of food security as guaranteeing that all people at all time have both physical and economic access to the basic food that they need (FAO, 1983).

According to FAO (2022) between 638 and 720 million individuals, or 7.8 and 8.8 percent of the world's population, are predicted to have experienced hunger in 2024. Based on the point estimate of 673 million in 2024, there will be 15 million fewer people than in 2023 and 22 million less than in 2022. According to FAO, IFAD, UNICEF, WFP and WHO, (2020), in 2020, around 720 to 811 million people faced hunger, out of which 50% existed in Asian developing countries, and the number of undernourished people in the world continued to rise by around 8.7%. Consequently, 1/3 of people did not have access to adequate food, and about 149.2 million children suffered from stunted growth. Therefore, according to United Nations (UN) projections, about 660 million people will face hunger in 2030 (FAO, 2022). Developing countries are increasingly worried about food security as they strive to attain Zero Hunger by 2030. The expected rise in hunger as a result of climate change is especially important in impoverished and less developed countries, particularly in Asia (Hameed et al., 2020). Furthermore, recent studies have revealed a 15.9% hunger rate in South Asian countries (Yadav & Lal, 2018; Azimi & Rahman, 2024), and aligned with these trends of food security, Pakistan has been notably moving toward insecurity in the recent decade (Munir et al., 2016; Syed et al., 2022; Masood & Javed, 2023). Pakistan's rural livelihood is entirely dependent on agricultural operations, either directly or indirectly, as is the case in other South Asian countries. Pakistan is the eighth most vulnerable country to climate change. Natural risks, low crop yields, soil erosion, and a reduction in the area of farms under administration are all causing problems for people (Zulfiqar et al., 2020).

Climate change susceptibility has also been observed to have a considerable negative influence on agriculture sectors in Pakistan's arid and semi-arid regions (Adnan et al., 2017). Such susceptibility puts pressure on agricultural methods and food supply, resulting in food security in Pakistan. Country is facing a number of challenges stemming from climate change that threaten food security, particularly in rural settings (Abid et al., 2025). The agricultural sector is regarded as the "mainstay of rural Pakistan" and is crucial to Pakistan's economic development (Abbas et al., 2022b). In the South Punjab region, erratic monsoon rains, increased intensity and frequency of droughts, and melting glaciers have contributed to declining water availability and shifts in cropping systems, impacting food security.

Seasonal rises in temperatures and increasingly variable climatic patterns have initiated an array of gradual yet significant changes in climate phenomena such as precipitation, humidity, thermals, wind intensity, wind direction, and rainfall that have, consequently, affected agricultural productivity and food security (Abbas et al., 2022b). This justifies the urgent need to assess the impacts of these climatic shifts on the dynamics of food security and livelihoods of the rural population. In addition, basmati rice is an important commodity in the international market contributing to the economy of Pakistan, and South Punjab is among the key rice-producing areas of the country where small farm systems are most practiced, constituting yet another rationale for this study on the vulnerability of rural populations in the wake of climate change. In Pakistan, the primary factors contributing to food insecurity are rapid population growth and poverty (Hussain & Routray, 2012). These issues impede individuals from fulfilling their nutritional needs (Islam et al., 2023; Haq et al., 2024). Consequently, the World Food Program (WFP) has ranked Pakistan 92nd out of 116 countries in terms of food security (WFP, 2022). Moreover, about 20.3% of the population in Pakistan is undernourished (FAO, 2020). In addition to this, recent climate change-related catastrophes have not only significantly affected the country's agriculture (Hussain et al., 2022; Sajjad et al., 2024) but have also exacerbated the vulnerability of food security, posing a significant challenge to the achievement of Sustainable Development Goal 2 (SDG 2) on a global scale.

Furthermore, there is a significant likelihood of food stress in Pakistan, particularly in the agrarian zones of the Indus Plain (Hussain & Routray, 2012; Hafeez et al., 2024). The Indus Plain is home to agrarian societies heavily reliant on agricultural production. Despite this, there is a scarcity of literature on food security and the factors influencing it.

Moreover, Global food security discussions mainly focus on the availability, storage, and wider distribution of food products on a global scale. Still, practices across the South Punjab region are more toward direct and indirect reliance on agriculture. Over the years, the environmental carrying capacity of this area has diminished to an environmentally stressed region due to the addition of certain socio-economic exploitation combined with ecological destruction through unsustainable practices in agriculture. A paucity of valuable water, as a result of changing precipitation patterns and erratic monsoon rains, for example, poses threats to farmers' interests in the area and exacerbates social capital losses through uncertainties in traditional food production.

The Indus Plain is home to agrarian societies heavily reliant on agricultural production. Despite this, there is a scarcity of literature on food security and the factors influencing it. This study aims to address this gap by offering a comprehensive overview of the food security situation in South Punjab and examining the factors that may have a substantial impact on or significant relationship with food security. Specifically, the study explores the complex interplay between climate change and food security in three key districts of South Punjab: Rahim Yar Khan, Rajanpur, and Bahawalpur.

Its findings are crucial to address challenges posed by food security as it involves farmers as a central point rather than following usual computational models and performance indices. Furthermore, the food basket of the region depends on small farm holdings; therefore, integrating crop varieties that are more potentially resilient to harsh climatic dynamics reflected by changes in the small farm system is necessary to assure food security.

The findings of this study are crucial for policymaking institutions, as they can enhance policy development, shed light on existing gaps in the domain, and ultimately contribute to the achievement of Sustainable Development Goal 2 (SDG 2), as committed by the nations. This study has been designed to prioritize household-level or community-level perceptions as the basis for conducting vulnerability analysis. It is essential to understand the vulnerability of the communities; not only considering their strained food security landscapes but also given their unique socio-political responses to shifting food availability.

Therefore, the main objective of this study is to analyse the status of food security in the districts of Rahim Yar Khan, Rajanpur, and Bahawalpur in South Punjab using relevant socio-economic and demographic indicators. Secondly to assess the relationship between climate change–related variables and food security outcomes in the selected districts, focusing on how climatic variations influence food availability, access, utilization, and stability.

2. Materials and methods

2.1. Description of Study Area

The study was conducted in the southern part of Punjab province, Pakistan. The study area is characterized by an arid and semi-arid climate and includes the unprivileged districts of Rajanpur, Rahim Yar Khan, and Bahawalpur. Geographically, these districts are located at the following coordinates: Bahawalpur (29.3541°N, 71.6908°E), Rahim Yar Khan (28.4211°N, 70.2986°E), and Rajanpur (29.1041°N, 70.33°E) (Fig. 1). The annual mean rainfall for Bahawalpur, Rahim Yar Khan, and Rajanpur is 143 mm, 100 mm, and 293 mm, respectively (PMD, 2022). These districts are part of the dryland areas along the southern edge of Punjab and have a high proportion of the rural population, with 68% in Bahawalpur and 79% in Rahim Yar Khan. Collectively, these districts cover a total area of 49,029 km² and have a total population of 7,936,974 (Nawaz-ul-Huda & Burke, 2017; GoP, 2023). The primary livelihood of the residents in the study area depends on agricultural activities (Yousaf, 2018).

2.2. Field Survey

The field survey was conducted in selected union councils in the Bahawalpur, Rahim Yar Khan, and Rajanpur districts. The target population consisted of farmers who rely on agriculture, which made them particularly vulnerable to climate change (Masood & Javed, 2023). Initially, a pilot survey was conducted to assist in developing a questionnaire.

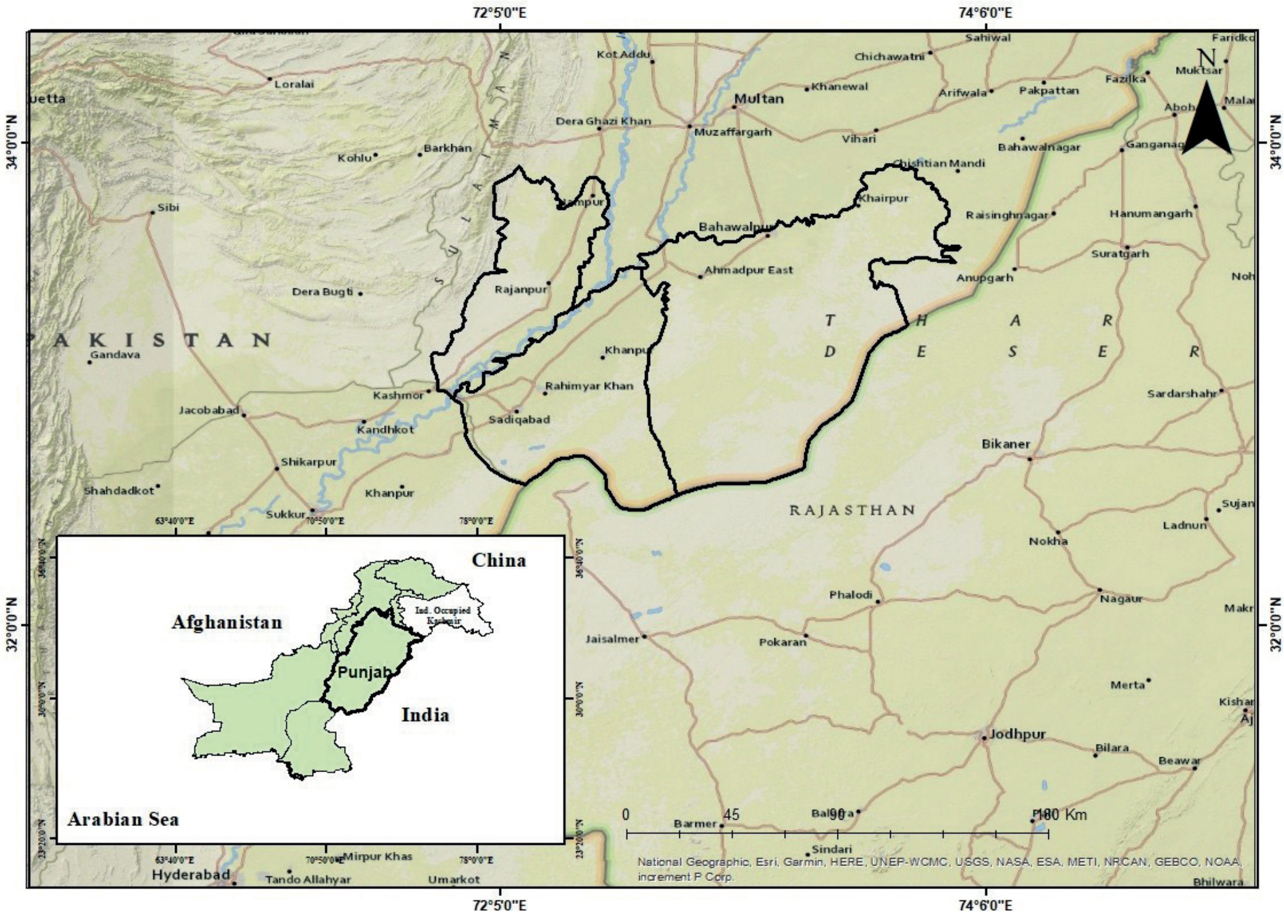

Figure 1. Geographical location of the Study area

The total number of respondents for the field survey was 399, using Slovin's Formula, as shown in equation 1.

$$n = N/(1+Ne^2) \quad (1)$$

where n = Number of samples, N = Total population and e = Error (tolerance level).

In addition, the GPS location of the respondents was recorded, as shown in Figure 2. The sampling technique used for the survey was disproportional stratified random sampling, which ensured equal representation of households from each district. A total of 66 union councils were surveyed across the study area, with 15 from Bahawalpur, 22 from Rahim Yar Khan, and 29 from Rajanpur based on the Desertification Vulnerability Indexed (DVI) (Mazhar et al., 2018).

2.3. Food Security Index

The food security index (FSI) was constructed using Categorical Principal Component Analysis (CATPCA) in SPSS. This method reduces a more extensive set of variables into smaller uncorrelated components. Based on existing literature, the four pillars of food security Availability, Access, utilization, and Stability were selected (Charlton, 2016). Table 1 presents a summary of the variables chosen and their sources.

The number of variables was reduced to components that describe the key variations in the data by clarifying the existing relationship among factors using a statistical technique, Varimax rotation. A, shown in Table 2.

Furthermore, the measure of internal consistency, how closely these four dimensions are significant to each other, along with their percentage of necessary variance, is represented in Table 3. Given this global context, disaster response practices provide a salient example of the importance of cross-regional food aid. As climate change is a multi-scalar phenomenon, insights into its impacts on diverse rural communities would inform useful global assessments of its impact on food security.

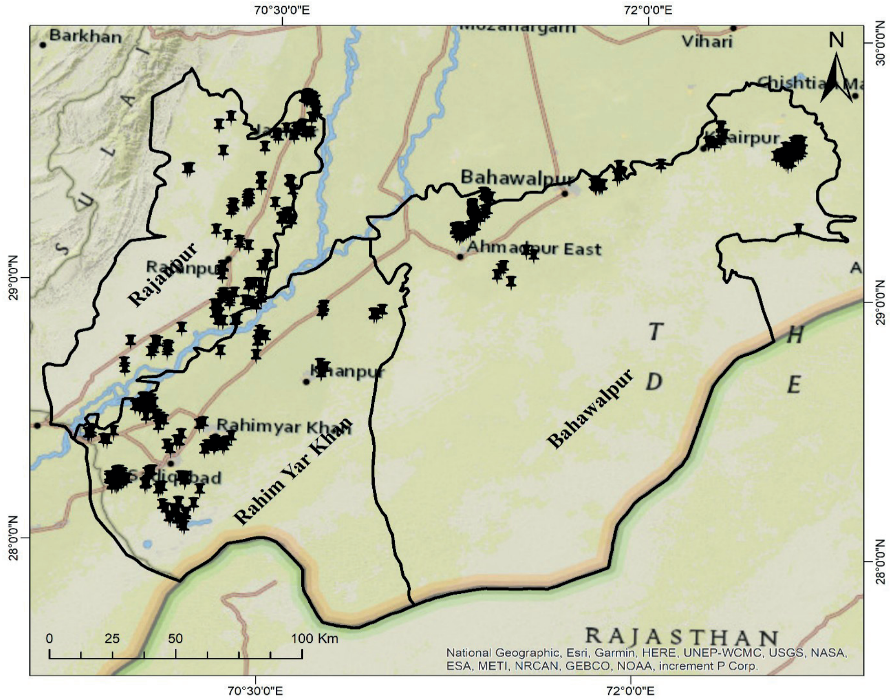

Figure 2. GPS location of the respondents

Table 1. Food security components of CATPCA

Pillar	Variable	Question from the survey	Categories	Scale in SPSS sheet
Food Availability	Access to Assets Type of House	What is the type of your house?	3	Nominal
	Community infrastructure: road	How frequently do you have access to the road?	5	Ordinal
	Facilities: Type of Floor	Living standard	8	Nominal
	Owned farming equipment	Do you use any farming equipment in your production?	6	Nominal
	Appliances home	Does the household own any of these appliances?	5	Nominal
	Do you think you are threatened by food insecurity?	Did desertification impact household food security?	5	Ordinal
Food Access	Garden Area	How much garden area do you have?	8	Ordinal
	Land titled property	How much area is cultivated by your household	5	Ordinal
	Crops cultivated	What crops are being cultivated by your household?	9	Nominal
	Livelihood diversification	Rank your diverse sources of income	5	Nominal
	Government relief	What kind of relief is provided by the government to farmers?	7	Nominal
Food Utilization	HH educated members	How many members of your family have received education to the following level?	7	Nominal
	Facilities: Clean Drinking Water	Living standard	2	Nominal
	Facilities: Sanitation	Living standard	2	Nominal
Food Stability	Weather disruption: Increase in average temperature	Impact of desertification on people, vegetation, livestock, and food security.	5	Ordinal
	Market disruption	Financial impact: reduction in average income and unemployment	5	Ordinal
	Household cash	Monthly income	6	Ordinal
	Loans	Do you have access to a loan?	3	Nominal
	Quality of soil:	Impact of desertification on people, vegetation, livestock, and food security.	5	Ordinal
	Soil water availability: irrigation canal	Impact of desertification on people, vegetation, livestock, and food security.	5	Ordinal

Table 2. Varimax rotated component loadings, with Kaiser Normalization from a four-dimensional NLPCA of food security. Component loadings where values > 0.40 are shown in bold

Variables	Dimension			
	1	2	3	4
Environmental impacts of desertification: gradual increase in average temperature	**.952**	-.045	.008	.035
Financial impacts of desertification: has it led to unemployment	**.951**	-.052	-.005	.113
Financial impacts of desertification: reduction in average household income	**.941**	.001	.024	.001
No livelihood activities	**.413**	.166	.165	.406
Crop cultivated by household	-.035	**.901**	.083	-.014
Area cultivated by household	.007	**.889**	.178	-.057
Garden area	-.057	**.635**	-.112	.293
Total farming equipment	-.081	**.418**	.356	-.171
Environmental impacts of desertification: decrease in soil productivity	.309	.367	-.199	-.295
Community infrastructure: irrigation canals	.106	.357	-.032	-.298
Access to assets type of house	.053	.050	**.857**	.067
Facilities, floor	.024	-.013	**.847**	.017
Community infrastructure: roads	-.012	-.129	**.556**	-.250
Number of people within the family under the level of education: illiterate	.012	.254	**.484**	-.120
Financial impacts of desertification: reduction in average household income	.209	.038	-.073	**.570**
Relief provided by the government	-.039	.062	-.173	**.554**
Appliances present	-.130	.075	.380	**-.536**
Approximate monthly income	.089	.164	.370	**-.477**
Easy access to loans by zari taraqiati bank	.016	-.143	.208	.341

Table 3. Model summary of NLPCA using Varimax rotation with Kaiser Normalization. Total Cronbach's Alpha is based on the total Eigenvalue

Dimen-sion	Cronbach's Alpha	Variance Accounted for Total (Eigenvalue)	% of variance
1	.714	3.059	14%
2	.663	2.616	12%
3	.675	2.601	12%
4	.543	1.819	8%
Total	.951[b]	10.096	46%

The object scores for each household on each component were used as an input variable to calculate the food security index (Rajesh et al., 2018) using equations 2 and 3

$$\text{NSFSIj} = \sum_{i=0}^{n} F_i\, C_{ji} \tag{2}$$

where NSFSIj represents the Non-Standardized Food Security Index for household j. Fi represents the percentage of variance explained by factor i, where i ranges from 1 to n, and n represents the total number of factors produced by the non-linear component analysis. Cji represents the object score coefficient of household j for factor i. The resultant values became the input for equation 2:

$$\text{SFSIj} = \left(\frac{\text{NSFSI}_j - \text{NSFSI}_{min}}{\text{NSFSI}_{max} - \text{NSFSI}_{min}}\right) \times 100 \tag{3}$$

where $SFSI_j$ represents the Standardized Food Security Index of a household j. $NSFSI_j$ represents the value of the Non-Standardized Food Security Index for household j. $NSFSI_{min}$ and $NSFSI_{max}$ represent the lowest and highest values of NSFSI, respectively, observed among all households. The resultant values of SFSI ranged from 0 to 100, where a value near 0 represents a household with the least Food Security, and 100 represents the households with maximum Food Security.

2.4. Mapping the Food Security Index

In this study, spatial analysis was performed to map the food security index (FSI) clusters using ArcGIS. This involved the application of Global Moran's I and Anselin's Local Moran's I statistics to identify spatial clustering patterns among households (Mazhar et al., 2021). A point shapefile containing respondent locations was utilized to calculate Global Moran's I, employing an inverse distance weighting interpolation. Subsequently, Anselin's Local Moran's I statistic was applied to visualize FSI clusters. The mean FSI score for households in each union council was classified into five distinct categories based on the object score, with higher class numbers indicating improved household food security. Additionally, the study identified four types of spatial clusters: High-High (HH), Low-Low (LL), High-Low (HL), and Low-High (LH). The HH and LL clusters

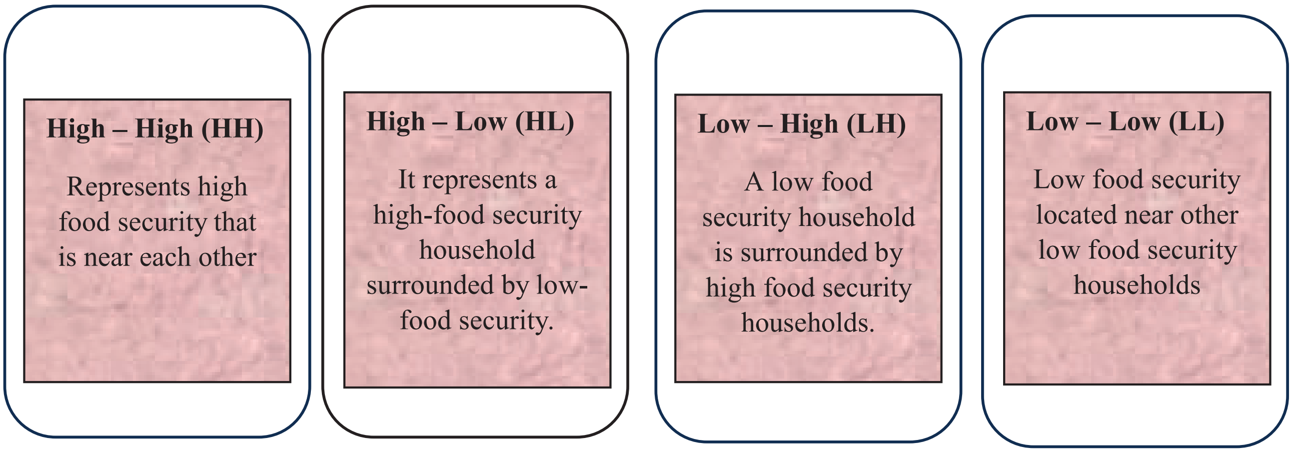

Figure 3. Different classes of food security clusters

denote areas where households with similar high or low food security levels are proximate to each other, respectively (Fig. 3). Conversely, HL and LH clusters represent spatial outliers, where high food security households are surrounded by low food security neighbors, and vice versa.

2.5. Measuring the Impact of Climate Change on Crops

Climate data on rainfall and temperature (annual means) from 1991 to 2021 were acquired from the Pakistan Meteorological Department (PMD) in Lahore to analyze the impact of climate change on crop yields. This study focused on the effects of mean annual rainfall and mean annual temperature on the primary crops of wheat and rice in the study area. The datasets obtained were used for further statistical investigation by applying Multiple Linear Regression (MLR). Previous studies, such as those by Abbas et al. (2022b), Mazhar et al. (2021), and Tariq et al. (2014), have utilized MLR to estimate the impact of temperature and rainfall on agricultural production. In this context, temperature and precipitation were standardized as climatic variables, and their relationship was evaluated to assess the impact of climate change on food production. The analysis used a satisfactory model, as depicted in Figure 4, through Multiple Linear Regression analysis. Furthermore, two major crops (wheat and rice) were taken as proxy indicators to assess the impact of climate change. The relationship between crop production and the area under cultivation was also examined. This analysis used the area under cultivation in thousands of hectares as an independent variable, along with temperature in °C and precipitation in inches. Crop production for wheat and rice was taken as the dependent variable, while the area under crop cultivation mean annual temperature, and mean annual rainfall were considered independent variables (Abbas et al., 2022b).

MLR was employed to describe the linear relationship between the dependent variable and the independent variables in equation 4.

$$Y = a + bx + e \tag{4}$$

where X is the independent variable, Y is the dependent variable, and e is the value of errors. Errors are the vertical distance between data points and lines.

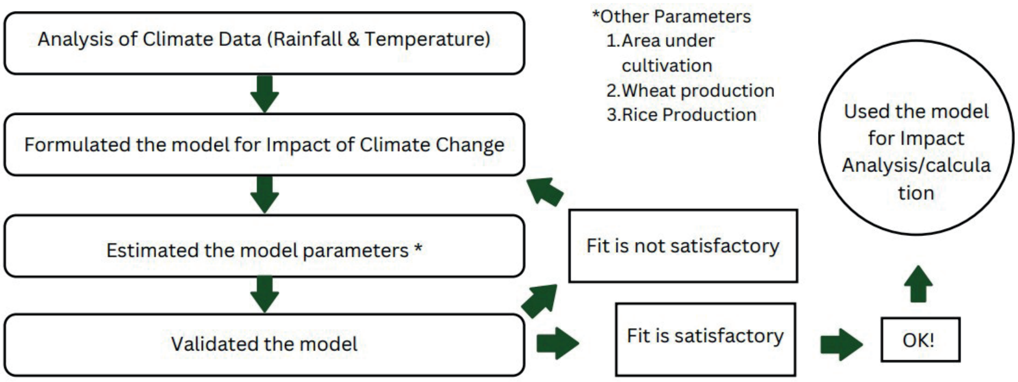

Figure 4. MLR model for calculating the impact of climate change on food production

2.6. Wheat and Rice

A thorough analysis of the underlying assumptions was conducted to enhance the accuracy of the regression models applied to wheat data. The results of the Durbin-Watson test indicated values of 1.718, 0.681, and 1.779 for the regions of Bahawalpur, Rahim Yar Khan, and Rajanpur, respectively. These values, remarkably those close to 2, suggest a lack of autocorrelation in the residuals, affirming these values' independence. Additionally, a linear relationship was corroborated through the probability-probability (PP) plot, while the scatterplot analysis confirmed the homogeneity of variance across the datasets. Moreover, the analysis ensured the absence of multicollinearity within the data, as evidenced by the coefficient table, which revealed variance inflation factors (VIF) values consistently below the threshold of 10 and tolerance values exceeding 0.2. Specifically, the tolerance recorded was 0.973, 0.760, and 0.773 for Bahawalpur, 0.992, 0.991, 0.999 for Rahim Yar Khan, and 0.839, 0.338, and 0.374 for Rajanpur. Correspondingly, the VIF values were found to be 1.028, 1.316, and 1.293 for Bahawalpur; 1.008, 1.010, and 1.001 for Rahim Yar Khan; and 1.192, 2.962, and 2.677 for Rajanpur.

The assumptions of regression models for rice accuracy were evaluated. Results showed that the Durbin Watson test values for Bahawalpur, Rahim Yar Khan, and Rajanpur were 0.949, 1.772, and 1.570, respectively. Hence, these values were close to 2, showing the residual values' independence. Besides this, a linear relationship was demonstrated by the p-plot; on the other hand, the scatterplot represented homogeneity of variance. Furthermore, the absence of multicollinearity in the data was assured by the coefficient table with a variance inflation factor (VIF) value below 10 and a tolerance value above 0.2. Moreover, the tolerance values were 0.909, 0.853, and 0.845 for Bahawalpur, 0.964, 0.953, 0.929 for Rahim Yar Khan, and 0.759, 0.886, and 0.808 for Rajanpur. Similarly, VIF values were 1.100, 1.172, and 1.184 for Bahawalpur, 1.037, 1.050, 1.0773 for Rahim Yar Khan, and 1.318, 1.128, and 1.237 for Rajanpur.

3. Results

3.1. Food Security Index

Figure 5 illustrates the spatial distribution of household Food Security Index (FSI) scores. The analysis indicates that most high food security clusters are concentrated in the northwestern region of Bahawalpur district. In contrast, Rajanpur district predominantly features high-low food security clusters, primarily located along its eastern boundary. Rahim Yar Khan district also exhibits high-low (HL) and low-low (LL) food security clusters.

Figure 6 depicts the proportion of food security scores for each district, with purple shadeon the map indicating higher

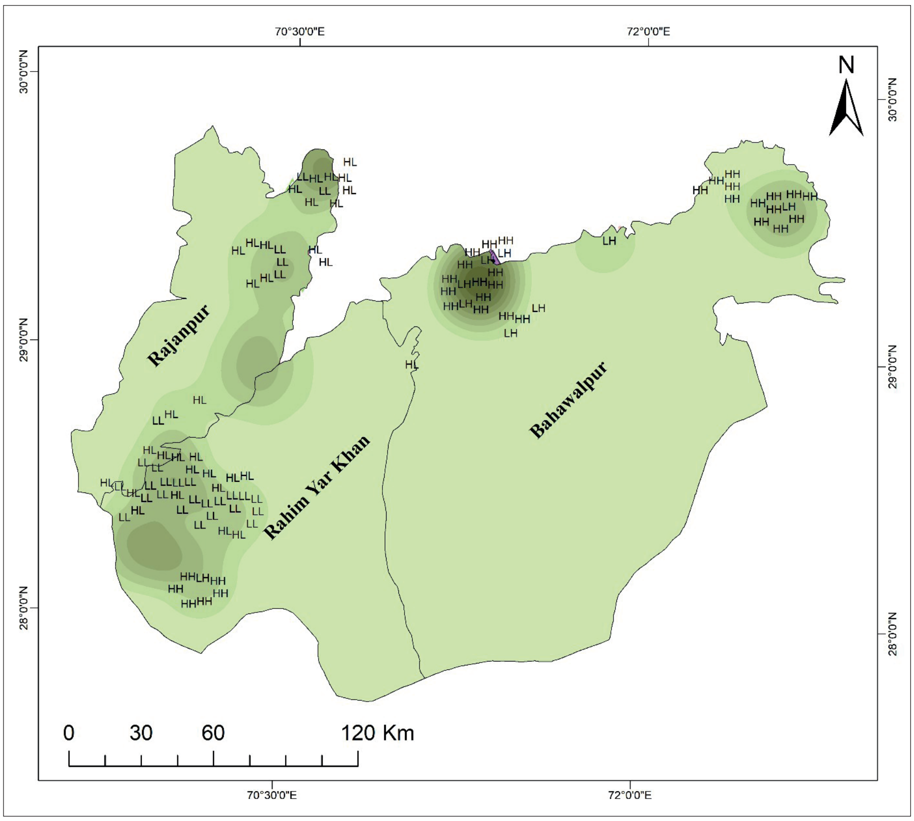

Figure 5. Food security clusters were identified using the Anselin Local Moran's I, showing the zoomed view of the study area

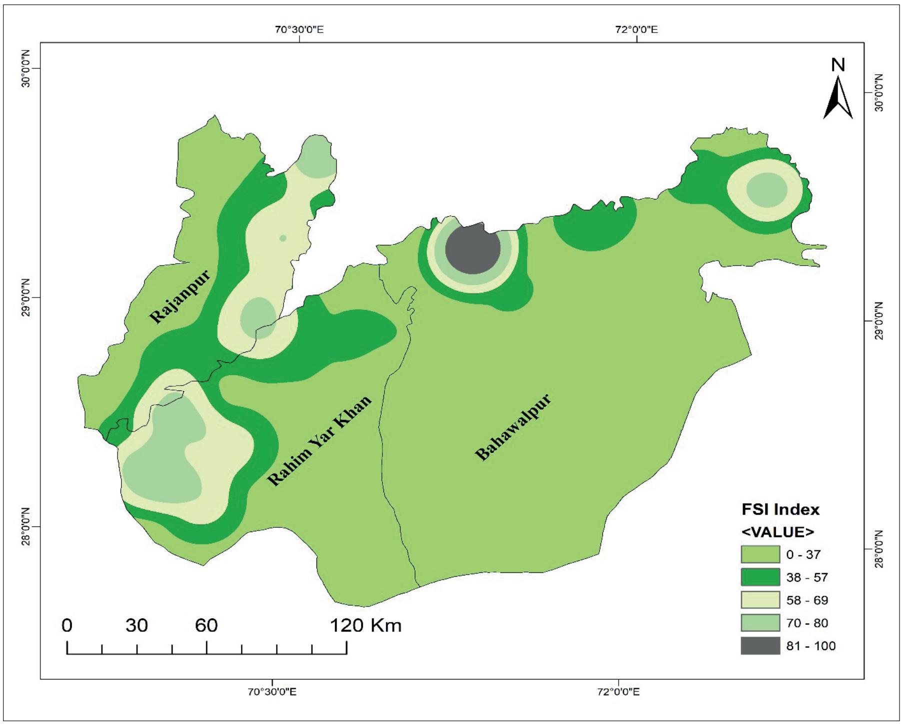

Figure 6. Proportion of food security index

food security, in same high food security cluster as was indicated by north western cluster high food security cluster indicated in Figure 5. The results highlight a significant level of food insecurity in Rajanpur. In contrast, Bahawalpur and Rahim Yar Khan exhibit relatively higher food security, as evidenced by the relevant shades showing higher FSI in these districts.

3.2. Climate Impacts on Wheat and Rice Crops Production

3.2.1. Wheat and Rice Production in Bahawalpur

The results showed that temperature, area under wheat cultivation, and precipitation significantly correlate with wheat production in Bahawalpur, as evidenced by p-values and F-test statistics. The p-value for these correlations is 0.000000, well below the 0.05 threshold for significance. Notably, as the dependent variable, wheat production exhibits a strong relationship with the area under wheat cultivation, with a significant value of 0.00000 and a coefficient of 2.577 (Table 4). The positive coefficient suggests increased area under cultivation is associated with increased wheat production. Precisely, a one-unit increase in the area cultivated with wheat corresponds to an average increase of 2.577 units in wheat production. The regression equation (5) for wheat production is expressed as follows:

$$Y=-1336.326+2.42X1+12.268X2+2.577X3 \qquad (5)$$

where: Y represents wheat production, X_1 is rainfall, X_2 is temperature, and X_3 is the area under wheat cultivation. In a parallel analysis, the investigation of rice production in Bahawalpur also meets the regression analysis assumptions. The p-p plot shows a normal distribution of the residuals. The scatter plot reveals homoscedasticity. However, the Durbin-Watson test yielded a value of 0.949, which fell below the acceptable range of 1.5 to 2.5, indicating potential autocorrelation in the residuals. Significant correlations were found for rice production with temperature, area under wheat cultivation, and precipitation, supported by appropriate p-values and F-test results. The dependent variable, rice production, shows a significant relationship between the area under rice cultivation and temperature, with p-values of 0.00000 and 0.001, respectively. The coefficient for the area under rice cultivation is 0.722, indicating that for every one-unit increase in the area under rice cultivation, rice production increases by an average of 0.722 units. Additionally, the coefficient for temperature is 1.132, suggesting that a one-degree rise in temperature leads to a corresponding increase in rice production. The regression for rice production is formulated in equation 6.

$$Y=-31.145+(-0.029)X_1+1.133X_2+0.722X_3 \qquad (6)$$

where Y represents rice production, X_1 represents rainfall, X_2 represents temperature, and X_3 represents the area under wheat cultivation.

3.2.2. Wheat and Rice Production in Rahim Yar Khan

The analysis revealed that temperature, area under wheat cultivation, and precipitation were significantly correlated with wheat production in Rahim Yar Khan with acceptable values of p-value and F-test. The p-value for these correlations is 0.000000, less than the 0.05 significance level. Furthermore, wheat production (dependent variable) demonstrated significant relationships with the area under wheat cultivation and temperature, with essential values of 0.016 and 0.0002, respectively (Table 4). The positive coefficients indicate that increased area under cultivation is associated with increased wheat production. Specifically, a one-unit increase in the area cultivated with wheat results in an average increase of 1.438 units in wheat production. Similarly, wheat production increases by an average of 33.675 units for every one-unit temperature increase. The regression equation (7) for wheat production is expressed as follows:

$$Y=-1239.88+6.138X_1+33.675X_2+1.438X_3 \quad (7)$$

where: Y represents wheat production, X_1 is rainfall, X_2 is temperature, and X_3 is the area under wheat cultivation. The analysis demonstrated that temperature, area under rice cultivation, and precipitation significantly correlated with rice production in Rahim Yar Khan, as indicated by p-values and F-test results that meet acceptable criteria, including a p-value of 0.000000, below the 0.05 significance threshold. In the regression analysis, rice production (the dependent variable) exhibited a significant relationship with the area under rice cultivation and temperature, with a significance value of 0.00000. Specifically, for each one-unit increase in the area under rice cultivation, rice production increases by an average of 0.562 units. Similarly, a one-unit increase in temperature corresponds to an average increase in rice production of 6.088 units. The regression equation (8) for rice production is expressed as follows:

$$Y=-165.181+0.341X_1+6.088X_2+0.562X_3 \quad (8)$$

where Y represents rice production, X_1 represents rainfall, X_2 represents temperature, and X3 represents the area under wheat cultivation.

3.2.3. Wheat and Rice Production in Rajanpur

The analysis indicated that temperature, area under wheat cultivation, and precipitation were significantly correlated with wheat production in Rajanpur. This was supported by acceptable p-values and F-test results, including a p-value of 0.000000, which is below the 0.05 significance level. Wheat production, the dependent variable, demonstrated significant relationships with the area under wheat cultivation and temperature, with essential values of 0.0000 and 0.09, respectively (see Table 3, 4). Specifically, wheat production increases by an average of 1.43 units for each one-unit increase in the area under cultivation. In contrast, the coefficient for temperature showed a negative correlation of -6.289, indicating that for every one-unit increase in temperature, wheat production decreases by 6.289 units.

The regression equation (9) for wheat production is expressed as follows:

$$Y=7.43+0.05X_1+(6.28)X_2+1.43X_3 \quad (9)$$

where: Y represents wheat production, X_1 is rainfall, X_2 is temperature, and X_3 is the area under wheat cultivation. Regarding rice production, the analysis in Rajanpur revealed significant correlations with temperature, area under rice cultivation, and precipitation, with an F-test p-value of 0.000000. The regression analysis indicated that rice production (the dependent variable) has a significant relationship with the area under rice cultivation and temperature, with a substantial value of 0.00000. Specifically, for every one-unit increase in the area under rice cultivation, rice production increases by an average of 0.058 units, and for each one-unit increase in temperature, rice production increases by an average of 1.550 units. The regression equation (10) for rice production is formulated as follows:

$$Y=-40.97+0.580X_1+1.550X_2+0.058X_3 \quad (10)$$

where Y represents rice production, X_1 represents rainfall, X_2 represents temperature, and X3 represents the area under wheat cultivation.

Table 4. Regression model for wheat and rice crop production

Variables	Crop Type	t value	Standardized β
Bahawalpur			
Rain	Wheat	0.513	2.424
	Rice	-0.201	-0.029
Temperature	Wheat	1.075	12.268
	Rice	3.623	1.133
Area	Wheat	10.451	2.577
	Rice	19.036	0.722
Rahim Yar Khan			
Rain	Wheat	0.671	6.138
	Rice	0.339	0.341
Temperature	Wheat	4.286	33.675
	Rice	7.023	6.088
Area	Wheat	2.565	1.438
	Rice	9.701	0.562
Rajanpur			
Rain	Wheat	0.024	0.05
	Rice	0.273	0.58
Temperature	Wheat	-1.718	-6.29
	Rice	7.191	1.55
Area	Wheat	11.132	1.435
	Rice	12.861	0.058

Dependent variable: wheat production, rice production.

4. Discussion

Traditional farming practices are associated with several vulnerabilities. They are primarily vulnerable to the state of the monsoon; the failure of the monsoon usually means there is a loss of crops. The second factor that affects them is pest attacks. The region gets warm and humid with the onset of the monsoon, making it too vulnerable to pest attacks such as locust swarms. Furthermore, the soil of the study area is being degraded due to water erosion resulting from high rainfall that is expected in monsoon seasons. The land holding is also becoming gradually less fertile due to excessive harvests. But the greatest present vulnerability is the shortage of water in the irrigation system, as both water channels and groundwater pumps have already dried up. Depleting groundwater levels increasingly facilitate salinity encroachment (Tabassum et al., 2025). These vulnerabilities are discussed in the text with the community members to identify the areas where the community might require support. The extremely limited amount of food production highlights the urgency of adaptive agriculture (Mariara & Kabara, 2018). The conventional methods need to be updated to sustain climatic shocks. It is mainly considered that these adaptive methods improve the overall understanding of farmers regarding present technology, educate them to reduce the cost of conventional production, and increase food production (Fanzo et al., 2024).

Disoriented rainfall patterns and non-stop monsoon rains, intensity, and temperature fluctuations were found to be affecting seasonal agricultural food productivity schedules very badly, not only for individuals but for larger populations. Numerous interconnected risks and uncertainties are associated with climate change and food security for both society and ecosystems. The four pillars of the FAO, derived from domestic production, illustrate the complexity of global food security (FAO, 2020; WFP, 2022). These elements must be present to reach a state of nutritional well-being where all physiological needs are satisfied: (i) there needs to be a sufficient and appropriate supply of food; (ii) people need to have access to sufficient resources (entitlements) to buy the right foods for a nutritious diet; (iii) food needs to be used through a sufficient diet, clean water, sanitation, and health care; and (iv) stability. Achieving all these aspects is necessary for food security. To precisely assess the status of global food security from such a broad concept is challenging. All of these pillars are under threat due to environmental and climatic catastrophes, i.e., changes in temperature and precipitation patterns (Kuang & Liao, 2020) . Hence, according to the results, more of the least developed aspects have been found in Rajanpur (Iftikhar & Mahmood, 2017) than in the other two districts.

On the other hand, Bahawalpur, Rahimyar Khan, and other districts of south Punjab need to be developed with infrastructure to support people. (Mahmood, 2023) In addition, results revealed that the area under cultivation (an independent variable) has a significant positive relationship with wheat and rice production, which are crucial food crops in the agrarian zones of south Punjab. So, the farmers grow these crops, especially wheat, in the maximum areas of their land for household and commercial use. Additionally, a field survey revealed that significant fertile land remains non-cultivated in a few areas of these districts, which still needs to be completed due to the low availability of technological and water resources.

The results empirically also showed that climate may affect the study area's food system and crop production due to abrupt changes in precipitation patterns and temperatures. Frequent flooding (due to variation in rainfall patterns) and the change in length of warmer and cooler seasons (i.e., temperatures) lead to the loss of significant productivity of these crops. According to Gregory et al. (2005), climate change's impact on food security differs for the region's different sects and food resources. Only a few food resources, like crops or livestock, are being used for household and commercial purposes in the study area. Furthermore, results delineate that although the production seems to be affected by temperature in the study area, the highest food insecurity exists in the Rajanpur district of the study area, while the other two districts, Bahawalpur and Rahim Yar Khan, have relatively better food security. Because wheat production in Rajanpur has a significant negative relationship with the temperature, and this increasing temperature pattern has increased the food insecurity of Rajanpur, and these results are also supported by other similar works (Iftikhar & Mahmood, 2017; Pervaiz et al., 2017).

Additionally, recent 2022 floods and temperature spikes have affected the district's crop production and livelihood patterns (Sajjad et al., 2022). In addition, multiple biophysical and socio-economic factors are affecting the region's food security pillars. These factors include decreased literacy rate, less technology, inefficient irrigation methods, hiking food prices, failure in property rights, and poverty, which are threat multipliers regarding climate change. Additionally, multiple studies were found to calculate the food security index in other regions globally by scheming water scarcity and heat stress (Dumortier et al., 2021; Rezaei et al., 2023). Furthermore, using different models, Kang et al. (2009) analyzed the food security perspective by evaluating crop productivity interlinked with water scarcity. These studies indeed suggest favorable effects in specific regions and conditions, but this is a first-ever empirical analysis to measure the impact of climate change on food security by measuring crop production through household field surveys, CATPCA, and application of geospatial analysis in the least developed areas of south Punjab. Hence, the impacts of climate change are threatening, and most scientists agree that it would significantly reduce crop productivity and increase food insecurity (Chen et al., 2020; Wang et al., 2020).

Rising temperatures and alterations in rainfall patterns are anticipated to reduce agricultural yields soon across South Punjab (Sajjad et al. 2019). An in-depth analysis of field research data shows that an increase in seasonal temperatures has already affected crop yields, alongside increased intra-seasonal rainfall variability. Moreover, changes in sowing and harvesting periods have further decreased yields compared to historical statistics. There seem to be noticeable disparities regarding the relative impact of climatic variables on the production of different crops. Our empirical evidence shows contrasting effects of temperature on yields of different crops. It is perhaps since the southwestern part of the region shares land space with larger parts of Baluchistan, which has similar temperature and crop ecologies. A good number of Riparian farmers also grow vegetables. A slight decrease in paddy productivity has been observed, but it requires more extensive study to forecast any trend. No clear-cut effect of temperature on cotton yields has been found. Lower cotton yields in intensity scale may be due to other factors, for instance, seed quality and changes in agronomic practices. Cotton is cultivated in centrally located tehsils, such as Chishtian, Haroonabad, and Hasilpur. Anticipated longer hot and dry weather might have a negative impact on cotton yields, alongside growing water scarcity. Onions strongly respond negatively to higher temperatures, resulting in low yields.

5. Conclusion and recommendations

The study area in South Punjab is susceptible to the impacts of climate change, and a consensus has been reached regarding the causal relationship of climate change with agroecological conditions, food security, and customs. Furthermore, the results of the study have revealed that food security is intricately tied to climate risks in the study area. Rural residents are most likely to experience climate-induced food security risks. The ability to implement their regular agricultural practices, such as altering the practice of traditional crop cultivation, being forced to find alternative livelihood options, and borrowing money, as well as cutting down on daily life expenses and sending family members, especially children, to cities for family support, is incredibly difficult.

The study investigated the impact of climate change on food security in the least developed regions of south Punjab. The analysis focused on major crops, rice, and wheat, using a mixed-methods approach incorporating quantitative, qualitative, and geospatial analysis of different variables such as temperature, precipitation, and area under production. The Food Security Index (FSI) identified significant spatial disparities across the various districts of the region. Bahawalpur showed higher food security, particularly in its southeast region, while Rajanpur faces severe food insecurity in its eastern parts. Furthermore, both high-low (HL) and low-low (LL) security clusters were found in Rahim Yar Khan. Moreover, in all districts of the study area, land utilization to ensure food availability is crucial.

Quantitative analysis demonstrated a significant positive relationship between cultivation and crop production. On the contrary, climate variables reveal complex relationships with crop production. For instance, in Rajanpur, increasing temperatures negatively correlate with crop production by exacerbating food insecurity. Meanwhile, temperature and precipitation positively impact Bahawalpur and Rahim Yar Khan, increasing crop yield.

Furthermore, the study underscores that climatic changes like altered precipitation and temperature patterns are increasing the vulnerability of south Punjab's agrarian society by reducing crop productivity through frequent flooding and shifts in seasonal durations. In addition, socio-economic factors with limited technological access, inefficient irrigation methods, poverty, and low literacy rates compound the region's food security challenge. Hence, these results emphasized the urgent need for adaptive measures to build resilient agricultural infrastructure, technological support, educational programs, crop diversification, and subsidies for small-scale farmers to mitigate the adverse impacts of climate change.

In conclusion, the study's policy recommendations are of practical significance. Empirical evidence from the survey requires comprehensive climate adaptation strategies that incorporate all the community-based initiatives, the participation of stakeholders, and research to safeguard food production and ensure sustainable livelihoods in vulnerable agrarian communities. These recommendations aim to promote and enhance food security in rural households, particularly in middle- and low-income countries. Overall, this study provides a holistic view of the complex interactions between food security and climate change, paving the way for informed and effective interventions. It is centered on achieving SDG 2: ending hunger and ensuring food security and calls for the need to design policies that match specific socio-geographical and agro-ecological conditions of rural communities

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