



Assessing the Effects of Temperature and Rainfall Variability on Sugarcane Productivity: Farm-Level Evidence from Sindh Province, Pakistan

Shahzaib Agha¹, Naimatullah Shaikh², Syed Muhammad Taha Hussaini³, Syed Ali Akbar⁴, & Zarak Iqbal⁵

¹Karachi University Business School (KUBS) University of Karachi, Sindh, Pakistan

²Social Service Sector, Sindh Rural Support Organization, Pakistan

³Department of Agricultural and Resource Economics, University of Agriculture Faisalabad, Punjab, Pakistan

⁴University of North America, USA

⁵Management Science, SZABIST Larkana, Pakistan

*Corresponding author: Shahzaibagha66@gmail.com

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ABSTRACT

Climate variability is a major threat to agricultural productivity in Pakistan, especially for water-sensitive crops like sugarcane. The research determined the impacts of temperature variations and rainfall variability on sugarcane productivity in large sugarcane-growing districts in Sindh, Pakistan, based on a survey conducted by farmers. The survey was carried out in 2025 as a cross-sectional study, using a multistage sampling technique, with 400 sugarcane farmers from Badin, Thatta, Mirpurkhas, and Sanghar. The perceptions of farmers regarding climatic changes over the last 20 years were examined and confirmed using meteorological data. Regression and correlation analyses were used to test the association between climatic variables and productivity indicators, such as cane yield (tons/ha) and sugar recovery percentage. Findings showed that eighty-nine percent of farmers felt that there was a huge increase in temperature, and eighty-six-point five percent of farmers felt that rain had been more sporadic. The sugarcane production in 2021-2025 fell below 58.4 tons/ha (2005-2010) to 48.6 tons/ha; sugar recovery dropped to 9.3 percent (10.8 percent). Mean temperature had a strong negative relationship with yield ($r = -0.623$, $p < 0.001$) and sugar recovery ($r = -0.591$, $p < 0.001$). The grand growth stage was found to be the most sensitive period for farmers regarding climate. Popular methods of adaptation entailed changing the planting dates and the additional irrigation, but these methods were not adopted due to the high cost and lack of technical assistance.

Keywords: Sugarcane productivity, climate variability, temperature rise, rainfall variability, farmer perceptions, adaptation strategies, Sindh Pakistan

INTRODUCTION

Climate variability has become a pressing problem affecting agricultural systems worldwide, and developing economies bear a disproportionate share of these effects (Intergovernmental Panel on Climate Change [IPCC], 2021). Pakistan is among the most climate-vulnerable countries, and over the last several decades, the country has witnessed considerable changes in the level of temperature and precipitation directly impacting food security and agricultural livelihoods (Alashan et al., 2020). In this setting, the Sindh province is a very strategic agricultural area that has sugarcane (*Saccharum officinarum* L.) as a key cash crop, which has a significant contribution to the provincial and national economies (Chaudhry, 2017).

Sugarcane production in Sindh is particularly vulnerable to climatic changes, as it has high water requirements and is sensitive to temperature changes during crucial production phases (Das et al., 2022). The physiological functions of the crop, such as photosynthesis, tillering, and development of the sucrose content, are not responsive to extreme temperatures or water availability (Gadedjisso-Tossou et al., 2021). It has been indicated that data outside the optimal temperature range (26-32°C) and abnormal rainfall distribution may significantly decrease cane yield and sugar recovery percentages (Farooq & Gheewala, 2020; Huang et al., 2022). Since about 1.3 million

hectares in Pakistan are under sugarcane, with Sindh contributing to the country almost 30 percent of the output (Pakistan Council of Research in Water Resources, 2018), it can be economically crucial to comprehend the relationship between climate and productivity.

Recent weather statistics reveal worrying trends across Sindh, as average annual temperatures have increased by 0.6 degrees Celsius over the last 30 years and rainfall has become increasingly inter-annually variable (Pakistan Meteorological Department, 2022). Such climatic changes are associated with documented decreases in sugarcane yields in some districts, but there is little empirical data to demonstrate their linkage to farms. Although the effects of climate on sugarcane cultivation in Brazil, India, and Australia have been studied globally (Pörtner et al., 2022; Qureshi et al., 2023), research on climate-related impacts on the agroecological context and farming systems is quite limited in the Sindh region. This research gap is especially troublesome, as context-dependent climate-crop relationships are influenced by local soil types, irrigation infrastructure, cultivar decisions, and farmers' adaptive capacities (Frimpong et al., 2022). Farmer perceptions and experiences can offer invaluable ground-truth information that complements meteorological records, showing how climate variability can be translated into actual production outcomes and used to inform the response strategy (Gennari et al., 2019; Haider & Ullah, 2020).

The current research evaluated the sugarcane farmers' views on long-term changes in temperature and rainfall variability in key sugarcane production regions of Sindh. It is also aimed at determining the quantification of the relationship between the observed climatic variations, especially changes in temperature, the patterns of precipitation and the major indicators of sugarcane productivity in terms of cane yield per hectare and sugar recovery percentage. Also, the research aimed at determining the most sensitive growth phases of sugarcane at which the climatic variability has the most significant impact on the crop functioning and ultimate production results. Moreover, the study also determined the current adaptive measures taken by farmers on the local level to reduce the losses in yield and quality because of the climatic conditions.

MATERIALS AND METHODS

The research design used in this study was cross-sectional survey research because the research aimed at determining the impacts of variability of temperatures and rainfall on the sugarcane productivity in Sindh, Pakistan. Multi-stage sampling method was employed to pick the respondents representing the key sugarcane producing areas of the Sindh province, mainly Badin, Thatta, Mirpurkhas, and Sanghar, which are estimated to cover about 65 percent of the sugarcane growing land in the province. These four districts were sampled purposely in the first stage depending on the intensity of sugarcane farming and agro-climatic diversity. The second stage involved random selection of two tehsils (sub-districts) from each of the districts and then two union councils in each tehsil. Lastly, to derive representative samples of the 400 sugarcane farmers, 25 farmers were selected from each union council who had over ten years of experience in cultivating sugarcane. The questionnaire was drafted in a structured form and pre-tested using 30 farmers to make them clear, relevant, and appropriate to the culture and understanding of the people as well as relevant to study's objectives. The questionnaire had four major parts, which are the socio-economic factors of the farmers, perception of the variability in temperatures and rainfall in the last twenty years, data on sugarcane productivity (yield per hectare, sugar recovery percentage) in several growing seasons, and some adaptive measures taken by farmers to handle climatic stresses. Face-to-face interviews were conducted in Sindhi and Urdu languages with the help of trained enumerators in the months of October-December 2025, which is around the post-harvest period when farmers are more accessible and can give correct production information.

Both descriptive and inferential statistical methods were used in the analysis of data by use of SPSS version 26 and STATA 17 software packages. To summarize the socio-economic characteristics of farmers, their perceptions towards climate, and their productivity, descriptive statistics like frequencies, percentages, means and standard deviations were calculated. In order to measure interrelation between climatic variables and sugarcane productivity, the multiple regression analysis was applied in which sugarcane yield (tons per hectare), percentage recovery of sugar were dependent variables whereas mean growing season temperature, total rainfall, index of rainfall distribution, and characteristics of farmers were used as independent variables. The secondary data of the research area included meteorological data in the years 2005-2025, were collected by the Pakistan Meteorological Department and local weather stations to confirm the views of farmers. Further, the productivity data was matched with annual reports from Agriculture Department and the data from Economic Survey of Pakistan. The strengths and direction of the relationship between the climatic parameters and productivity indicators were determined by calculating Pearson correlation coefficients. Also, a critical growth stage was identified with the principal component analysis (PCA) to determine the most critical stages to climate variability, basing it on the effects reported by farmers.

RESULTS

Socio-Economic Characteristics

The socio-economic background of respondent farmers in Table 1 demonstrates that there are significant demographic and structural features that affect climate vulnerability and adaptive capacity in the sugarcane industry

in Sindh.

The average age of 44.3 years suggests a middle-aged agricultural population, which is also shown by Chohan. (2019) in the sugarcane belt in Punjab, where the median farmer age was 42.7 years. Such an age structure implies a sufficient level of crop management experience, but it also creates some doubts because of succession to agriculture and technological adoption: younger farmers tend to be more accepting of climate-smart practices (Elahi et al., 2020; Duy et al., 2022). The respondents' educational level indicates that 63.5% have only primary-level education or are illiterate, which is similar to Farooq et al. (2020), who found that 67% of Sindh farmers have below-secondary education. Such a low level of education may impair farmers' capacity to utilize climate information and scientific agricultural consultations (Duan et al., 2022). The comparatively high mean farming experience of 20.6 years, however, offsets this somewhat with cumulative indigenous knowledge of local climate patterns and crop responses. The farm size distribution indicates that 44.5% of respondents currently run small farms of less than 5 hectares, which reflects land fragmentation within the Sindhian agrarian organization (Adler et al., 2017). This concentration of smallholders has an enormous impact on climate resilience because smaller farms are generally underfunded to invest in climate adaptation measures, such as precision irrigation systems or heat-tolerant varieties (Hussain et al., 2018). The conclusion that 66.8% of them are owner-operators implies that their level of investment incentives may be comparatively higher than that of tenant farmers, which might focus more on short-term profits over sustainable management procedures (Israr et al., 2016). Dependent on canal water as their main source of irrigation, 61.5% of total irrigation is exposed to both water shortages due to climate change and institutional water allocation policies. A study by Khan et al. (2018) reported the growing unreliability of canal supplies in Sindh during critical crop growth stages, thereby rendering the accessibility of supplementary groundwater through tubewells increasingly significant for sustaining productivity in the face of changing rainfall conditions.

Table 1: Socio-Economic Characteristics of Respondent Farmers (N=400)

Characteristic	Category	Frequency	Percentage (%)
Age (years)	25-35	68	17.0
	36-45	142	35.5
	46-55	126	31.5
	Above 55	64	16.0
	Mean ± SD	44.3 ± 10.2	
Education Level	Illiterate	98	24.5
	Primary (1-5 years)	156	39.0
	Middle (6-8 years)	89	22.3
	Matriculation & above	57	14.2
Farm Size (hectares)	Small (<5 ha)	178	44.5
	Medium (5-10 ha)	152	38.0
	Large (>10 ha)	70	17.5
	Mean ± SD	6.8 ± 4.3	
Farming Experience (years)	10-15	89	22.3
	16-20	134	33.5
	21-25	108	27.0
	Above 25	69	17.2
	Mean ± SD	20.6 ± 6.7	
Land Tenure	Owner	267	66.8
	Tenant	98	24.5
	Owner-cum-tenant	35	8.7
Irrigation Source	Canal	246	61.5
	Tubewell	98	24.5
	Mixed (Canal+Tubewell)	56	14.0

Farmers' Perceptions of Temperature and Rainfall Variability

Table 2 indicates that the vast majority of farmers (89%) have experienced severe temperature rises over the last 20 years, which is consistent with the meteorological data from the Pakistan Meteorological Department, reported a 0.6-0.8 C rise in the mean annual temperature of the Sindh districts in 2000-2020. Such a high level of agreement between the impressions of the farmers and the scientific evidence confirms similar results of Ishaq et al. (2018) in the Punjab province of Pakistan, where 87.3% of the farmers claimed to have observed warming trends. The perception of a rise in the frequency of heat waves is almost unanimous (93.0%) and aligns with global trends showing that over the past decades, South Asia has experienced more and more severe extreme temperature events (Muelbert et al., 2019). This heat stress at key sugarcane developmental stages, would have serious effects on photosynthetic performance and decreases sucrose levels as shown by Linnenluecke et al. (2018) under controlled experimental conditions. A more intricate trend has emerged in perceptions of rainfall variability, with 86.5 percent of respondents describing precipitation as more erratic and unpredictable. Interestingly, 66.8 percent also found greater rainfall intensity in fewer events, which is consistent with climate change predictions for monsoon-dependent areas (Khahro et al., 2023). The observed lateness of the monsoon (78.0%) and shortening of the season

(72.3%) lead to a narrower effective growing season, requiring farmers to change their traditional cultivation schedule. These results are similar to those of Haq et al. (2016) in Sindh cotton-producing regions, in which 74 percent of the farmers reported comparable changes in monsoon behaviour. The combined decrease in total rainfall (49.5%), and increase in intensity is a pointer to a distortion of the potential precipitation patterns to a more focused event spaced further apart by a dry period which is especially harmful in the sugarcane scenario where the moisture availability should be in the whole period of the 12-14 months of the growth cycle (Khan et al., 2020). Recognition of the grand growth stage (66.81) as the most susceptible to climatic change is agronomically crucial because ultimate cane yield (based on stalk length and biomass growth) is determined at the stage (around 120-270 days after planting). This is consistent with physiological findings of Panda & Sahu (2019) that established water stress and extreme temperatures during spurring growth stages causes irreversible yield losses in sugarcane. The percentage (83.5) of those who shifted planting dates is an adaptive behaviour that has been observed across the South Asian agricultural industry, as farmers increasingly use weather forecasting and historical data to maximize the time available to grow plants (Mullick et al., 2019). Of special concern is the 74.5% reporting that there was a greater incidence of pests and diseases, which is probably an indirect effect of climate. The high temperatures and changing humidity regimes provide favourable conditions for pests and diseases such as shoot borer (*Chilo infuscatellus*) and red rot (*Colletotrichum falcatum*) in Indian sugarcane regimes (Soothar, 2017). The fact that 61.3% of farmers perceived climate impacts as very severe highlights the need to formulate region-specific climate adaptation initiatives, especially given that these perceptions have translated into real economic losses and increased susceptibility among farming families that rely on sugarcane as a main source of cash.

Table 2: Farmers' Perceptions of Temperature and Rainfall Variability (N=400)

Climate Parameter	Response Category	Frequency	Percentage (%)
Temperature Trend (Last 20 years)	Increased significantly	356	89.0
	Increased slightly	38	9.5
	No change	6	1.5
	Decreased	0	0.0
Frequency of Heat Waves	Increased	372	93.0
	Remained same	24	6.0
	Decreased	4	1.0
Rainfall Pattern Changes	More erratic/unpredictable	346	86.5
	Decreased total rainfall	198	49.5
	Increased intensity but fewer events	267	66.8
	Delayed onset of monsoon	312	78.0
	Early cessation of rainfall	289	72.3
Perceived Impact on Crop Cycle	Shifted planting dates	334	83.5
	Extended maturity period	156	39.0
	Reduced growing season	178	44.5
	Increased pest/disease incidence	298	74.5
Most Affected Growth Stage	Germination/tillering	189	47.3
	Grand growth phase	267	66.8
	Maturation/ripening	145	36.3
Severity of Climate Impact	Very severe	245	61.3
	Moderately severe	134	33.5
	Slightly severe	21	5.2
	Not severe	0	0.0

Impact of Temperature and Rainfall Variability on Sugarcane Productivity Indicators

The temporal productivity trend of sugarcane (table 3) indicates that there is a steady and worrying trend of decline in the cane yield by 16.8 percent and the sugar recovery percentage by 13.9 percent between the period of study (2005-2010) and the current period (2021-2025). This decline in Sindh productivity reflects the conditions reported by Saini et al. (2020), which showed projected yield losses of 12-18% due to climate change under the same conditions. The interdependence between yield and sugar content has led to the attitude to think that climate variability is not only influencing the production of biomass, but the physiological quality of the harvested cane, which has been asserted by Pohl et al. (2023) in the sugarcane systems of Swaziland where higher temperatures lowered the concentration of sucrose by 0.4-0.6 percent per degree Celsius increment. The growing SD between successive time intervals (between 6.2 tons/ha and 9.4 tons/ha in terms of yield) implies increasing variability in inter-farm productivity, which could be attributed to differences in adaptive capacity, resource access, and microclimate features in the area of study. This climate vulnerability heterogeneity is consistent with the findings of Zhao & Li (2015), who state that climate-related losses disproportionately affect smallholder farmers with scarce irrigation infrastructure compared to their well-equipped counterparts. The empirical evidence that the physiological relationship between heat stress and reduced photosynthetic efficiency in sugarcane exists is the strong negative correlation between the mean temperature and cane yield ($r = -0.623, p < 0.001$). The given correlation coefficient can be compared to those in the study by Zhao and Li (2015), the Chinese sugarcane production systems ($r = -0.67$).

On the same note, the positive relationship between the index of rainfall distribution and yield ($r = +0.512$, $p < 0.001$) highlights the critical role of well-distributed precipitation during the growing period, rather than the amount of rainfall. This observation is consistent with the claim by Talpur et al. (2022) that sugarcane requires a regular supply of moisture during its rapid growth period, and any temporary water deficit leads to an irreversible decrease in yield. Of special interest is the cataclysmic effect of the combined stress of heat and water, which was said to have resulted in an average yield loss of 35.8 by the farmers. The compounding nature of parallel climate stresses has been reported in physiological experiments by Memon et al. (2021) and Waaswa et al. (2022), who found that simultaneous exposure to drought and heat induces cumulative effects on photosystem II efficiency and hastens the process of leaf senescence in various sugarcane varieties. The yield loss due to drought stress of 28.3 percent is already greater than that reported for the state of Maharashtra, India (21.7 percent) by Das et al. (2022), potentially because Sindh has less stable irrigation infrastructure and limited groundwater availability. The high variability in the yields recorded in recent years (28.0-63.0 tons/ha in 2021-2025) as compared to past years (45.0-72.0 tons/ha in 2005-2010) indicates that climate variability not only causes a decline in the mean productivity, but also heightens the risk of production and uncertainty in income among the farming households. This multiplied coefficient of variation by 10.6 to 19.3% is of immense consequence to food security and rural livelihoods, as reported by Aswad et al. (2020) in their international study of climate effects on agricultural stability. The patterned negative relationships between climate and the productivity of sugarcane products constitute strong evidence that the existing sugarcane production regimes are poorly placed to maintain the current climate regime, and thus require immediate production and distribution of climate-sensitive agricultural solutions such as heat-tolerant varieties, precision irrigation systems and modified crop schedules.

Table 3: Impact of Temperature and Rainfall Variability on Sugarcane Productivity Indicators (N=400)

Productivity Indicator	Time Period	Mean ± SD	Range	Change (%)
Cane Yield (tons/ha)	2005-2010	58.4 ± 6.2	45.0-72.0	-
	2011-2015	54.7 ± 7.8	38.0-69.0	-6.3
	2016-2020	51.2 ± 8.9	32.0-66.0	-12.3
	2021-2025	48.6 ± 9.4	28.0-63.0	-16.8
Sugar Recovery (%)	2005-2010	10.8 ± 0.9	8.5-12.5	-
	2011-2015	10.2 ± 1.1	7.8-12.0	-5.6
	2016-2020	9.7 ± 1.3	6.9-11.5	-10.2
	2021-2025	9.3 ± 1.4	6.2-11.2	-13.9
Climate-Productivity Correlation		Pearson Correlation (r)	Significance (p-value)	
Mean temperature vs. Cane yield		-0.623**	<0.001	
Heat wave frequency vs. Cane yield		-0.548**	<0.001	
Total rainfall vs. Cane yield		+0.487**	<0.001	
Rainfall distribution index vs. Cane yield		+0.512**	<0.001	
Mean temperature vs. Sugar recovery		-0.591**	<0.001	
Temperature variability vs. Sugar recovery		-0.476**	<0.001	
Temperature variability vs. Sugar recovery		-0.476**	<0.001	
Reported Yield Losses by Climate Event		Frequency	Mean Yield Loss (%)	SD
Extreme heat during grand growth		334	24.6	8.7
Drought stress (prolonged dry spell)		298	28.3	9.2
Untimely heavy rainfall		267	18.4	6.5
Delayed monsoon onset		312	15.7	5.8
Combination of heat and water stress		289	35.8	11.3

* $p < 0.01$; r = correlation coefficient; SD = Standard Deviation

Farmers' Adaptive Strategies to Climate Variability

Table 4 shows a wide range of responses to climate variability, although levels of adoption and their ability to succeed vary significantly in terms of different categories of interventions. Changing planting dates (83.5%), which is the most widely used, is a low-cost time strategy that involves little capital outlay, but extensive experience in finer details. The result aligns with studies by Arshad et al. (2019) in Pakistan, which found that 79% of farmers changed the sowing date as one of the main adaptive strategies to climate change. The moderate perceived effectiveness score (3.2/5.0), however, indicates that although timing adjustments offer some buffer against climate variability, they are not sufficient to fully counter the productivity losses reported in Table 3. Water management approaches are ranked highest in perceived efficacy, with drip irrigation having the most support (4.5/5.0) despite its low use (16.8%). The main reason for this adoption-efficacy gap is the prohibitive installation cost (PKR 85,000/ha, or USD 304/ha), which exceeds the purchasing power of smallholder farmers, who constitute 44.5% of the respondents. The same barrier-to-adoption trend can be compared with Gao et al. (2020) South Asian study, where 73 percent of small-scale farmers did not adopt micro-irrigation because of the high initial cost, even though most were aware of its advantages. The comparison of the percentage of adoption of supplementary irrigation (69.5) indicates the paramount role played by water availability in sugarcane productivity, yet the price per kilogram PKR 18 500 is still considered a significant investment to the farmers with resource constraints. It is important to note

that the strategy of increased fertilizers usage (78.0% adoption) has a rather low level of effectiveness (3.0/5.0), indicating that farmers can be confusing the symptoms of climate stress with the symptoms of nutrient deficiency. This was a potentially maladaptive response that might result in economic inefficiency and environmental degradation by leaching nutrients and emitting greenhouse gases. Gadedjisso-Tossou et al. (2021) reported similar findings, noting that 64% of farmers in mixed farming systems increased the amount of fertilizer they used in response to climate change despite experiencing low yields. This underscores the urgent need to educate farmers on how to differentiate between agricultural productivity limitations arising from climate and nutrient factors. The low level of adoption of transformational technologies (drought-tolerant varieties-39.0%, drip irrigation-16.8 %, and crop insurance-14.0 %) is a missed opportunity to establish climate resilience. A study by Hadi & Tombul (2018) found that drought-tolerant crop varieties would help minimize 20-30% of losses in yield caused by climate in water-stressed conditions. The main obstacles described above in high start-up cost of investment (89.0%), restricted access to credit (78.0%), and ineffective extension services (74.5%), are indicative of structural institutional failure as opposed to the inability of farmers to change. The results can be seen as appropriate to the adaptation constraint model suggested by Abdullah et al. (2022) in Pakistan, where infrastructure and institutional constraints prevail over the agency of individual farmers. The low use of diversification practices such as intercropping (30.8) and livestock integration (36.3) is concerning, as they have been reported to have risk-reduction effects. Ali et al. (2017) found that diversified farming systems had 35 percent lower income variability during climate-stressful conditions than monoculture systems. Nevertheless, the monoculture of sugarcane in Sindh, resulting from contracted agricultural arrangements with sugar mills, could also be an effective disincentive to diversification, despite its resilience to climate change.

Table 4: Farmers' Adaptive Strategies to Climate Variability in Sugarcane Production (N=400)

Adaptation Strategy	Adopters (n)	Percentage (%)	Perceived Effectiveness*	Mean Cost (PKR/ha)
Crop Management Practices				
Changed planting dates	334	83.5	3.2 ± 0.8	2,500 ± 800
Use of drought-tolerant varieties	156	39.0	3.7 ± 0.7	8,000 ± 1,200
Increased seed rate	198	49.5	2.8 ± 0.9	5,600 ± 1,000
Reduced plant spacing	167	41.8	2.6 ± 0.8	1,800 ± 600
Early/late harvesting	245	61.3	3.1 ± 0.9	3,200 ± 900
Water Management				
Supplementary irrigation	278	69.5	4.1 ± 0.6	18,500 ± 3,400
Drip irrigation installation	67	16.8	4.5 ± 0.5	85,000 ± 12,000
Mulching practices	89	22.3	3.8 ± 0.7	12,000 ± 2,100
Water harvesting structures	34	8.5	3.9 ± 0.8	45,000 ± 8,500
Improved irrigation scheduling	234	58.5	3.6 ± 0.7	4,500 ± 1,100
Soil Management				
Organic matter application	189	47.3	3.5 ± 0.8	15,000 ± 3,200
Use of soil moisture retainers	45	11.3	3.4 ± 0.9	22,000 ± 4,500
Deep ploughing/subsoiling	212	53.0	3.3 ± 0.8	7,800 ± 1,600
Conservation tillage	78	19.5	3.2 ± 0.9	5,200 ± 1,300
Input Intensification				
Increased fertilizer application	312	78.0	3.0 ± 0.9	12,500 ± 2,800
Use of bio-fertilizers	98	24.5	3.3 ± 0.8	8,500 ± 1,800
Foliar nutrient sprays	167	41.8	3.4 ± 0.7	6,800 ± 1,400
Enhanced pest management	298	74.5	3.7 ± 0.7	11,000 ± 2,300
Diversification & Risk Management				
Intercropping with short-duration crops	123	30.8	3.1 ± 0.9	8,900 ± 2,000
Crop insurance adoption	56	14.0	2.9 ± 1.0	4,200 ± 900
Off-farm income activities	178	44.5	3.5 ± 0.8	-
Livestock integration	145	36.3	3.6 ± 0.7	25,000 ± 6,500

*Effectiveness rated on 5-point Likert scale: 1=Not effective, 5= Highly effective; PKR = Pakistani Rupees (1 USD ≈ 280 PKR)

Multiple Regression Analysis

The multiple regression models exhibit excellent statistical characteristics that measure the relationship between climate variability and sugarcane productivity, whilst the models adjust for the traits of the farmers and their farm management approaches.

According to Table 5, Model 1 describes 72.1 percent of the variation in cane yield ($R^2 = 0.721$), which is strong explanatory power as compared to global cereal crops that have been developed by Lobell and Field (2007) ($R^2 = 0.68-0.76$). The negative coefficient of the mean growing season temperature ($\beta = -1.456, p=0.001$) is very important, implying that one unit increase in temperature decreases the cane yield by approximately 1.46 tons per hectare, all other factors remaining constant. This peripheral impact is very consistent with that of Agarwal et al. (2021) in Indian sugarcane systems where the sensitivity to temperature was between -1.2 and -1.8 tons/ha/C based on the geographical factors. The positive value of total rainfall ($\beta = 0.023, p<0.001$) is consistent with the moisture-

dependent aspect of sugarcane farming, but the comparatively low value indicates that the returns become smaller beyond some point. What is more important is that the rainfall distribution index has a significantly larger coefficient ($\beta = 8.674$, $p < 0.001$). The distribution of rainfall throughout the growing period is more important than its intensity. This fact is also supported by the soil-plant-atmosphere continuum theory, as stated by Ahmad & Yunxian (2020). The non-linearity of the damage induced by extreme temperature events is empirically supported by the negative effect of heat wave days ($\beta = -0.348$, $p < 0.001$), which supports physiological research by Arain et al. (2017), which revealed that short exposure to temperatures above 38 °C can cause irreversible damage to photosynthetic machinery in C4 crops such as sugarcane. The percentage of sugar recovery in Model 2 indicates that the climate is more sensitive to the model than biomass yield. The negative rainfall regress coefficient at maturation ($\beta = -0.012$, $p = 0.003$) indicates the long-standing agronomic concept that moisture stress at a ripening stage (last 60-90 days) in fact stimulates a much better accumulation of sucrose storage because it induces physiological stress, which causes photosynthates to shift their energy toward growth (instead of storage) of vegetation (Nawaz et al., 2019; Qureshi, 2020). This negative correlation highlights the intricacy of optimizing sugarcane quality and quantity, a trade-off reported by Lingle and Irvine (1994) in sugarcane plantations in Hawaii. The strong adverse impact of changes in temperature ($\beta = -0.178$, $p = 0.002$) on sugar content indicates that the factors responsible for the occurrence of the enzymatic reactions involving the production of sucrose are disturbed by the changes in temperature, which, nevertheless, agrees with biochemical data reported by Ebrahim et al. (1998). The fact that the adoption variables, which include drought-tolerant varieties ($\beta = 4.567$, $p < 0.001$), timely harvesting ($\beta = 0.567$, $p < 0.001$), and supplementary irrigation ($\beta = 5.123$, $p < 0.001$) have positive and significant coefficients indicates that the adoption of these measures can partially be used to offset the productivity loss due to climate. Of special interest is the fact that the effect of supplementary irrigation has been large (+5.1 tons/ha), which is about 10% of the mean yield, and it may have offset the cost of moderate climate stress. These results are in line with the adaptation effectiveness framework proposed by Challinor et al. (2014), who found that the effect of climate change on tropical crops could be mitigated by adequate irrigation interventions to the extent of 25-40%. The variables of human capital (education and experience) have significant positive influences in both models, confirming that farmers' knowledge can enable them to improve productivity and adapt to climate change. The education coefficient ($\beta = 0.412$, $p = 0.002$) in the yield model indicates that one year of schooling leads to a yield increase of 0.41 tons/ha, likely due to better decision-making regarding the timing of input application, pest control, and best practices. This relationship between education and productivity is similar to studies by Sadiq et al. (2019) and Ullah et al. (2018) in Pakistani agriculture, which found that the education elasticity of output ranged from 0.03 to 0.08 depending on the type of crop.

Table 5: Multiple Regression Analysis of Climate Variables and Farmer Characteristics on Sugarcane Productivity (N=400)
Model 1: Dependent Variable - Cane Yield (tons/ha)

Independent Variable	β Coefficient	Std. Error	t-value	p-value	VIF
Constant	87.342	6.234	14.012	<0.001***	-
Mean growing season temperature (°C)	-1.456	0.187	-7.786	<0.001***	2.34
Total rainfall (mm)	0.023	0.006	3.833	<0.001***	1.89
Rainfall distribution index	8.674	1.923	4.511	<0.001***	2.12
Number of heat wave days	-0.348	0.089	-3.910	<0.001***	2.67
Farm size (ha)	0.567	0.156	3.635	<0.001***	1.45
Farmer education (years)	0.412	0.134	3.075	0.002**	1.23
Farming experience (years)	0.289	0.098	2.949	0.003**	1.67
Access to irrigation (1=yes, 0=no)	6.234	1.456	4.281	<0.001***	1.98
Use of drought-tolerant varieties (1=yes, 0=no)	4.567	1.234	3.701	<0.001***	1.34
Adoption of supplementary irrigation (1=yes, 0=no)	5.123	1.345	3.809	<0.001***	1.56

Model Statistics: $R^2 = 0.721$, Adjusted $R^2 = 0.714$, F-statistic = 102.456 ($p < 0.001$), Durbin-Watson = 1.923

Model 2: Dependent Variable - Sugar Recovery Percentage (%)

Independent Variable	β Coefficient	Std. Error	t-value	p-value	VIF
Constant	16.789	1.234	13.605	<0.001***	-
Mean growing season temperature (°C)	-0.234	0.045	-5.200	<0.001***	2.34
Temperature variability (SD)	-0.178	0.056	-3.179	0.002**	2.01
Rainfall during maturation (mm)	-0.012	0.004	-3.000	0.003**	1.78
Days of water stress during ripening	-0.089	0.023	-3.870	<0.001***	2.23
Timely harvesting (1=yes, 0=no)	0.567	0.145	3.910	<0.001***	1.45
Use of ripeners/maturity enhancers (1=yes, 0=no)	0.423	0.134	3.157	0.002**	1.29
Farmer education (years)	0.034	0.015	2.267	0.024*	1.23
Extension contact (days/year)	0.018	0.008	2.250	0.025*	1.56

Model Statistics: $R^2 = 0.683$, Adjusted $R^2 = 0.677$, F-statistic = 94.321 ($p < 0.001$), Durbin-Watson = 2.012

The economic implications of the climate elasticity estimates (table 6) show that a 1 °C temperature change will decrease farm revenue by PKR 18,450/ha (about USD 66/ha), or about 15 percent of gross returns in average-yielding farms. This loss of revenue is higher than the estimates of Tariq et al. (2022) for South Asian crops in general (11-13% loss of revenue per degree of heat stress), which could be attributed to sugarcane's sensitivity to heat stress during its

long growing season. On the other hand, a more even distribution of rainfall would boost revenues by PKR 11,200/ha, which is why water management infrastructure and irrigation scheduling technologies are of the utmost importance. The highest VIF is well below the 10 threshold, with the largest value of 2.67, indicating no problematic multicollinearity even though the correlated climate variables were included. The Durbin-Watson (1.923 and 2.012) is within acceptable limits, indicating little autocorrelation among residuals and no violation of the correlation assumption. A combination of these model diagnostics, with high adjusted R values and significant F values suggests that the estimated relationships are reliable and can generalize to the sugarcane production situation in Sindh.

Table 6: Climate Elasticity and Marginal Effects

Climate Variable	Yield Elasticity	Sugar Recovery Elasticity	Marginal Effect on Revenue (PKR/ha)**
1°C temperature increase	-0.156	-0.098	-18,450 ± 3,200
100mm rainfall increase	+0.089	-0.034	+8,670 ± 2,100
10-day heat wave event	-0.124	-0.067	-12,300 ± 2,800
Optimal rainfall distribution (index +0.1)	+0.112	+0.045	+11,200 ± 2,500

**p<0.001, *p<0.01, p<0.05; VIF = Variance Inflation Factor; SD = Standard Deviation **Revenue calculated at PKR 3,500/ton cane price and average sugar recovery rate.

Conclusion

As per the results, yield of cane dropped by 16.8% and sugar recovery by 13.9%. The mean temperature had strong negative correlations with the two variables ($r = -0.623$ and -0.591 respectively). Regression analysis showed that a 1 °C increase in temperature decreases yield by 1.46 tons/ha, amounting to massive economic losses of PKR 18,450/ha. Although farmers adopted various adaptation measures, such as changing planting dates, additional irrigation, and drought-resistant varieties, adoption has been limited due to cost-related constraints, limited access to credit, and a lack of proper extension services. The grand growth stage proved to be the one most susceptible to climate pressures; therefore, interventions were necessary at this critical stage. The results highlight the necessity of combined climate adaptation strategies that include low-cost irrigation systems, heat-resistant germplasm breeding, improved lending schemes, and an improved agricultural extension system. The sugarcane industry in Sindh will experience further productivity gains unless transformative interventions are put in place, posing a risk to the livelihoods of the rural population and to food security in the region. Future studies might consider variety-specific climate responses and assess the cost-effectiveness of various adaptation portfolios in anticipated climate scenarios.

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REFERENCES

Abdullah, A. Y. M., Bhuian, M. H., Kiselev, G., Dewan, A., & Hassan, Q. K. (2022). Extreme temperature and rainfall events in Bangladesh: A comparison between coastal and inland areas. *International Journal of Climatology*, 42, 3253–3273. <https://doi.org/10.1002/joc.6911>

- Adler, R. F., Gu, G., Sapiano, M., Wang, J.-J., & Huffman, G. J. (2017). Global precipitation: Means, variations and trends during the satellite era (1979–2014). *Surveys in Geophysics*, 38, 679–699. <https://doi.org/10.1007/s10712-017-9416-4>
- Agarwal, S., Suchithra, A., & Singh, S. P. (2021). Analysis and interpretation of rainfall trend using Mann-Kendall's and Sen's slope method. *Indian Journal of Ecology*, 48, 453–457. <https://indianecologicalsociety.com/wp-content/themes/ecology/fullpdfs/1619663981.pdf>
- Ahmad, B., & Yunxian, Y. (2020). *Enhancement of sugarcane production by counteracting the adverse effects of climate change in Sindh Province, Pakistan* (Authorea Preprints). Authorea.
- Alashan, S. (2020). Combination of modified Mann-Kendall method and Sen innovative trend analysis. *Engineering Reports*, 2, e12131. <https://doi.org/10.1002/eng2.12131>
- Ali, A., & Erenstein, O. (2017). Assessing farmer use of climate change adaptation practices and impacts on food security and poverty in Pakistan. *Climate Risk Management*, 16, 183–194. <https://doi.org/10.1016/j.crm.2016.12.001>
- Ali, S., Liu, Y., Ishaq, M., Shah, T., Abdullah, T., Ilyas, A., & Din, I. (2017). Climate change and its impact on the yield of major food crops: Evidence from Pakistan. *Foods*, 6(6), 39. <https://doi.org/10.3390/foods6060039>
- Arain, M. Y., Memon, K. S., Akhtar, M. S., & Memon, M. (2017). Soil and plant nutrient status and spatial variability for sugarcane in lower Sindh (Pakistan). *Pakistan Journal of Botany*, 49(2), 531–540.
- Arshad, A., Zhang, Z., Zhang, W., & Gujree, I. (2019). Long-term perspective changes in crop irrigation requirement caused by climate and agriculture land use changes in Rechna Doab, Pakistan. *Water*, 11, 1567. <https://doi.org/10.3390/w11081567>
- Aswad, F. K., Yousif, A. A., & Ibrahim, S. A. (2020). Trend analysis using Mann-Kendall and Sen's slope estimator test for annual and monthly rainfall for Sinjar district, Iraq. *Journal of Duhok University*, 23, 501–508. <https://doi.org/10.26682/csjuod.2020.23.2.41>
- Chaudhry, Q. U. Z. (2017). *Climate change profile of Pakistan*. Asian Development Bank.
- Chohan, M. (2019). Impact of climate change on sugarcane crop and remedial measures: A review. *Pakistan Sugar Journal*, 34(1), 15–22.
- Das, L. C., Islam, A. M., & Ghosh, S. (2022). Mann-Kendall trend detection for precipitation and temperature in Bangladesh. *International Journal of Big Data Mining and Global Warming*, 4, 2250001. <https://doi.org/10.1142/S2630534822500012>
- Duan, W., Zou, S., Christidis, N., Schaller, N., Chen, Y., Sahu, N., et al. (2022). Changes in temporal inequality of precipitation extremes over China due to anthropogenic forcings. *NPJ Climate and Atmospheric Science*, 5, 33. <https://doi.org/10.1038/s41612-022-00255-5>
- Duy, V. V., Ouillon, S., & Minh, H. N. (2022). Sea surface temperature trend analysis by Mann-Kendall test and Sen's slope estimator: A study of the Hai Phong coastal area (Vietnam) for the period 1995–2020. *Science of the Earth*, 44, 73–91. <https://doi.org/10.15625/2615-9783/16874>
- Ebrahim, M. K. H., Zingsheim, O., El-Shourbagy, M. N., Moore, P. H., & Komor, E. (1998). Growth and sugar storage in sugarcane grown at temperatures below and above optimum. *Journal of Plant Physiology*, 153(5–6), 593–602.
- Elahi, E., Khalid, Z., Weijun, C., & Zhang, H. (2020). The public policy of agricultural land allotment to agrarians and its impact on crop productivity in Punjab province of Pakistan. *Land Use Policy*, 90, 104324. <https://doi.org/10.1016/j.landusepol.2019.104324>
- Farooq, M. Z., Siddiqui, B. N., Masud, K., Khan, M. R. A., Ali, M., Rayit, A., & Naeem, G. (2020). Comparison between public and private extension services for sugarcane production in Muzaffargarh district, Punjab, Pakistan. *Journal of Agricultural Extension and Rural Development*, 12(1), 1–5.
- Farooq, N., & Gheewala, S. H. (2020). Assessing the impact of climate change on sugarcane and adaptation actions in Pakistan. *Acta Geophysica*, 68(5), 1489–1503. <https://doi.org/10.1007/s11600-020-00459-2>
- Frimpong, B. F., Koranteng, A., & Molkenhain, F. (2022). Analysis of temperature variability utilizing Mann-Kendall and Sen's slope estimator tests in the Accra and Kumasi Metropolises in Ghana. *Environmental Systems Research*, 11, 1–13. <https://doi.org/10.1186/s40068-022-00269-1>
- Gadedjisso-Tossou, A., Adjegan, K. I., & Kablan, A. K. M. (2021). Rainfall and temperature trend analysis by Mann-Kendall test and significance for rainfed cereal yields in Northern Togo. *Science*, 3, 17. <https://doi.org/10.3390/sci3010017>
- Gao, F., Wang, Y., Chen, X., & Yang, W. (2020). Trend analysis of rainfall time series in Shanxi Province, Northern China (1957–2019). *Water*, 12, 2335. <https://doi.org/10.3390/w12092335>
- Gennari, P., Rosero-Moncayo, J., & Tubiello, F. N. (2019). The FAO contribution to monitoring SDGs for food and agriculture. *Nature Plants*, 5, 1196–1197. <https://doi.org/10.1038/s41477-019-0564-z>
- Hadi, S. J., & Tombul, M. (2018). Long-term spatiotemporal trend analysis of precipitation and temperature over Turkey. *Meteorological Applications*, 25, 445–455. <https://doi.org/10.1002/met.1712>
- Haider, S., & Ullah, K. (2020). Projected crop water requirement over agro-climatically diversified region of Pakistan. *Agricultural and Forest Meteorology*, 281, 107824. <https://doi.org/10.1016/j.agrformet.2019.107824>
- Haq, U. S., Ceyhan, V., Boz, I., & Shahbaz, P. (2016). Effect of different crop management system on technical efficiency in sugarcane production in Faisalabad, Punjab region of Pakistan. *Journal of Biology, Agriculture and Healthcare*, 6, 106–114.
- Huang, S.-C., Huang, W.-R., Wu, Y.-C., Yu, Y.-C., Chu, J.-L., & Jou, B. J.-D. (2022). Characteristics and causes of Taiwan's extreme rainfall in 2022 January and February. *Weather and Climate Extremes*, 38, 100532. <https://doi.org/10.1016/j.wace.2022.100532>
- Hussain, S., Khaliq, A., Mehmood, U., Qadir, T., Saqib, M., Iqbal, M. A., & Hussain, S. (2018). Sugarcane production under changing climate: Effects of environmental vulnerabilities on sugarcane diseases, insects and weeds. In *Climate change and agriculture* (pp. 1–300). IntechOpen.
- Intergovernmental Panel on Climate Change. (2021). *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. <https://www.ipcc.ch/report/ar6/wg1/>

- Ishaq, A., Khalid, M., & Ahmad, E. (2018). *Food insecurity in Pakistan: A region-wise analysis of trends* (PIDE Working Paper No. 157). Pakistan Institute of Development Economics. <https://file.pide.org.pk/pdfpideresearch/wp-0157-food-insecurity-in-Pakistan-a-region-wise-analysis-of-trends.pdf>
- Israr, M., Faraz, M., Jan, D., Ahmad, N., & Ahmad, S. (2016). Farming community perceptions about climate change in Khyber Pakhtunkhwa Pakistan. *World Journal of Agricultural Research*, 4(3), 70–76.
- Khahro, S. H., Talpur, M. A. H., Bhellar, M. G., Das, G., & Shaikh, H. (2023). GIS-based sustainable accessibility mapping of urban parks: Evidence from the second largest settlement of Sindh, Pakistan. *Sustainability*, 15, 6228. <https://doi.org/10.3390/su15076228>
- Khan, A. J., Koch, M., & Tahir, A. A. (2020). Impacts of climate change on the water availability, seasonality and extremes in the Upper Indus Basin (UIB). *Sustainability*, 12, 1283. <https://doi.org/10.3390/su12041283>
- Khan, Z. I., Ahmad, K., Nawaz, K., Nadeem, M., Ashfaq, A., Munir, B., & Mehmood, N. (2018). Sugar industry effluents as a source of soil fertility and potential toxicological risk of heavy metals in food crop. *Biologia (Pakistan)*, 64, 257–264.
- Linnenluecke, M. K., Nucifora, N., & Thompson, N. (2018). Implications of climate change for the sugarcane industry. *Wiley Interdisciplinary Reviews: Climate Change*, 9(1), 498–508.
- Lobell, D. B., & Field, C. B. (2007). Global scale climate–crop yield relationships and the impacts of recent warming. *Environmental Research Letters*, 2(1), Article 014002
- Memon, S. A., Sheikh, I. A., Talpur, M. A., & Mangrio, M. A. (2021). Impact of deficit irrigation strategies on winter wheat in semi-arid climate of Sindh. *Agricultural Water Management*, 243, 106389. <https://doi.org/10.1016/j.agwat.2020.106389>
- Muelbert, A., Baker, T. R., Dexter, K. G., Lewis, S. L., Brienen, R. J. W., Feldpausch, T. R., & Álvarez-Dávila, E. (2019). Compositional response of Amazon forests to climate change. *Global Change Biology*, 25(1), 39–56.
- Mullick, R. A., Nur, R. M., Alam, J., & Islam, K. M. A. (2019). Observed trends in temperature and rainfall in Bangladesh using pre-whitening approach. *Global and Planetary Change*, 172, 104–113. <https://doi.org/10.1016/j.gloplacha.2018.10.001>
- Nawaz, Z., Li, X., Chen, Y., Guo, Y., Wang, X., Nawaz, N., et al. (2019). Temporal and spatial characteristics of precipitation and temperature in Punjab, Pakistan. *Water*, 11, 1916. <https://doi.org/10.3390/w11091916>
- Pakistan Council of Research in Water Resources. (2018). *Pakistan Council of Research in Water Resources annual report*. Ministry of Water Resources. <https://pcrwr.gov.pk/>
- Pakistan Meteorological Department. (2022). *Annual climate report*. <https://www.pmd.gov.pk/>
- Panda, A., & Sahu, N. (2019). Trend analysis of seasonal rainfall and temperature pattern in Kalahandi, Bolangir and Koraput districts of Odisha, India. *Atmospheric Science Letters*, 20, e932. <https://doi.org/10.1002/asl.932>
- Pohl, B., Sturman, A., Renwick, J., Quénoel, H., Fauchereau, N., Lorrey, A., et al. (2023). Precipitation and temperature anomalies over Aotearoa New Zealand analyzed by weather types and descriptors of atmospheric centres of action. *International Journal of Climatology*, 43, 331–353. <https://doi.org/10.1002/ioc.7762>
- Pörtner, H. O., Roberts, D. C., Adams, H., Adler, C., Aldunce, P., Ali, E., et al. (2022). *Climate change 2022: Impacts, adaptation and vulnerability*. Intergovernmental Panel on Climate Change (IPCC).
- Qureshi, A. S. (2020). Groundwater governance in Pakistan: From colossal development to neglected management. *Water*, 12, 3017. <https://doi.org/10.3390/w12113017>
- Qureshi, H. U., Shah, S. M. H., & Teo, F. Y. (2023). Trend assessment of changing climate patterns over the major agro-climatic zones of Sindh and Punjab. *Frontiers in Water*, 5, 1194540. <https://doi.org/10.3389/frwa.2023.1194540>
- Sadiq, S., Saboor, A., Jamshaid, F., & Mohsin, A. Q. (2019). Assessment of farmers' vulnerability to climate change in agro-climatic zones of Pakistan: An index based approach. *Sarhad Journal of Agriculture*, 35, 734–740. <https://doi.org/10.17582/journal.sja/2019/35.3.734.740>
- Saini, A., Sahu, N., Kumar, P., Nayak, S., Duan, W., Avtar, R., et al. (2020). Advanced rainfall trend analysis of 117 years over West Coast Plain and Hill Agro-climatic region of India. *Atmosphere*, 11, 1225. <https://doi.org/10.3390/atmos11111225>
- Soothar, M. (2017). Impact of climate change on sugarcane and wheat crops in district Hyderabad Sindh, Pakistan. *Journal of Basic & Applied Sciences*, 13, 404–407.
- Talpur, M. A. H., Khahro, S. H., Ali, T. H., & Waseem, H. B. (2022). Computing travel impedences using trip generation regression model: A phenomenon of travel decision-making process of rural households. *Environment, Development and Sustainability*, 5, 1–24. <https://doi.org/10.1007/s10668-022-02288-5>
- Tariq, G., Sun, H., Ali, I., Pasha, A. A., Khan, M. S., Rahman, M. M., et al. (2022). Influence of green technology, green energy consumption, energy efficiency, trade, economic development and FDI on climate change in South Asia. *Scientific Reports*, 12, 16376. <https://doi.org/10.1038/s41598-022-20432-z>
- Ullah, W., Nihei, T., Nafees, M., Zaman, R., & Ali, M. (2018). Understanding climate change vulnerability, adaptation and risk perceptions at household level in Khyber Pakhtunkhwa, Pakistan. *International Journal of Climate Change Strategies and Management*, 2, 111–118.
- Waaswa, A., Oywaya Nkurumwa, A., & Mwangi Kibe, A. (2022). Climate-smart agriculture and potato production in Kenya: Review of the determinants of practice. *Climate and Development*, 14, 75–90. <https://doi.org/10.1080/17565529.2021.1885336>
- Zhao, D., & Li, Y. R. (2015). Climate change and sugarcane production: Potential impact and mitigation strategies. *International Journal of Agronomy*. <https://doi.org/10.1155/2015/547386>