



## Impact of Global Warming on Crop Production: Example from Farmers' Insight and Adaptation Measures

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**Abstract:** Globally, existing social, economic, and agricultural systems foster extreme inequity and irrationality, leading to problems such as poverty, racial discrimination, misogyny, and environmental degradation. Many of these problems are getting worse, increasing the likelihood of social and environmental collapse. However, climate change has severely affected the social, economic, and agricultural sectors worldwide, including in Pakistan. This article examines the autonomous climate change adaptation approaches adopted by farmers in Punjab, Pakistan, and assesses their influence on crop yield. The study utilizes a simultaneous equation model to analyze the effects of various adaptation measures on both adapters and non-adapters. Findings from data collected from 390 sugarcane growers reveal a high level of awareness of current climate conditions, leading them to undertake appropriate adaptation measures. However, limited knowledge of climate change and limited arable land significantly affect farmers' adaptive decision-making. While some farmers employ strategies such as improved irrigation and increased fertilizer use, many still lack sufficient adaptation measures. The study establishes that non-adapted growers experience a negative impact on sugarcane production. Therefore, the article recommends that policymakers focus on addressing the gaps in adaptation strategies adopted by sugarcane growers to mitigate the effects of climate change. Moreover, policymakers should develop appropriate adaptation strategies to help farmers cope with climate-related disasters, thereby enhancing farmers' incomes and promoting the revitalization and modernization of agriculture in rural areas.

**Keywords:** Environmental justice; economic justice; crop; climate change; rural; Pakistan

### 1. Introduction

Agriculture is the most significant sector of emerging economies, including Pakistan's economy, providing direct and indirect support to the country's people and accounting for 21% of the Gross Domestic Product (GDP). Agriculture is under pressure to boost output levels to satisfy rising demand as the population grows. Sugarcane is Pakistan's principal cash crop. It is a C4 crop grown primarily in tropical and subtropical countries and is the world's primary source of bioenergy (Ir, 2007). It is one of the most significant crops, accounting for approximately 75% of global sugar production for human consumption (Dehlavi, 2015). In Pakistan, sugarcane was grown on 1260 thousand hectares in the 2021-22 crop year, compared to 1160 thousand hectares last year, with a production of 88.651 million tons (Muslehuddin & Faisal, 2006). Colombia (123.0 tons ha<sup>-1</sup>), Australia, Egypt, and the United States are all large sugarcane producers (99.3, 87.3, and 74.6 tons ha<sup>-1</sup>, respectively) (Devaraja, 2008). Pakistan's ha<sup>-1</sup> output is around 43 tons, which is slightly lower than that of other major crop-producing countries. Sugarcane is grown in Sindh, Khyber Pakhtunkhwa (KPK), and Punjab in Pakistan, with Punjab being the leading producer (Rahman et al., 2012).

Sugarcane provides money not only to sugar mills but also to sugar and sugar product dealers in Pakistan. However, this crop accounts for approximately 64% of Sindh's total agricultural production (Haq, 2013). There are 9 sugar plants in KP, 48 in Sindh, and 91 in Punjab, producing around 3.2 million tons of sugar to supply Pakistan's needs. There is a significant gap between supply and demand. This disparity can be attributed to poor farming methods, unfavorable atmospheric conditions, and other factors, such as unfavorable stakeholder

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attitudes and government policies ([Mallawaarachch & Ahmad, 2018](#)). Climate change has various reasons, not all of which affect rural sugarcane output ([Ahmad, 2022](#)). It is critical to identify the significant factors impeding sugarcane output, particularly climate change. However, it is vital to assess the detrimental impact of climate change on sugarcane production in Pakistan. Environmental change is becoming a more pressing concern worldwide ([Sitko, 2022](#)). Climate change and related calamities are affecting agricultural production and growth patterns, threatening the income flexibility and sustainability of farms. Climate change is an incontestable reality of life, and Pakistan is the most impacted nation. Between 1999 and 2018, Pakistan lost a total of US\$3.79 million due to climate change, ranking it as the fifth-most-affected nation worldwide ([Ali & Rose, 2021](#); [Asif, 2013](#); [Eckstein, 2019](#)). An observed upsurge in temperature of 0.6 to 1.0°C and an increase in rainfall of 18% to 32% during the last century might affect agricultural productivity in secondary economies that rely on agriculture, such as Pakistan ([Asif, 2013](#)). Some analysts anticipate that this condition may worsen, posing substantial challenges for Pakistan's agricultural industry ([Shakoor, 2011](#)).

Emerging countries are likewise affected by environmental issues. However, due to inadequate adaptation, the impacts are more pronounced and fatal in underdeveloped nations ([Salman, 2018](#); [Suleri, 2018](#)). While mitigation is the most effective strategy to address climate change, it is expensive in terms of money, time, and effort. Adaptation to varied climatic scenarios is a practical approach in emerging nations such as Pakistan to mitigate severe climate impacts on the agriculture sector ([Adger, 2003](#); [Hassan & Nhemachena, 2008](#)). Agriculture accounts for most of Pakistan's economy, contributing 18.9% to the country's annual GDP. Although this industry is critical to the Pakistani economy, it also confronts many limitations related to food, natural disasters, climate change, and drought ([Antwi-Agyei, 2018](#); [Rehman, 2019](#)).

The potential climate-related threats are evident and genuine, but what is concerning is that the farming industry is disrupted and unclear; therefore, adaptation is not only an efficient strategy but also helps proportionally minimize the negative consequences of ecological risk ([Maponya & Mpandeli, 2012](#)). Almost every civilization has adaptation measures, but climate awareness may play an essential role, and adaptation measures are directly tied to education, access to resources, and awareness. In addition, small-scale growers in Pakistan lack access to these mechanisms. A larger proportion of the population (29.5%) lives in poverty, limiting growers' ability to address climate challenges ([Ali & Rose, 2021](#)). Adaptation is therefore a challenge for emerging countries, which is exacerbated by high levels of climate change vulnerability, poverty, and limited capacity to adapt at the farm level ([Asian Development, 2017](#); [Khan & Ali, 2015](#); [Liu et al., 2010](#)). Furthermore, due to farmers' limited financial and technical capacity, ineffective climate strategies have constrained existing resources for climate adaptation ([Muslehuddin & Faisal, 2006](#)).

As a result, targeted adaptation programs are required to identify the factors that affect farmers' knowledge and adaptive responses ([Below et al., 2015](#); [Bradshaw et al., 2004](#)). Despite the social, environmental, and economic repercussions of different adaptation techniques utilized by farmers ([Mallawaarachch & Ahmad, 2018](#); [Müller et al., 2017](#)), climate awareness is critical. Consequently, it is vital to investigate how growers perceive climate and adapt to it. Furthermore, the type and degree of mitigation strategies adopted are critical to the prognosis ([Ali & Rose, 2021](#)). Despite substantial research on farmers' climate awareness and adaptive behavior, the factors underlying adaptive behavior remain under investigated ([Adger, 2003](#); [Azmi, 2011](#); [Makate et al., 2017](#)). While the many adaptation strategies used by farmers have social, environmental, and economic implications, climate knowledge is critical.

Therefore, it is critical to investigate how sugarcane growers perceive and adapt to climate change. Furthermore, the extent of adaptation methods used to mitigate climate change has an important influence on climate change. While farmers' perceptions and adaptation behavior under climate conditions have been extensively studied, further research is needed on the determinants of adaptation behavior. So far, climate research in Pakistan has focused on predicting the impacts of climate change on specific agricultural yields. As sugarcane is an industrial crop in Pakistan, this research aims to fill a research gap in the field of agriculture. According to the Pakistan Statistics Authority's Workforce Survey (2017-2018), the agriculture industry employs 39% of the workforce (30.2% male and 67.2% female). Pakistan's average yearly temperature has increased considerably during the last century. Temperatures throughout the country are expected to rise by 0.6-1.0°C by the end of the twenty-first century. Thus, identifying climate and its influence on sugarcane output is critical, especially given changes in Pakistan's agricultural sector and several environmental disasters. The essential goal of the recent work is to



evaluate growers' perspectives and adaptation techniques in the research area in response to the effects of climate change on sugarcane output.

The current paper is separated into six units, the first of which is the introduction. Section two explains the materials and procedures. Section three displays the study results. Section four contains the discussion, while section five describes the research's detailed conclusions.

## 2. Materials and Methods

### 2.1 Area of Study

The available data were collected in Punjab, Pakistan, in 2022, focusing on sugarcane-producing areas. Punjab is the most populous province and an important agricultural area of Pakistan. Its population surpasses 110 million, the vast majority of whom reside in remote areas (80%) and are utilized in the agricultural sector. This province accounts for more than 50% of the nation's agricultural GDP. The province's total area is 5.03 million hectares, of which 4.2 million hectares are arable (approximately 83%). The agricultural system, public services, and trade are the province's primary sources of income. Numerous crops significant to the farming sector are grown, including sugarcane, rice, barley, millet, maize, tobacco, wheat, etc. The province's climate varies from region to region and encompasses most of Pakistan's climatic zones. Since most of the province belongs to the arid ecoregion, rainfall also varies greatly. On the contrary, the eastern part of the studied province is the wettest part of the country, particularly during the monsoon season (Khan & Ali, 2015).

### 2.2 Technique for Data Assortment and Sampling

The existing data were gained in Pakistan's Punjab province; this analysis is based on the original data. In September 2022, a complete questionnaire survey of 390 sugarcane growers was conducted. To obtain basic information from sugarcane producers, a multi-stage random sampling method was used. To assess current growers' perspectives on climate and its effect on sugarcane production in Punjab. Firstly, data were gathered in three districts (Bahawalpur, Muzaffargarh, and Rahimyar Khan) based on the contribution of agriculture to output in each district (Figure 1). Secondly, a tehsil was selected to administer the study design questionnaire, and thirdly, a union council (UC) was selected from each nominated tehsil. Fourthly, four villages were randomly selected for each UC, and basic data were collected from sugarcane producers in these villages. The design questionnaire for this study is divided into many parts. The central part of the program questionnaire included information on the socioeconomic and demographic attributes of sugarcane producers. The remainder of the questionnaire was planned to capture important information on producers' perceptions of climate and its impact on sugarcane productivity. The strategic questionnaire was first written in English and later translated into the local language to facilitate use by sugarcane producers. The study's objective and intended usage were clarified by all selected sugarcane farmers.

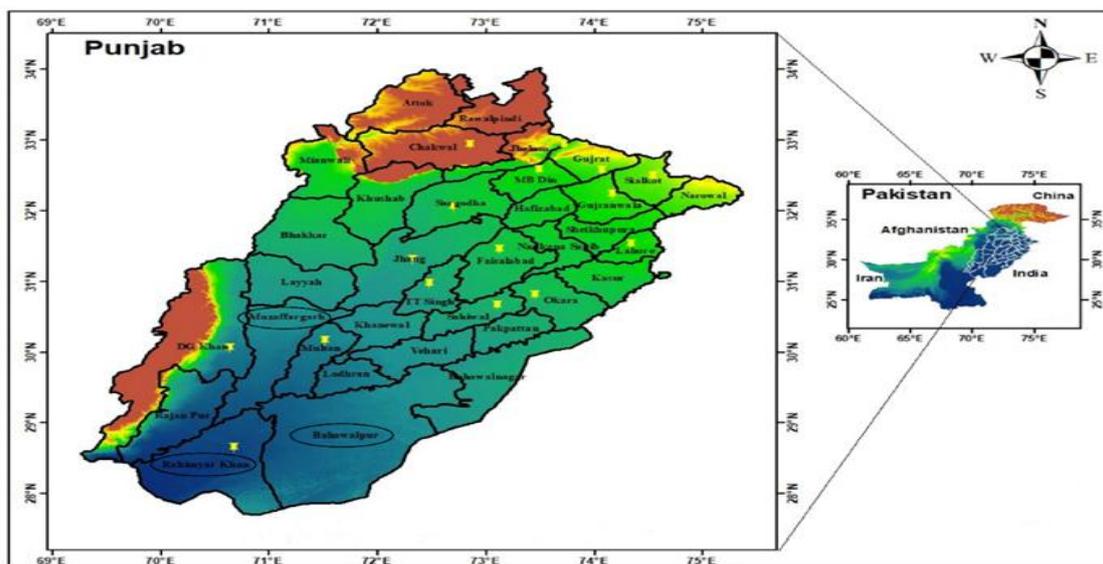


Figure 1: Punjab Map

### 2.3 Estimating Climate Change Adaptation and Sugarcane Production

Worldwide, climate change's effects are already being felt. In terms of the incidence of extreme climatic events such as extreme temperatures, unpredictable rainfall, floods, droughts, or crop diseases, climate change is defined as observed changes in the local environment over the past 10 to 20 years or more. Climate change and its influence on sugarcane production can be modeled using a two-stage approach. First, we utilized the selection model to choose climate change adaptation strategies. If hazard-averse farmers adopt climate adaptation to generate revenue, the variable  $A^*$  represents the net income.

$$A_i^* = Z_i a + \eta_i \text{ with } A_i = 1, \text{ if } A_i^* > 0 \text{ and } 0 \text{ otherwise} \quad (1)$$

In equation 1, where  $(A_i=1)$  if  $A_i^* > 0$  and 0, then farmer I would adopt the climate adaptation policy. The sugarcane producers' decision is influenced by the factors represented by vector  $Z$ . Farmers' characteristics and climatic information provided by extension workers were selected as dependent variables based on the elements of sugarcane producers' decision-making regarding climate adaptation ([Adger, 2003](#); [Hassan & Nhemachena, 2008](#); [Khan & Ali, 2015](#)). Social and demographic factors, such as gender, age, educational background, labor contributions, available land for cultivation, and climate awareness, can be used to identify their characteristics. Notably, available data at the administration level is limited to environmental threats such as drought and frost.

The second-step method mimics the effects of adaptation on sugarcane production. The most straightforward and most suitable alprafenone step equation (OLS) in the crop production equation, which includes dummy variables. However, this technique could lead to several problems when measuring the influence of sugarcane production on adaptation. Adaptation could be endogenous, consequently, resulting in biased results. Additionally, estimation inconsistency and biased sample selection might lead to skewness in the outcome ([Iat, 2014](#)). An equation model for estimating climate adaptation and its impact on crop production in endogenously changed crops, utilizing occupancy info maximum likelihood ([Makate et al., 2017](#)). The present data uses variables associated with climate awareness and environmental information as selection models. As shown in Table A1, climate change insights and perceptions sharply disrupted sugarcane growers' adaptation choices, but not sugarcane productivity among non-adopters. Therefore, reproducing as beneficial selection instruments.

$$y_{1i} = \beta_1 x_{1i} + \varepsilon_{1i} \text{ if } A_i = 1 \quad (2)$$

$$y_{0i} = \beta_0 x_{0i} + \varepsilon_{0i} \text{ if } A_i = 0 \quad (3)$$

Where  $Y_{1i}$  &  $Y_{0i}$ , respectively, represent the production per hectare of sugarcane determined by log adopters and non-adopters. Seed, technology, labor, and fertilizer are examples of input vectors  $Y_i$  provided in the logarithmic form. The vector of a parameter to be evaluated is  $\beta$ , and the error term is  $\varepsilon$ . Equations 1 and 3 assume that the error terms have a three-variable normal distribution with  $(\eta, \varepsilon_{1i}, \varepsilon_{0i}) \sim N(0, \Sigma)$  ([Khan, 2013](#)).

$$\text{COV}(\eta, \varepsilon_A, \varepsilon_N) = \Sigma = \begin{cases} \sigma_n^2 & \sigma_{\eta A} & \sigma_{\eta N} \\ \sigma_{A\eta} & \sigma_A^2 & \sigma_{AN} \\ \alpha_{m1} & \sigma_{NA} & \sigma_N^2 \end{cases} \quad (4)$$

Predictable values of  $\varepsilon_1$  and  $\varepsilon_0$  On-zero stated as ([Salvatore Di Falco et al., 2011](#); [Khanal et al., 2018](#))

$$E\{\varepsilon_{1i} | A_i = 1\} = \sigma_{1i} \frac{\varphi(Z_i a)}{1 - \Phi(Z_i a)} = \sigma_{1\eta} \lambda_{1i} \quad (5)$$

$$E\{\varepsilon_{0i} | A_i = 0\} = -\sigma_{0i} \frac{\varphi(Z_i a)}{1 - \Phi(Z_i a)} = \sigma_{0\eta} \lambda_{0i} \quad (6)$$

The four conditional crop yield predictions can be studied using the Endogenous Switching Regression (ESR) method ([S. Di Falco et al., 2011](#)).

$$E(y_{1i} | A_1 = 0) = \beta_{1x1i} + \sigma_{1i} \lambda_{1i} \quad (7)$$

$$E(y_{0i} | A_1 = 0) = \beta_{0x0i} + \sigma_{0i} \lambda_{0i} \quad (8)$$



$$E(y_{0i}|A_1 = 1) = \beta_{0\chi_{1i}} + \sigma_{0i}\lambda_{1i} \quad (9)$$

$$E(y_{0i}|A_1 = 0) = \beta_{0\chi_{1i}} + \sigma_{0i}\lambda_{1i} \quad (10)$$

Equations seven and eight reflect the apparent projections in the sample. Equations nine and ten demonstrate that the alternative outcomes are inconsistent. Furthermore, the difference between equations seven and nine can be used to estimate the average treatment effect on the treated (ATT). As a result, the difference between equations eight and ten could be considered the average treatment impact for untreated (UT) families. Equations seven and eight show prospective heterogeneity's influence on the "adopter" group ten. Additionally, the variation between (9) and (8) was used to analyse the influence of fundamental heterogeneity in the 'non-adopters' group. For further information on the ESR model, see (S. Di Falco et al., 2011).

### 3. Empirical Results

#### 3.1 Study's descriptive statistics

Table 1 demonstrates an overview and descriptive information about the sugarcane growers questioned. The research revealed that, on average, 85.6% of growers are aware of climate change, 68.6% have developed adaptation plans for changes in sugarcane yield, and 41% have obtained climate change data from external sources. Farmers have taken some steps to adapt their sugarcane to the climate. In general, important policies included increased irrigation frequency, greater use of fertilizers and pesticides, and the adoption of climate-adapted crop varieties. Furthermore, about 62% of farmers used more than one acclimatization method, and 3% used more than three. Farmers often knew that the research areas had higher temperatures and less rainfall. Additionally, we gathered complete production data for different manufacturing phases. Household labour and services are two categories of labour conflict. Sugarcane crops are typically sown over an area of 0.482 hectares, and the yield is 24319 kg/ha. Fertilizers, housekeeping, and technology are the three main inputs for farmers, with minimal rent and labour costs. Sixty-one percent of the respondents, who were on average 55 years old, had more than nine years of schooling.

**Table 1:** Detailed description, type, and unit of selected variables.

Variable Name	Variable type and Description	Mean	S. D
<b>Adopt</b>	Dummy (1= growers adapt to climate change, 0 = No)	0.685	0.352
SP	Sugarcane production kg/ha	24319.72	2557.27
LA	Land area under sugarcane (ha)	0.482	0.791
SU	Seeds usage kg/ha	2413.04	687.32
TC	Technology cost (per hectare, PKR)	1526.853	701.715
HL	Household labor input (per hectare, PKR)	2638.080	2135.371
EC	Employment cost expenditure (per hectare, PKR)	180.419	581.991
FU	Fertilizer usage (per hectare, PKR)	2476.440	697.026
PU	Pesticide usage (per hectare, PKR)	542.944	296.527
IC	Irrigation cost (per hectare, PKR)	463.738	459.876
G	Dummy (1 = farmers is male, 0 = No)	0.723	0.448
A	Farmers' age	55.123	10.210
ES	Dummy (1 = farmers' education status, 0 = No)	0.614	0.477
HS	Household size (number)	7.060	2.51
CM	Dummy (1 = farmers are cooperative members, 0 = No)	0.765	0.425
WS	Workforce as a share of the total household population	0.603	0.222
ES	Dummy (1 = farmers receive extension service, 0 = No)	0.721	0.435
CP	Dummy (1 = farmers' perception about climate change, 0 = No)	0.919	0.286
CC	Dummy (1 = farmers trust climate change impact on sugarcane production, 0 = No)	0.867	0.352
CI	Dummy (1 = farmers gained warning climate information, 0 = No)	0.978	0.121

In this analysis, farmers who opted for at least one adaptation method were called "adopters," while those who adopted none were called "non-adopters." Table 2 shows differences in household features between adopters and non-adopters, with the latter having notably higher average sugarcane yields. Some costs for non-adopters,

such as irrigation and employment costs, are much higher than those for adopters. Additionally, adopters are more aware of climate change and its impact on sugarcane productivity, and they have access to climate knowledge.

**Tables 2:** Sugarcane cultivator’s characteristics of adopters and non-adopters.

Variable Name	Adopters		Non-Adopters		Difference
	M	S. D	M	S. D	
Adapt 1/0	1.000	0.000	0.000	0.000	
SP	2420.887	6822.167	2357.206	6829.708	636.81**
LA	0.809	2.146	0.588	0.948	0.221
SU	1129.629	306.923	1127.578	375.437	12.051
TC	1548.522	651.598	1427.338	906.063	120.184
HL	2708.825	2219.873	2297.456	1644.566	411.369
EC	408.226	905.401	133.105	478.036	275.121 **
FU	544.795	300.001	534.028	281.712	10.767
PU	2520.898	721.167	2467.206	692.978	53.692
IC	593.72	469.75	436.741	454.060	156.979 **
G	0.731	0.444	0.685	0.469	0.046
A	56.238	10.256	55.574	11.241	0.664
ES	0.612	0.488	0.63	0.487	-0.018
HS	0.175	0.127	0.175	0.127	0.038
CM	0.587	0.947	0.808	2.147	0.210
WS	0.597	0.218	0.637	0.236	-0.040
ES	0.621	0.495	0.64	0.491	-0.019
CP	0.977	0.150	0.63	0.487	0.347 ***
CC	0.977	0.150	0.278	0.452	0.699 ***
CI	0.508	0.501	0.056	0.231	0.452 ***

**Note:** \*\* and \*\*\* indicate statistical significance at 5% and 1%, respectively.

Table 2 presents the characteristics of sugarcane cultivators across several factors. Most farmers fall within the 31-40 years old category (49.6%), followed by those aged 41-50 years old (30.8%). Regarding extension services, most farms reported no engagement (92%), while a small percentage reported a rating of 1 (4.6%). Regarding the number of workers, most farms employed 2-3 workers (40.11%), followed by 4-5 (23.83%) and 6-10 (24.70%). Regarding the cultivated area, the highest proportion of farms fell within the 11-20 acres category (34.96%). These findings provide valuable insights into the age distribution of farmers, engagement with extension services, worker count, and cultivated area, which can inform agricultural support and decision-making processes within the sugarcane farming industry.

### 3.2 Measurements for Adaptation to Climate Change and Sugarcane Production Equations

The following equations are generated and adaptively selected based on ESR model estimates ([Khanal, 2018](#)). The ESR model findings are shown in Table 3, and the assessment of the adaptation selection equation is shown in the second column, which illustrates the factors that influence climate adaptation. The statistically significant, positive area coefficient indicates that growers with larger parcels are more likely to use climate adaptation approaches.

Both the optimistic and statistically substantial impacts of climate knowledge and perception suggested that sugarcane farmers who were aware of and exposed to climate were more inclined to adjust. The ESR for crop yield was calculated using the evaluated values in columns 3 and 4 of Table 3. Because the observed correlation coefficients were not statistically distinct from zero, sample selection bias might not have existed in the research population ([Piao, 2010](#)).

Furthermore, it was suggested that the samples were heterogeneous, as evidenced by differences in the coefficients of the sugarcane production equation between adopters and non-adopters ([Antwi-Agyei, 2018](#); [Khanal, 2018](#); [Piao, 2010](#)). According to Table 3 findings, both adopter and non-adopter groups' lower sugarcane yields can be attributed in part to the area. The yields of sugarcane for adopters and non-adopters, however,



appeared to be affected differently by factors such as education, gender, household size, organic manure use, irrigation facilities, and cost. Results in three columns showed that irrigation systems and schooling are crucial determinants of adopters' ability to produce sugarcane. Additionally, home labour input seems to affect non-adopter sugarcane production.

**Table 3:** Displays the outcomes of a regression analysis on the production of sugarcane and the endogenous switching of climatic adaptability.

Variable	Adaptation		Sugarcane Production (Log)			
			Adopters		Non-Adopters	
	M	S. D	M	S. D	M	S. D
G	0.263	1.10	-0.003	-0.07	0.118 **	2.55
A	-0.002	-0.20	0.001	0.58	0.000	0.06
ES	-0.017	-0.07	0.065 *	1.91	0.060	1.15
HS	0.029	0.062	0.022	0.027	0.005	0.023
CM	0.588	0.948	0.809	2.146	0.219	0.588
WS	-0.616	-1.36	0.070	0.98	0.138	1.48
ES	0.028	0.063	0.021	0.026	0.005	0.023
LA	0.298 *	1.85	-0.021 **	-2.55	-0.073 **	-2.17
SU (log)	0.005	0.023	-0.053	-1.28	-0.098	-0.85
TC (log)	-0.003	-0.07	-0.007	-1.10	-0.006	-1.13
HL(log)	0.002	0.59	-0.009	-1.19	-0.105 ***	-2.97
EC (log)	0.022	0.027s	-0.007	-1.35	-0.001	-0.10
FC (log)			0.068	1.26	0.045	0.64
PU (log)			0.042	1.57	0.051	1.27
IC (log)			0.012 ***	4.88	-0.002	-0.27
Rent (0/1)	0.157	0.43	-0.007	-1.35		
CP	1.877 ***	4.91	0.029	0.062		
CI	1.259 ***	4.65				
CONS	-0.923	-1.34	8.189 ***	16.63	9.613 ***	9.81
$\sigma_1$			-1.402 ***	-29.70		
$\sigma_0$					-1.999 ***	-10.83
$p_1$			0.347	1.54		
$p_0$	Adaptation				0.584	0.70

Note: The symbols \*, \*\*, and \*\*\* denote statistically significant differences at 10%, 5%, and 1%, respectively.

The possibilities for sugarcane output by growers are shown in Table 4 together with estimates of the impacts of average treatment and possible heterogeneity. The predicted sugarcane yield shown in columns (a) and (b) is seen in the sample. If the adopter chooses not to adopt, column (c) represents the anticipated sugarcane yield, and cell (d) represents the potential sugarcane yield if the non-adopter decides to adopt. Adopters will enhance yields if they do not adapt.

Additionally, if non-adopters did not adapt, they would lose. Additionally, Table 4's final row demonstrates that under the counterfactual scenario, adopters' productivity will be noticeably higher than that of non-adopters. Significant heterogeneity effects imply that, regardless of climate concerns, adopters are more "productive wells" than non-adopters due to heterogeneity. These results suggest that, if it increases growers' yields, climate change adaptation benefits agricultural output. Our findings are consistent with those reported in Nepal (S. Di Falco et al., 2011), which also indicated that crop production increases with adaptation. The influence of adaptation on agricultural productivity, however, varies in strength. For instance, (S. Di Falco et al., 2011) reported that adaptor farmers in research produced considerably greater yields (33%) than our example, which saw a 24% boost. Comparable, their analysis indicated that farmers who did not adapt would have had a 22% higher output if they had; however, in our instance, this number is far lower at 5%. The disparity in estimates may be due to variations in agricultural practices and ecological characteristics.

**Table 4:** Effects of treatment and heterogeneity on adaptation's potential effects on average sugarcane production.

Sub-samples	Stage of Decision		Effects of Treatment
	To-Adapt	Not-to-Adapt	
Adopters	(a) 1177.12 (11.301)	(c) 1214.530 (12.010)	TT= -37.41 *** [-2.677]
Non-adopters	(d) 1331.575 (21.238)	(b) 1486.767 (26.423)	TU= -155.192 *** [-5.168]
Heterogeneity influences	BH <sub>I</sub> = 189.192 *** [1.765]	BH <sub>2</sub> = 360.212 *** [1.628]	TH = -171.02 [-4.289]

Note that the \*\*\* symbol denotes 1% statistically significant. TT stands for the treatment effect (adaptation) on the treated (for example, rural households that adapted); TU stands for the treatment effect (for example, adaptation) on the untreated (i.e., farm households that did not adapt); BH<sub>i</sub> stands for the effect of base heterogeneity for rural households that adapted I = 1) and did not adapt I = 2); and TH stands for (TT-TU), or transition phase heterogeneity.

#### 4. Discussion

Past research has shown that several agricultural sector adaptation strategies have produced inconsistent results (Adger, 2003; Müller et al., 2017). Why did adaptation strategies result in adverse findings and fail to reduce environmental risk? Here are some significant reasons why essential adaptation measures have fallen short. First, as reported by (Liu et al., 2010). The volume and frequency of watering should be appropriately reduced throughout the crop growth phase (Liu et al., 2010). Therefore, if intensive irrigation is used at the wrong times, the adaptive activities producers take to increase irrigation frequency and volume in response to decreased rainfall might negatively affect sugarcane production. Second inputs of fertilizers are important for cumulative crop yields in Ethiopia and Nepal (Abid, 2015; Deressa, 2009). However, the use of inorganic fertilizers in Pakistan is higher than in Ethiopia and Nepal (Rehman, 2019). Numerous studies have found that small farmers face high risks and are willing to use additional fertilizers to mitigate the potential drastic effects of climate change on farm productivity (Below et al., 2015; Jat, 2014; Maponya & Mpandeli, 2012).

However, local farmers in Pakistan continue to misuse fertilizers due to limited technical information, the absence of an agricultural workforce, and the recurrent usage of old practices. Chemicals and pesticides cause serious environmental harm (Australian Bureau of, 2005). The unnecessary use of chemical fertilizers reduces arable land fertility, pollutes water resources (Australian Bureau of, 2005), and undermines sustainable agricultural development (Rehman, 2019). Hence, adaptation activities that enhance fertilizer use in response to climate change hazards can increase food production under conditions of poor soil fertility. However, excessive use of chemical fertilizers and pesticides by growers can drastically impact sugarcane yields and undermine the ecosystem. Third, in response to low rainfall and increased pest and disease pressures, many producers have switched to deficit- and disease-resistant sugarcane varieties. However, improved sugarcane varieties tailored to complex ecological settings may result in crop failure, and disease- and drought-resistant varieties may not yield well.

Adaptation is essential to reduce the impacts of climate change, maintain farmers' incomes, and ensure sustainable agricultural development (Reidsma, 2015). The Pakistani agricultural sector faces severe ecological and resource constraints, such as limited irrigation systems and degraded ecosystems, that may be beyond the reach of small farmers despite their adaptive capacity. Consequently, the local government of Punjab should take the necessary steps to help rural farmers take appropriate adaptation measures, and the government should closely monitor infrastructure development, farming classes, farming discipline, and "water-saving organizations, agricultural information, and quality management systems for agricultural products. Then, rural small growers may waste energy and resources and even suffer losses if they fight alone. The results of further research show that, on the one hand, for growers' sake, sustainable farming growth requires the design of irrigation and fertilization engineering approaches to improve the efficiency of fertilizer and water use. Also, focus on research and hybridization of varieties with better genetic resources, which can help increase tolerance to abiotic or biotic stresses and improve sugarcane production under adverse ecological conditions. In addition, governments need to ensure that scientific knowledge, guidance on prevention and use, and materials are communicated to farmers and rural communities in a way that is easy and safe, to achieve the best outcomes in the current climate. This experiment examines rural growers' perceptions of climate change, adaptation, and its



influence on sugarcane yields. Further research will be done on the explanation for this miracle and whether it suggests a widespread issue affecting several regions or breeds.

## 5. Conclusions

Climate change is an environmental risk common to all commercial sectors, particularly agriculture. In addition, in Pakistan, decades of subtle changes in the global and local environments have strongly influenced production systems and incomes. Probable defeats at the farm level could be mitigated through appropriate adaptation to climate change. Pakistan is facing dangerous weather phenomena, such as unusually heavy rains and flash floods, which are causing significant damage to crops and growers' property. These sufferers are likely to rise as climate impacts intensify in the future. Given the significance of the agricultural sector to the economy and rural sources of revenue, the implications of climate adaptation approaches are far-reaching. While adaptation approaches are vital, not all small farmers apply them. Most farmers and related urban populations in developing republics, including Pakistan, are heavily dependent on agriculture. Hence, adapting to the significant impacts of climate change could be detrimental to improving rural food security and protecting households' livelihoods.

The primary objective of the present study was to examine climate self-adaptation among rural growers and its effects on sugarcane production. Based on a survey of 390 respondents in Punjab, Pakistan, the findings indicate that approximately 80% of growers are aware of climate change, and nearly 70% have implemented adaptation strategies. Factors such as farm areas, perceptions of climate, and information provided by farmers significantly influence adaptation decisions.

Table A2. Climate-related risks (temperature and precipitation) affect sugarcane productivity and yield. Adapted from farmers' reported experiences and documented climate-smart adaptation practices in sugarcane cultivation. However, sugarcane farmers still lack adequate adaptation measures, resulting in increased irrigation and greater use of compost and pesticides.

The results show that climate adaptation practices have substantially increased sugarcane yields, although some farmers may exhibit maladaptive responses to climate change. Overall, climate change has negatively affected the production of staple crops worldwide, including in Pakistan. With a rapidly growing population and a large proportion living below the poverty line, the country faces serious food security challenges. Therefore, governments should develop sustainable strategies to address these issues and ensure long-term food security.

Table A3. Farmers' perceptions of climate change, its effects on sugarcane yield, and corresponding adaptation strategies (% of respondents). The table is based on field survey data summarizing growers' climate perceptions, yield impacts, and adaptation responses in sugarcane farming systems. Sugarcane yields may increase because of effective adaptation to climate change.

In the short term, crop output can be maintained through access to information on available resources and appropriate adaptation strategies. Combinations of adaptation measures outperform individual measures in supporting effective adaptation. National sugarcane production could increase through climate adaptation, thereby improving producers' net financial positions and overall living standards. Based on regional farm requirements and climate challenges, tailored recommendations for adaptive support should be developed. The study findings demonstrate that increased yields are a major benefit of adopting adaptation strategies.

However, inadequate development initiatives, limited adaptation measures, and insufficient information remain significant barriers to accessing support. With the cooperation and active involvement of governmental and non-governmental organizations, these limitations can be addressed by improving access to climate information, raising awareness of adaptation strategies, educating sugarcane growers, and strengthening their adaptive capacities. Given the importance of smallholder farmers in rural Pakistan, targeted strategies to reduce their resource constraints deserve special attention. Agriculture requires both localized climate-specific practices and macro-level support, including resource availability, pricing policies, and environmental considerations. More effective adaptation to environmental change depends on policy decisions that will have

significant long-term impacts on agricultural productivity. Therefore, future research should consider these constraints. This study contributes to the existing literature on the importance of climate-smart agriculture planning in low-income and emerging economies, particularly Pakistan. The knowledge and skills of smallholder farmers play a critical role in reducing the impacts of climate change on sugarcane yields, as they influence the effectiveness of institutional programs. These factors should be incorporated into the design and implementation of future policies. Overall, additional national-level studies are needed to inform policy development and support sustainable adaptation choices for smallholder farmers in Pakistan.

**Table A1:** Estimates of the parameters and validity evaluations of the assessment methods.

Variables Name	Probit Model <sup>a</sup>	OLS Model <sup>b</sup>
	Adopt 1/0	Non-Adopt Yield/ha
	Mean (S.D)	Mean (S.D)
G	0.244 (0.236)	0.117 ** (2.08)
A	-0.003 (0.0012)	0.000121 (0.04)
ES	0.033 (0.0230)	0.089 (1.45)
WS	-0.437 (0.0335)	0.144 (1.31)
ES	0.444 (0.110)	0.207 (1.48)
LA	0.015 (0.010)	-0.059 (-1.38)
CP	1.878 *** (0.0333)	0.011 (0.056)
CI	1.229 *** (0.262)	-0.136 (0.0109)
(log) SU	0.144 (1.31)	-0.029 (-0.30)
(log) TC	0.124 (1.21)	0.034 (0.40)
(log) HL	0.205 (1.41)	0.00365 (0.s)
(log) EC		-0.071 * (-3.02)
(log) PU		0.00104 (0.12)
(log) FP		-0.0138 (-0.22)
(log) IC		0.054 (1.14)
Rent (0/1)	0.121 (0.224)	
CONS	-0.640 (0.512)	8.725*** (8.25)
Valid test on data sources	$\chi^2 = 77.55$ ***	F-stat. = 1.77
Number of respondents	390	51

Models a and b (pseudo R2 = 0.304; R2 = 0.445). Statistical validity is indicated by the symbols \*, \*\*, and \*\*\* at 10%, 5%, and 1%, respectively.

**Table. A2:** Perception of sugarcane growers on climate change and its impact on sugarcane production and adaptation actions

Climatic limitations	Related Climate risks	Growers have a substantial influence on sugarcane productivity	Farmers' adaptation activities
Temperature	Improved temperature	A greater need for irrigation results from increased evapotranspiration. increased insect and disease infestation, new pests and illnesses introduced, reduced grain quality, decreased yield	Cultivate short-lived cultivars, cultivate pest- and insect-resistant cultivars. Variety planting locations should be changed in the irrigation system, weeding should be increased, and additional pesticides should be used.



<b>Precipitation</b>	<p>The rainfall schedule has changed, with the monsoon starting later than usual and less access to the surface. Groundwater is subject to long periods of drought, and floods and landslides are brought on by infrequent but intense rainfall.</p>	<p>Poor germination, reduced tiller count, delayed panicle starts, and decreased grain and panicle due to water stress, implantation delay, water shortage for irrigation, crop loss brought on by heavy rain or hailstorm, destruction of irrigation canals and water resources, eroding soil, decline in soil quality, and reduced yield.</p>	<p>Techniques for conserving soil include minimizing tillage, Seed priming, relocating varieties' planting sites, changing the planting date, sowing or harvesting crops with direct seeding, increasing seed production, short-duration growth, and Selecting Varieties that cultivate drought-resistant plants. To enhance/increase the usage of chemical fertilizers, improve/increase the usage of farmyard manure, build waterways when there is a lot of rain, cultivate flood-resistant plants, and change to a different crop</p>
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**Table. A3:** Growers' awareness of climate change and its impact on sugarcane production, and the proportion of growers' adaptation measures.

Climate change perception	%	Climate change effect on sugarcane yield	%	Adaptation approaches	%
No change	8	No impact	16	No change	17
Reduced precipitation	62	Climate change effects on sugarcane yield	13	Change sugarcane varieties (drought tolerant and disease)	23
Enhanced drought consequences	64	No impact	30	Expand pesticide and fertilizer utilization	48
Enhanced perception	11	More infestation of insects and diseases	41	Afforestation	6
Enhanced temperature	45	Required more irrigation	63	Purchase climate protection	10
Enhanced heavy rainfall (flood)	4	Sugarcane loss due to precocity	27	Drill the deep well	3
Reduced temperature	16	Yield decreases due to lodging	41	Change the seeding and harvesting date	7

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### **Data availability**

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

### **Declarations**

#### **Ethics approval and consent to participate**

This study was conducted in accordance with ethical guidelines, and all necessary approvals were obtained.

#### **Consent for publication**

Not applicable.

#### **Competing interests**

The authors declare no competing interests.

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