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Climate Change Impacts on Sugarcane Productivity: Adaptive Strategies for Resilient Agroecosystems

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ABSTRACT

Climate change, water shortages, and elevated temperatures make it hard to cultivate sugarcane sustainably especially in the semi-arid areas. Climate-smart agriculture can serve as an effective measure of improving the productivity of crop while making it resilient to environmental stresses. Hence, the current study was conducted for evaluating the performance of the selected climate smart practices such as drip irrigation, wheat straw mulching, and heat-resistant sugarcane variety on sugarcane yield in Jaranwala, District Faisalabad, Punjab, Pakistan. The trial was arranged in the Randomized Complete Block Design (RCBD) with four treatments and three

replications. The treatments were the conventional farmers' practice (CPF-237), drip irrigation (CPF-237), wheat straw mulching at 8 t ha⁻¹ (CPF-237), and heat-resistant sugarcane variety (CPF-249) in basin irrigation. The yield of the sugarcane crop was measured by harvesting the net plot area at crop maturity and then calculating the cane weight in tons per hectare (t ha⁻¹). The data was subjected to analysis of variance (ANOVA) and the means of different treatments were compared using the Least Significant Difference (LSD) test at 5% probability. The results indicated that all climate-smart practices showed significant improvement in cane yield when compared with conventional farmer practice. The maximum cane yield was observed in case of drip irrigation (72 t ha⁻¹), heat tolerant variety (70 t ha⁻¹), and wheat straw mulching (68 t ha⁻¹), while the minimum cane yield was obtained in case of conventional farmer practice (55 t ha⁻¹). The findings show that the drip irrigation improved cane yield by 30.9%, heat tolerant variety by 27.2%, and wheat straw mulching by 23.6% than control.

Keywords— Sugarcane, Climate-smart agriculture, Drip irrigation, Wheat straw mulching, Heat-tolerant variety, Sugarcane yield, Sustainable agriculture

1. Introduction

Sugarcane, *Saccharum officinarum* L., is one of the most important commercial crops grown in the tropics and sub-tropics of world. It is the main raw material for sugar production (around 80% of the world's sugar) and is also used as a valuable source of bioethanol, bioelectricity, paper, animal feed, and other value-added products. Sugarcane is important for food security, renewable energy production and sustainable rural development due to its high biomass production and various industrial applications. World-wide, sugarcane is grown in over 100 countries with a variety of climatic conditions, the top some of the sugarcane producers are the countries of Brazil, India, China, Thailand and Pakistan. The crop is an important source of employment, industrialization and foreign exchange earnings for the nations. Besides sugar production, sugarcane processing also produces economic valuable by-products like molasses, bagasse, press mud, ethanol and electricity from the cogeneration, which enhances the profit and sustainability for the sugar industry (Rasool & Arslan, 2019). Sugarcane is the second most significant cash crop of Pakistan after cotton and forms a significant share of the agricultural economy in Pakistan. The crop is raw material for the country's sugar industry, which employs thousands of farm households and several industries in the country's transportation, cultivation, and processing sector. Punjab enjoys the best agro-climatic conditions and it has a large irrigation network and thus also the largest share in the national production of sugarcane, accounting for the highest percentage of the planted area and yield. Even though the sugarcane is an important crop in Pakistan, the productivity level of it is still not at the global level. According to the latest report by FAO released recently, Pakistan is one of the highest producing countries in the world due to the total production of sugarcane, but the yield per hectare is comparatively low. Irrigation system inefficiency, poor use of better cultivars, water shortages, pest and disease pressures, soil degradation, and poor crop management have

been blamed as these are the factors that have contributed to the productivity gap. These are important to overcome to enhance the profitability of the farm and ensure sustainable sugar industry.

Sustainable sugarcane production systems have been further emphasized by the emerging demand of population growth, climate variations and increased competition for freshwater. There has been a great focus on research and policy aimed at making agriculture more productive and water efficient and at improving its resilience to environmental stresses. Therefore, the use of climate smart agronomic practices such as adoption of efficient irrigation technologies, soil moisture conservation technologies and stress tolerant cultivars have been suggested as the potential solution to boost sugarcane production while preserving natural resources and promoting sustainable agriculture. Water is one of the most pressing challenge for sustainable sugarcane production globally and in arid and semi-arid regions, where irrigation is necessary to ensure sugarcane productivity. Sugarcane is a crop that demands a lot of water and needs plenty of moisture in the soil during its vegetative and grand growth phases to maximize biomass and sucrose yield. But, the growing competition for fresh water, dwindling ground water supplies, poor irrigation practices, and a fast-growing population have placed strain on fresh water supplies for agriculture. Therefore, water-use efficiency is a key focus for maintaining sugarcane production under future climatic conditions (Mazhar et al., 2025).

Because Pakistan's agriculture is highly dependent on Indus River Basin irrigation, it is seen as one of the most vulnerable countries to water scarcity and climate change. This irrigation network is one of the world's largest, however weather extremes such as droughts, and excess groundwater extraction have significantly curtailed water supply for crop production, and the variability of river flows has continued to increase. Climate projections also suggest that increased temperatures will occur in Punjab and Sindh, with changes in precipitation and increased extreme weather events, which will negatively impact the productivity of sugarcane by putting additional stress on crop water needs and decreasing the efficiency of irrigation. The direct effects of climate change on the physiology of sugarcane include changes in photosynthesis, transpiration, and sucrose accumulation. High temperatures above the optimal crop growth range will speed up the evapotranspiration rate, reduce developmental stages, and lead to higher physiological stress, especially during tillering and cane elongation. Excessive heat stress can decrease the growth of stalks, diameter of the canes, dry matter production and ultimately commercial cane yields. Added to these, irregular rainfall and extended dry spells exacerbate these impacts as they reduce soil moisture availability during sensitive growth periods (Chohan, 2019).

The future climate scenarios have been simulated in the Indus River Basin and it has been found that the climate scenarios in the future will have significant impacts on the water productivity of sugarcane and irrigation demand. Increase in maximum and minimum temperature are projected to affect evapotranspiration and water use of crop for major sugarcane growing areas of Pakistan under Representative Concentration Pathways (RCPs) 4.5 and 8.5. The results confirm the need to implement irrigation water management systems that would enhance irrigation efficiency and conserve scarce water resources, otherwise, traditional irrigation methods will be less and less

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efficient. In addition to water constraint, the effects of climate change on sugarcane production are also contributing to secondary constraints such as the increased occurrence of pests and diseases, soil salinity, nutrient-use inefficiency, and degradation of soil physical properties. All these factors together lead to reduced productivity and resilience of traditional production systems (Alvar-Beltrán et al., 2021).

Therefore, recent reviews have pointed out the importance of using efficient irrigation technologies and stress tolerant cultivars, enhanced nutrient management and soil conservation practices as component of climate smart agriculture systems to maintain the productivity of sugarcane in the face of environmental changes. The increasing effects of water scarcity and climate variability are a clear indication that the conventional methods of producing sugarcane are not able to meet the productivity needs of the future. The adoption of the resource-efficient technologies like drip irrigation, conservation mulching and heat-tolerant varieties is a practical solution to improve the water-use efficiency, mitigate the climate-related risks and ensuring long-term sustainability of sugarcane production, specifically in semi-arid areas like Faisalabad (Rasool & Arslan, 2019).

Under the condition of water scarcity, drip irrigation technology has been developed as one of the most efficient irrigation technologies for sustainable sugarcane production. Drip irrigation is not flood or surface irrigation, but the water is transported directly to the crop root zone with a network of emitters, which helps to reduce evaporative losses, deep percolation losses, and runoff. This careful application promotes improved soil moisture distribution, increased nutrient availability and optimizes rooting space, leading to greater water-use efficiency and crop productivity. Sugarcane is one of the most water-consuming field crops, and irrigation inefficiency due to poor irrigation practices can cut irrigation efficiency and profitability in half. Recent reviews have highlighted that the use of drip irrigation has the potential to significantly decrease irrigation water use, and increase cane yield, sucrose content and fertilizer-use efficiency by fertigation. Moreover, drip irrigation is an eco-friendly irrigation method compared to flood irrigation due to the decrease in weed growth, less leaching of nutrients and better soil aeration (Anjaly et al., 2024).

A number of field studies have shown beneficial effect of drip irrigation on productivity of sugarcane under various agro-climatic conditions. The water productivity and cane yield were found to be significantly higher under drip fertigation than conventional irrigation method and this improvement was attributed to the synchronization of water and nutrient supply in the crop during its growth period by Prabhakar Reddy et al. (2018). Alvar-Beltran et al. (2021) found, similarly, that an increase in irrigation efficiency via adoption of advanced irrigation technologies is vital for future climate scenario in Indus River Basin in Pakistan to maintain productivity of sugarcane (Alvar-Beltrán et al., 2021). In recent times, various developments have been made in the management of drip irrigation, which aim at maximizing water productivity through proper irrigation management and application techniques. In the case of cane crops, for instance, the use of pulsed drip irrigation has demonstrated to be more economical than conventional drip irrigation for water usage and to enhance cane growth, sugar yield and ethanol production. Similarly, subsurface drip irrigation has shown to be more

water productive with its ability to provide sufficient moisture to the active root zone and minimize evaporative water loss, especially in water limited environments (Reddy et al., 2018).

Drip irrigation can also help improve the productivity of the land and promote climate-smart agriculture by increasing the land's resilience to drought and water scarcity. Efficient water delivery helps crop keep physiological activity when water availability is limited, which decreases climatic stress impacts. A recent comprehensive review supported that drip irrigation in combination with improved nutrient management, conservation and cultivar resistance to climate change is one of the most promising practices to improve water productivity of sugarcane while ensuring sustainable agricultural development in response to climate change (Kaushal et al., 2012). Given the growing scarcity of freshwater resources in Pakistan, especially in Punjab, the use of drip irrigation could be beneficial to the productivity of sugarcane and conserve the irrigation water. So, the assessment of the effectiveness of drip irrigation vis-à-vis the farmer's practice is very important to understand appropriate management strategies for climate smart irrigation that would increase the yield and sustainability of the agriculture (de Menezes et al., 2024).

Mulching is known to be one of the most important conservation practices that promote soil moisture retention, soil temperature control, weed control and soil physical properties. Wheat straw is one of the organic residues that is widely available in the production of cereals, making it one of the cheapest and least polluting mulching materials. Wheat straw left on the soil surface provides protection to prevent soil evaporation, decreases runoff, enhances infiltration of rainwater, and dampens soil temperature extremes. The improvements promote a more favorable soil environment for root growth and microbial activity to ensure crop productivity under water-limited circumstances. In semi-arid or arid areas where the rain is irregular and its evaporative demand is high, the effectiveness of wheat straw mulch is of major value (Akhtar et al., 2018). Many field trials have been conducted and have shown that the straw mulch does indeed hold more water in the soil than does bare soil, in that it lowers the loss of water from the soil surface by evaporation. Better soil water availability helps keep crops in a physiological state to withstand periods of dryness, increases nutrient uptake, and aids in yield stability and increased biomass production. Moreover, straw decomposes slowly and releases organic matter into the soil, which helps to promote soil structure, aggregate stability and long-term water holding capacity (Gmach et al., 2019).

Sugarcane residue or straw mulch has been found to enhance the soil water regime and sugarcane performance in sugarcane cultivation especially under drought conditions. Aquino et al. (2018) found that the cane yield was significantly higher under sugarcane straw retention than under complete removal of sugarcane straw when water was scarce. They said these gains were due to better soil moisture conservation and lower evaporation and that residue retention is a good drought stress management practice that does not impact cane quality. Similarly, long-term trials in Brazilian sugarcane systems revealed that over milling caused deforestation of soil water, and caused water stress to last longer; with adequate levels of surface residue soil water was maintained and conditions for crop growth were improved (Wang et al., 2018).

In addition to conserving water, wheat straw mulch has the additional benefit of

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reducing erosion, moderating soil temperature changes, controlling weeds and increasing soil biological activity. These impacts result in better nutrient cycling and increasing the climate resilience of cropping systems in response to the changing climate. Hence, residue mulching emerged as a key element of climate smart agriculture, as in addition to increasing resource-use efficiency and soil quality, it has a positive impact on production risk due to drought and heat stress. Hence, recent reviews have suggested the use of straw mulching along with judicious management of the sugarcane irrigation system and use of better cultivars to optimize water productivity for sustainable sugarcane cultivation in future climatic conditions (Sheini-Dashtgol et al., 2020).

With the rise in the frequency of heatwaves and exposure to high temperatures, it is becoming a significant constraint in sustainable sugarcane production globally. Sugarcane, a C4 crop, has a relatively high photosynthetic efficiency, however, temperatures above the optimum growth range have a negative impact on physiological, biochemical and metabolic processes that lead to cane growth and sucrose accumulation. Hence, the development and use of heat-tolerant sugarcane cultivars in the context of climate change has emerged as a major adaptation measure to ensure productivity in the new climate. Heat stress can impact all sugarcane growth stages, with impact on reduction of chlorophyll stability, efficiency of photosynthesis, stomatal conductance, relative water content, and an increase in oxidative damage of plant tissues. Such physiological changes lead to reduced biomass build-up, stalk elongation, and cane and sugar production (MANN, 2022). Experimental investigations have confirmed that heat tolerant cultivars have higher chlorophyll content, better membrane stability, higher antioxidant activity and better photosynthetic performance under high temperature conditions than heat susceptible cultivars. In the last few years, the advancement in sugarcane breeding has been expedited using conventional breeding techniques coupled with genomics, molecular markers, high throughput phenotyping and physiological screening to develop climate resilient cultivars. These methods give breeders the ability to select for genotypes with improved adaptation to heat, drought and other abiotic stresses that would also have good cane yield and sucrose content. Current breeding programs thus focus on enhancing stress resistance, whilst also improving agronomic traits to ensure the continued production of a stable crop in the face of changing climatic conditions (Dinesh Babu et al., 2022).

Biotechnology has also proved to be a useful tool for the improvement of heat tolerance in sugarcane, besides conventional breeding. The development of functional genomics, transcriptomics, gene editing and molecular breeding techniques has led to better understanding of the genes and regulatory pathways involved in thermotolerance and that are sensitive to stress. These technologies offer the opportunity to create cultivars that are more resistant to long-term heat stress, better osmotic adjusters and have a higher antioxidant defense system. The use of modern biotechnological methods in conjunction with traditional breeding will be increasingly important for the creation of more climate-resilient varieties of sugarcane for tomorrow's agriculture, according to recent reviews (Mehdi et al., 2020).

Heat tolerant varieties provide some agronomic and economic benefits in addition to yielding at high temperature. Stress-tolerant cultivars tend to perform more consistently

in different stress environments while using water more efficiently, have a better ability to ratoon and lower the risk of production under environmental extremes. The recent reviews on climate adaptation in sugarcane have consistently suggested the need for heat-tolerant cultivars as an integral part of climate-smart agriculture, along with efficient irrigation and better soil management practices. With the expected rise in temperature in South Asian region, it is necessary to evaluate and use heat-tolerant varieties of sugarcane to maintain cane productivity in Pakistan. Thus, comparison of improved heat-tolerant cultivars in local agro-climatic conditions can give useful information for selecting suitable climate-resilient production strategies that will increase productivity and decrease vulnerability due to future climate change (Kohila & Gomathi, 2018).

The latest research in sugarcane has shown that through implementing climate-smart technologies, such as drip irrigation, residue mulching, nutrient management, and stress-tolerant varieties, water-use efficiency, productivity, and stress resilience can be significantly enhanced. However, most published studies have examined these management practices individually and under certain environmental conditions. Thus, little information is available about their comparative performance under the same agro-climatic condition, especially in regions with limited water resources and rising temperatures, which are suitable for sugarcane cultivation. Therefore, there is a lack of information about their comparative performance under similar agro-climatic conditions, especially in semi-arid sugarcane growing areas, where water stress and high ambient temperatures are limiting factors for productivity (Dingre, 2023).

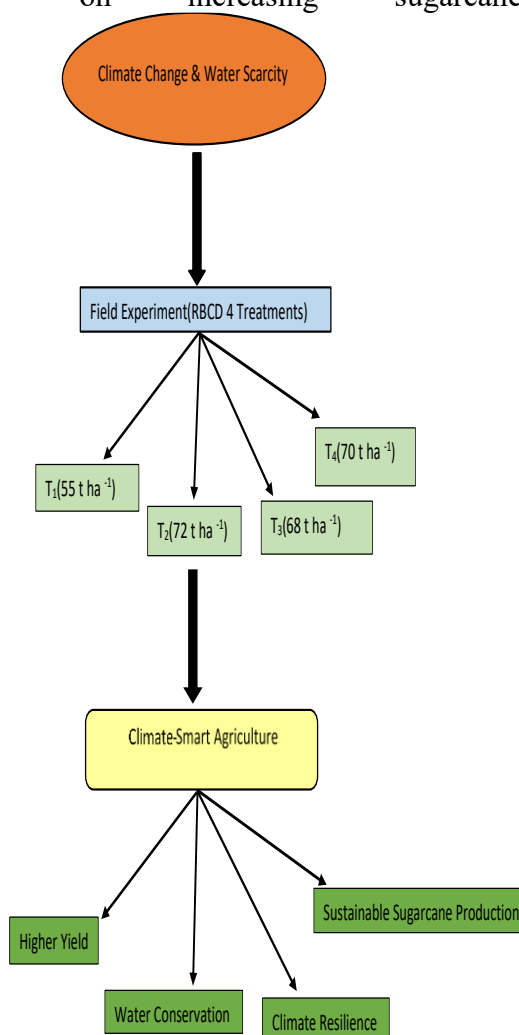
While the improvement in irrigation efficiency and cane output associated with drip irrigation has been documented consistently, the improvement in soil moisture conservation associated with residue mulching has been demonstrated, but most studies have investigated one or the other technology in isolation of the other technology and conventional farmer practices. Likewise, there is significant progress in the development of heat-tolerant sugarcane cultivars via conventional breeding and modern genomic techniques, but few comparative field studies of these cultivars with other climate-smart production strategies under identical production conditions. This restricts the capacity of some farmers and policy makers to determine the most appropriate and economically viable adaptation strategies to be pursued in specific agro-ecological areas (Mazhar et al., 2025).

In the context of Pakistan, where the production of sugarcane is being increasingly challenged by increasing temperature, irregular rainfall and reduction in freshwater, extensive comparative research based on both efficient irrigation practices and soil moisture management coupled with climate-resilient cultivars is limited. In recent years, several reviews have pointed out the need for location specific assessments of climate smart technologies to provide evidence-based recommendations for increasing the productivity of sugarcane while maximizing the use of resources during projected climate change (Meena et al., 2022).

Thus, the present study was conducted to evaluate the effect of four management practices (conventional farmer practice (control), drip irrigation, wheat straw mulching, and heat-tolerant sugarcane variety) on productivity of sugarcane under agro-climatic conditions of Jaranwala, Faisalabad, Pakistan. The study aims were to:

Compare the yield of sugarcane under conventional and climate smart agronomic practices.

1. Assess the impact of drip irrigation, wheat straw mulching and heat tolerant variety on increasing sugarcane prod



activity.

2. Find the best possible climate smart management practices to support sugarcane cultivation in the semi-arid environments.
3. Develop scientific information for water management and climate adaptation plan

Fig 1. Graphical Abstract of Climate-smart agricultural practices improve sugarcane productivity and enhance resilience under semi-arid conditions.

for sugarcane crop in Pakistan.

2. Material and Methods

2.1 Study Area

The field experiment was carried out at the Agronomic Research Area, Jaranwala, Faisalabad, Punjab, Pakistan during 2021/23 cultivation period. The experimental site is situated in the agro ecological zone of semi-arid, hot summer, mild winter and low

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to moderate annual precipitation region of Central Punjab. The region gets hotter during the sugarcane growing season and in summer months the maximum temperatures are often above 40°C, which makes it suitable for testing the water-limited climate-smart management practices in the region.

The soil type of the experimental site was classified as ****sandy loam**** soil type that represents the major agricultural soil of Faisalabad region. Sandy loam soils are well drained, have a moderate water holding capacity, and are well aerated, and can be used for the growing of sugarcane as long as proper irrigation and nutrient management are employed (Alvar-Beltrán et al., 2021).

The experiment was carried out under field conditions to assess the performance of the tested climate smart interventions such as drip irrigation, wheat straw mulching and heat tolerant sugarcane variety against the conventional farmer practice. The agronomic practices adopted for sugarcane cultivation in Punjab were adhered to throughout the experimental period, unless mentioned in the treatments.

2.2 Experimental Design and Treatments

The experiment was conducted to assess the effectiveness of some climate-smart management practices for enhancing sugarcane productivity under field condition. The study has compared three interventions, namely, drip irrigation, wheat straw mulching, and heat-tolerant sugarcane cultivar, to a farmer practice.

The experiment was designed as a Randomized Complete Block Design (RCBD) with four treatments and three replications. Each experimental plot measured ****6 m × 5 m (30 m²)****. Experimental error due to field variability was minimized by randomization of treatments within each replication (Gomez & Gomez, 1984).

The four treatments in the study were:

T₁: Conventional farmer practice of sugarcane variety CPF-237 (Control).

In the second stage (T₂), the sugarcane variety CPF-237 was employed in drip irrigation.

T₃: Wheat straw mulching (8 t ha⁻¹) with the sugarcane cultivar CPF-237

T₄: Sugarcane variety CPF-249 which is heat tolerant.

The individual or independent effects of these climate smart interventions were assessed rather than their combined or interactive effects. Each treatment was a unique management, designed to improve sugarcane yield in a changing climate with variable water availability.

The planting of sugarcane was done on 20 February 2021, on rows 90cm apart with 30cm between plants, as per the recommended agronomic practices for the region. Harvesting of the crop was completed on 15 December 2023 when it was physiologically mature (Farooq et al., 2020).

The experiment was conducted to investigate the individual impacts of these climate-smart interventions, not their combined or synergistic impacts.

Table 1. Experimental Treatments of different variety of sugarcane and their mulching effect

Treatment	Variety	Irrigation	Mulching
T ₁	CPF-237	Basin Irrigation(Control)	No mulch

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T ₂	CPF-237	Drip Irrigation	No mulch
T ₃	CPF-237	Furrow Irrigation	Wheat Straw (8 t ha ⁻¹)
T ₄	CPF-249	Basin Irrigation	No mulch

2.3 Crop Establishment and Management

The experiment was conducted following the recommended agronomic practices for sugarcane farming in Punjab, Pakistan. In the control (T₁), drip irrigation (T₂) and wheat straw mulch (T₃) treatments, the recommended commercial variety CPF-237 of sugarcane was considered. However, the heat tolerant variety CPF-249 was assessed for the effect of treatment T₄. Both these varieties have been recommended for farming in Punjab owing to their desirable agronomic properties.

The crop was sown on 20th February 2021, with row spacing being 90 cm and the distance between plants being 30 cm. Identical land preparation and crop establishment practices were followed for all experimental treatments in order to ensure that there is no other variable apart from the climate smart interventions under study.

Recommended rates of N, P, and K fertilizers (250:125:125 kg ha⁻¹), respectively, were applied to provide adequate crop nutrition. Fertilizer application was uniformly done across all treatments in accordance with recommended agronomic practices in sugarcane grown in Punjab so that differences in crop performance will not be due to any variations in nutrients.

In the case of T₂ (drip irrigation) treatment, drip lines were installed along each crop row, and water was provided based on crop water requirement throughout the crop life period. However, other treatments were managed according to irrigation practices recommended in the corresponding treatments. Drip irrigation system was properly maintained to provide uniform water distribution in root zones.

In the case of T₃ (wheat straw mulching) treatment, wheat straw was applied uniformly at the rate of 8 t ha⁻¹ after crop establishment. Wheat straw was applied uniformly in the field to conserve soil moisture by reducing evaporation losses from the soil, suppressing weed growth, and improving soil microenvironment.

Other than the specified treatments, all other agronomic practices including intercultural practices, pest and diseases control, and harvest operations were uniformly done across all experimental fields.

2.4 Data Collection

The yield of sugarcane was measured during physiological maturity on 15 December 2023. The border rows in the plots were not considered while harvesting to exclude any edge effect, and the harvested canes of the net plot area were manually collected. The harvested canes of each net plot were weighed by using a weighing scale and recorded as weight in kilograms (kg).

The measured cane yield from each net plot was then transformed into ton per hectare (t ha⁻¹) by using the following formula:

$$\text{Yield (t ha}^{-1}\text{)} = [\text{Net plot yield (kg)} \times 10,000] / [\text{Net plot area (m}^2\text{)} \times 1000].$$

where 10,000 is the total area of one hectare (m²) and 1,000 is the conversion constant from kilograms to ton.

2.5 Statistical Analysis

The experimental results on sugarcane yields were analyzed by ANOVA for the Randomized Complete Block Design (RCBD). The statistical analyses were conducted using the software ****Statistix 8.1****. The means of treatments were compared using the **Least Significant Difference (LSD)** test at the **5% probability level ($P \leq 0.05$)**. The differences between the means of the treatments were statistically significant if the calculated probability value was $P \leq 0.05$.

3. Results and Discussions

3.1 Results

3.1.1 Effect of Climate-Smart Management Practices on Sugarcane Yield

During the study period (2021–2023), the productivity of sugarcane was found to differ among the evaluation of management practices. Significant yield variation in canes was found between the conventional farmer practice and the climate-smart agronomic interventions. Table 1 shows the quantitative comparison of sugarcane yield under various treatments and the graphical representation of the performance of various treatments is shown in Figures 1 and 1.2.

Table 2. Quantitative assessment of sugarcane yield and percentage increase across various treatments (2021–2023).

Treatment	Management Strategy	Yield (t/ha)	Yield Increase (%)
T1	Farmer Practice (Control)	55	—
T2	Drip Irrigation	72	30.9
T3	Mulching (Wheat Straw)	68	23.6
T4	Heat-Tolerant Variety	70	27.2

Of all the treatments evaluated, drip irrigation (T2) resulted in the highest sugarcane yield of 72 t ha⁻¹, which is 30.9% more than the conventional farmer practice (T1) with the lowest yield of 55 t ha⁻¹. The second variety was the heat tolerant variety (T4) that gave 70 t ha⁻¹, an increase of 27.2% over the control treatment. The wheat straw mulching (T3) also showed its beneficial effect on the productivity of sugarcane with recorded yield of 68 t ha⁻¹ which is 23.6 % higher than the conventional production system.

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Sugarcane yield Analysis (2021-2023)

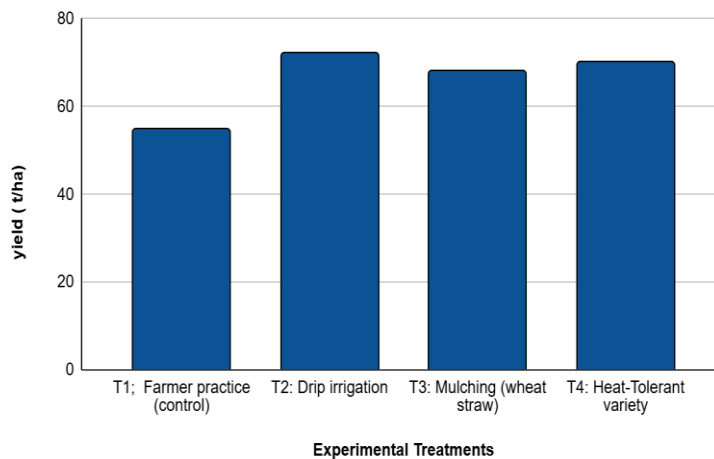


Figure 2. Comparative analysis of sugarcane yield performance under various experimental treatments (2021-2023)

All three climate-smart management practices were more effective than the conventional farmer practice in terms of sugarcane yield, overall. The following treatments were observed based on their productivity; Drip Irrigation (T2), Heat-Tolerant Variety (T4), Wheat Straw Mulching (T3) and Farmer Practice (T1). The results showed that the improved agronomic management practices have significant potential to improve the productivity of sugarcane in the condition of the present study.

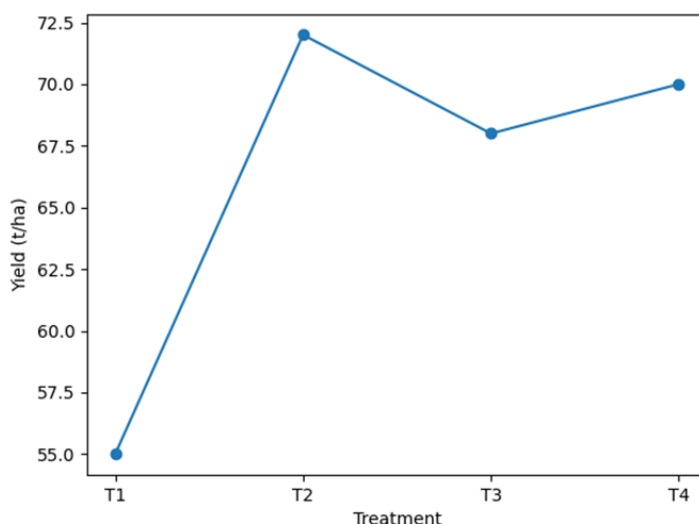


Figure 3. Line graph showing the percentage of sugarcane productivity by various treatments

3.2 Discussion

3.2.1 Effect of Drip Irrigation on Sugarcane Yield

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The present study revealed that drip irrigation was the most effective climate-smart management practice for addressing the productivity of sugarcane under agro-climatic conditions of Jaranwala, Faisalabad. Of the treatments evaluated, drip irrigation resulted in the highest cane yield of 72 t ha⁻¹ which is a 30.9% higher than the conventional farmer practice (55 t ha⁻¹). This significant growth is a testament to the critical importance of efficient irrigation and its contributions to sustaining sugarcane production amidst water scarcity and climate variability (Reddy et al., 2018).

This might be due to the fact that drip irrigation can deliver water to the root zone in a controlled and efficient way. Drip irrigation method, as compared to the traditional surface irrigation method, avoids evaporation, runoff and deep percolation of water and thus enhances soil moisture conditions during the entire crop growing period. Proper soil moisture ensures good root growth, better nutrient uptake, better photosynthetic activity, more biomass production, and higher cane production. Moreover, synchronizing water supply with crop demand means less moisture stress at important crop growth phases like tillering and cane elongation where moisture stress is critical (Arun Kaushal et al., 2012).

The results obtained in the present study support many recent studies which showed positive effects of drip irrigation on sugarcane productivity. Prabhakar Reddy et al. (2018) reported that drip fertigation resulted in significantly higher cane production and water productivity than other irrigation methods, because of better nutrient and water utilization. In another comprehensive review, Kaushal et al. (2019) have also demonstrated that drip irrigation can enhance irrigation efficiency, lower the unproductive water loss and enhance the yield of sugarcane. Anjaly

et al. (2024), also highlighted that drip irrigation is one of the most effective agronomic management practices for improving water productivity of sugarcane under water scarcity situations (Anjaly et al., 2024).

The observed increase in yield is also consistent with the climate-based simulation studies carried out in South Asia. Alvar-Beltran et al. (2021) found that the future climate scenarios are likely to increase the water needs of crops in the Indus River Basin, which is the reason why efficient irrigation technologies are of great importance for ensuring agricultural production in the future (Alvar-Beltrán et al., 2021). Similarly, Dingre (2023) pointed out that scientific management in irrigation for sugarcane using micro-irrigation system is very useful to maximize water-use efficiency in water stressed areas (Dingre, 2023).

Drip irrigation has a number of environmental and economic benefits besides improving productivity. The efficient use of water decreases the pressure on scarce freshwater resources, energy use in pumping water and can result in better fertilizer-use efficiency if coupled with fertigation. The reduction in water losses also helps in sustainable groundwater management, which is becoming crucial in regions like Punjab, Pakistan, which are in a semi-arid condition and have large dependence on irrigation water. These advantages have derived it a vital part of climate-smart farming that can enhance productivity and natural resource utilization.

Overall, the results of the present study suggest that drip irrigation is an efficient and effective method of enhancing the productivity of sugarcane under water limited conditions. Application of efficient irrigation technologies in sugarcane production

systems has a potential to improve yield, increase the efficiency of use of resources and increase the resilience to future climate change challenges.

All three climate-smart farmer practices proved to be more successful than the conventional farmer practice with regard to sugarcane yield, overall. The observed productivity of the treatments was compared as follows: Drip Irrigation (T2) > Heat-Tolerant Variety (T4) > Wheat Straw Mulching (T3) > Farmer Practice (T1). The findings suggest that there is a distinct benefit of implementing better agronomic management to boost sugarcane productivity under the condition of present study.

3.2.2 Effect of Wheat Straw Mulching on Sugarcane Yield

The present study revealed that wheat straw mulching (T3) significantly enhanced the productivity of the sugarcane crops over conventional practice of the farmers with 68 t ha⁻¹ cane yield which is 23.6% higher than the control treatment. Wheat straw mulching markedly improved the productivity of wheat crop over the non-mulch treatments, but was slightly lower than drip irrigation and the heat-tolerant variety, indicating its role as a suitable soil management practice for coping with climate change under semi-arid conditions (Bhatt et al., 2023).

The enhanced sugarcane production with wheat straw mulching is mainly due to its soil moisture saving and creation of a better soil microenvironment. A layer of wheat straw on the soil surface provides a protective cover that prevents direct evaporation, helps to reduce soil temperature variation and improve infiltration with less surface runoff of rain water. The conditions provide a more consistent soil moisture regime throughout the crop growing season, minimize drought stress, and encourage continuous plant growth. Also, as wheat straw decomposes slowly, it delivers organic matter to the soil, which enhances the soil structure, aggregate stability, microbial activity and water-holding capacity of the soil. The combination of these improvements provides favorable root development and nutrient uptake and ultimately, crop productivity (Bhatt et al., 2023).

The results obtained from the present study support the previous studies that showed the positive results of residue mulching on sugarcane production. Aquino et al. (2018) found that straw mulch on the soil surface had a positive effect on sugarcane and maintained soil moisture under water stress conditions without negatively affecting industrial quality. Likewise, it has been observed from long-term trials that partial crop residue retention has positive effects on soil water availability and sustainable production of sugarcane especially in drought prone areas (de Aquino et al., 2018).

Studies recently carried out have also demonstrated the productivity and water-use efficiency benefits of residue mulching. Trash mulching along with optimized irrigation management was found to increase the yield of sugarcane, water use efficiency and improved soil physical characteristics by Kumar et al. (2024). Similarly, recent reviews on climate-smart agronomy have confirmed that the reduction of soil evaporation, the improvement of soil moisture conservation, the suppression of weed growth and the enhancement of crops productivity are the positive effects of organic mulches in water-limited production systems. The advantages are especially important in areas where climate change is causing more extreme temperatures and weather patterns (Demo & Asefa Bogale, 2024).

Wheat straw mulching has not only the advantages of improving yield, but also has

significant environmental and agronomic advantages. Crop residues used as mulch help to sustainable management of residues, minimise soil erosion, sequester carbon and improve soil biological activity. Such enhancements boost sugarcane productivity systems' adaptive capacity to climatic variability and decrease reliance on over-irrigation. Thus, wheat straw mulching in conjunction with other climate-smart technologies like water use efficiency and better cultivars can offer a more sustainable, management strategy in a context of growing water scarcity in sugarcane production (Msomba et al., 2024).

In overall conclusion it can be said that the study showed that wheat straw mulching proved to be an effective agronomic practice in improving soil moisture conservation and soil health which ultimately boosted the yield of sugarcane. The yield response was somewhat less than when drip irrigation was used, but the relatively low cost and ease of implementation make wheat straw mulching an option for wheat straw management for sugarcane growers in semi-arid conditions (Kumar et al., 2024).

3.2.3 Effect of Heat-Tolerant Variety on Sugarcane Yield

In the present study, the heat-tolerant sugarcane variety (T4) significantly enhanced the productivity of cane as compared to that of the farmer practices. The heat-tolerant variety yielded 70 t ha⁻¹, which is a 27.2% higher than the control variety. While yield was slightly lower under drip irrigation than under other irrigation systems, higher than wheat straw mulching, suggesting that genetic improvement, especially for heat tolerance, can be a significant factor in maintaining sugarcane productivity under increased temperature stress (Mehdi et al., 2020).

This improved performance of the heat-tolerant variety could be explained by its higher capacity for coping with high-temperature environment without causing any physiological or metabolic abnormalities. The effects of heat stress on photosynthesis, chlorophyll synthesis, stomatal conductance, production of reactive oxygen species and decreases in biomass accumulation and cane yield are well documented. The heat-tolerant cultivars have adaptive mechanisms like improved membrane stability, efficient antioxidant defense systems and osmotic adjustment which enable them to sustain their photosynthesis and continue growth under high temperatures. These physiological benefits therefore help to optimize the development of cane and productivity in heat stress conditions (Kumar et al., 2024).

An additional desirable trait in heat-tolerant varieties is the ability to retain chlorophyll stability and photosynthetic efficiency under heat stress conditions. Maintaining a high level of chlorophyll pigments allows light to be intercepted and continues carbon assimilation, providing a continual supply of photosynthates for elongation of the stalk and accumulation of sucrose. Furthermore, these cultivars have increased root growth and water-use efficiency that help them to access soil moisture when demand for it is great, thus minimizing the impact of drought and heat stress on crop growth (Shabbir et al., 2021).

The results of the present study corroborate with earlier reports on the advantage of cultivars of sugarcane that are tolerant to heat. Under the high temperature stress, Kohila and Gomathi (2018) showed that the heat-tolerant sugarcane genotypes had greater chlorophyll contents and membrane stability and antioxidant activity, which led to better growth performance compared to the susceptible cultivars. Likewise, Mehdi

et al. (2020) found that the heat tolerant sugarcane varieties displayed better heat tolerance-related physiological and biochemical responses which resulted in higher biomass and sucrose content under heat stress conditions (Kohila & Gomathi, 2018).

The need to develop climate-resilient sugarcane cultivars to face the impacts of global warming has also been highlighted in recent reviews. Shabbir et al. (2021) pointed out that the combination of the conventional breeding and molecular/biotechnological methods has been a catalyst in the creation of sugarcane varieties that are more tolerant to heat stress and other abiotic stresses. Similarly, Meena et al. (2022) found that the developments in the fields of genomics, physiology and phenomics have aided in the identification and selection of stress-tolerant cultivars that can sustain productivity in the face of climate change. The present study has shown that field trials of using a heat-tolerant variety are a useful way to increase sugarcane yield, which supports these findings (Meena et al., 2022).

Practically, cultivation of heat-tolerant sugarcane varieties is a useful adaptation option for hot climate regions facing the impact of climate variability and temperature extremes. In contrast to the management practices that would need extra infrastructure or additional operational costs, use of improved cultivars can be easily integrated into current production practices, enabling farmers to improve productivity with reduced risk from heat stress. This strategy is especially relevant in semi-arid regions like Faisalabad where the rise in temperature is likely to create major problem in future sugarcane production.

The results of the present study suggest that cultivation of heat-tolerant varieties of sugarcane as a climate-smart strategy is an effective approach for boosting sugarcane productivity under heat-stress conditions. The adoption of stress-tolerant cultivars along with irrigation and soil moisture management techniques could add to the resilience and sustainability of sugarcane cultivation in water-constrained regions.

3.2.4 Implications for Climate-Smart Sugarcane Production

Results of the present study have shown that there is significant potential to boost sugarcane productivity using climate-smart management practices under water scarcity and climate variability. Increased cane yields in all three interventions—drip irrigation, wheat straw mulching and heat-tolerant sugarcane variety—compared with the conventional farmer practice demonstrates that both improved management practices and genetic adaptation may contribute to enhancing the resilience of sugarcane production systems. The findings highlight the need for implementing climate smart agricultural technologies to ensure the sustainability of sugarcane production and mitigate negative effects of environmental stresses .

Drip irrigation was the best treatment evaluated for cane yield followed by the heat-tolerant variety and wheat straw mulching. It is important to note that drip irrigation is more efficient than other methods, and hence, efficient water management in sugarcane cultivation is crucial, especially in semi-arid areas where fresh water supplies are becoming scarce. Wheat straw mulching helped to increase the soil's water holding capacity and soil health while the heat tolerant variety increased the crop's physiological tolerance to high temperatures. These practices together tackle various constraints on sugarcane production, hence offer complementary solutions for adapting to climate change.

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In recent years, the studies have highlighted the importance of implementing several climate smart technologies to achieve sustainable sugarcane production, instead of using any single management practice. Bhatt et al. (2022) found that synergies among efficient irrigation systems, conservation-based soil management and stress-tolerant cultivars can significantly enhance resource use efficiency, crop productivity and environmental sustainability (Bhatt et al., 2023). Likewise, Meena et al. (2022) noted that progress in sugarcane breeding, precision water management, and better agronomic management is vital to sustaining sugarcane production in the context of the evolving climate. The present observations support the results of this study, which showed that various climate-smart interventions could singly increase productivity, and together build the resilience of sugarcane production systems (Meena et al., 2022).

There are also significant economic and environmental gains for adopting climate-smart practices. Water use reduction and irrigation efficiency via improved irrigation practices, evapotranspiration reduction from residue mulching, and reduction of yield losses due to high-temperature stress from the use of heat-tolerant cultivars. These practices, collectively, help to use natural resources more effectively, minimize production risk and promote the long-term sustainability of sugarcane cultivation. They can also be implemented to help support the national efforts for better water management, increased production, and better climate change adaptation in the agricultural sector (Alvar-Beltrán et al., 2021).

The results of this study indicate from a practical point of view that farmers should be encouraged to use climate-smart technologies as per available resources and production constraints of the area. Drip irrigation can provide significant water productivity benefits when irrigation water is scarce. Wheat straw mulching is a simple, inexpensive way to retain soil moisture and enhance soil quality in regions where irrigation facilities are not as readily available. Similarly, the development and use of heat-tolerant sugarcane cultivars is a promising long-term adaptation approach to sustain productivity of sugarcane crops in the face of rising temperatures. There is potential for further enhancing the resilience, productivity and sustainability of sugarcane production in semi-arid environments like Faisalabad by incorporating these practices in the same production system (Anjaly et al., 2024).

In conclusion, the current study shows that there is an effective and sustainable way to enhance the productivity of sugarcane crops in the face of changing climate by implementing climate-smart management practices. Adopting efficient irrigation methods, residue mulching, and stress-tolerant cultivars can be a major step in improving the resource-use efficiency, boosting climate resilience, and promoting sustainable sugarcane cultivation in water-scarce areas.

4. Conclusion

This study aimed at assessing the effectiveness of certain climate-smart agriculture interventions, namely drip irrigation, mulching with wheat straw, and heat-tolerant sugarcane variety, on sugarcane production in the field in Faisalabad, Punjab Province of Pakistan. The obtained results proved that all three interventions increase cane yield compared to the farmer practice, which means that they have a positive effect on the productivity of sugarcane under conditions of increased water scarcity and climate change.

In the experiment, the highest cane yield was achieved in the case of drip irrigation (72 t ha⁻¹), next – the heat-tolerant variety of sugarcane CPF-249 (70 t ha⁻¹), and wheat straw mulching (68 t ha⁻¹); the farmer practice had the lowest yields (55 t ha⁻¹). Thus, efficient irrigation practices, soil moisture management, and stress-resistant cultivars can positively influence the performance of sugarcane. Drip irrigation is the most productive intervention, but it proves the necessity of improving irrigation practices; wheat straw mulching shows the importance of proper crop residue management for preserving soil moisture and creating a beneficial soil environment. At the same time, the successful application of a heat-tolerant variety demonstrates the contribution of genetic selection in the adaptation to rising temperatures.

These findings imply that the application of climate-smart agriculture could enhance the sustainability of the sugarcane production system in semi-arid areas significantly. Drip irrigation may be considered a solution by the farmers if feasible and appropriate conditions in terms of water availability and facilities exist. Another cost-effective and easily applicable technique is to use mulch of wheat straw, which could help conserve soil moisture. Heat-tolerant crop varieties may serve as another technique aimed at reducing losses from heat stress.

Whereas in the current study, cane yield was used as the major performance parameter, subsequent studies must include other parameters such as water use efficiency, juice quality, sucrose content, and cost-benefit analysis. In addition, the combination of different climate smart interventions across different agroecological zones and planting seasons will help understand the efficacy of these interventions. The findings from such studies will help develop climate smart strategies for management of sugarcane.

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