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Climate change and sugarcane production options in Pakistan: A perspective review

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Abstract

Sugarcane (*Saccharum officinarum* L.) is one of Pakistan's most important commercial crops, primarily cultivated in Punjab, Sindh, and Khyber Pakhtunkhwa provinces. It plays a vital role in the national economy by supporting the sugar industry, rural livelihoods, and agricultural GDP. However, the sustainability of sugarcane production is increasingly threatened by changing climatic conditions. Rising temperatures, irregular rainfall patterns, prolonged droughts, and frequent heatwaves are adversely affecting crop physiology, water availability, and sucrose accumulation. Research indicates that sugarcane yield in Pakistan may decline by 6–10 % with each 1 °C rise in mean temperature, particularly in semi-arid regions. In addition, water scarcity, salinity build-up, and the spread of climate-favoured pests further compound yield instability. To sustain production and improve resilience, adaptive measures such as the introduction of drought- and heat-tolerant varieties, adoption of drip and sprinkler irrigation systems, and optimization of sowing and harvesting times have shown considerable potential. Improved ratoon management, integrated nutrient use, and the application of climate-smart tools such as crop modelling and remote sensing are also being explored to enhance resource-use efficiency and forecast yield performance. This review synthesizes the impacts of climate variability on sugarcane cultivation in Pakistan and outlines key adaptation and mitigation strategies necessary to secure the crop's long-term sustainability and contribution to national food and energy security.

Keywords: Climate change, Crop modelling, Sugarcane production options, Sugarcane irrigation

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Introduction

The increasing temperature worldwide, frequent droughts, erratic rains, and fluctuating weather patterns combined with climate change have put the planet's food security at risk (Ishtiaq et al., 2022; Batool et al., 2025). The Intergovernmental Panel on Climate Change (IPCC) has suggested that the mean global temperature will increase within the range of 2 to 5 °C and that the global carbon dioxide concentration will reach approximately 550 ppm by the end of 2050. Tropical and subtropical environments will face even harsher scenarios regarding temperature increases and associated dryness (Mazhar et al., 2023). The most vulnerable areas to climate change are Asia and Africa and these regions occupy the populations of people having relatively low income and these people are living due to agricultural set ups but climate change scenarios are going to drop in the agricultural yield so ultimately these people will be affected (Mazhar et al., 2024; Safder et al., 2025; Ullah & Imran, 2025). The predictions of the extent of climate change involve thoroughly understanding how much temperature will increase under a specific duration and how frequent rainfall or precipitation patterns will be (Trenberth, 2011). Second, the behaviour of cropping systems in response to global climate change is of prime importance. The behaviour of crops under changing climatic patterns depends upon the biological characteristics of the planted material and surrounding environment of the planted material, which include the soil parameters and plant–microbe interactions (Jaber & Fayyadh, 2019). Finally, the response of the global food economy under the pressure of climate change on agricultural cropping systems is important. Under changing climates, some areas of the globe are more susceptible and vulnerable than other areas. Therefore, agricultural practices will shift to areas that are expected to bear little impact from climate change, agricultural productivity will ultimately be disturbed, and food prices will inflate, compromising food security (Jaber & Fayyadh, 2019).

Sugarcane (*Saccharum officinarum* L.) is one of the most important C4 crops cultivated worldwide to meet 75 % of the total white sugar demand (Ali et al., 2021; Fioranelli & Bizzo, 2023; Rahman, 2025). The production of sugarcane worldwide is experiencing a flatter curve due to climate change-mediated issues (Rasool & Arslan, 2019). Pakistan cultivates approximately 1.2 million hectares of sugarcane, and the yield of sugarcane is approximately 63,800 thousand Metric Tons (TMT) after Brazil, with 739,300 TMT yield; India, with 342,200 TMT yield; China, with 125500 TMT productivity; and Thailand, with 100,100

TMT (Hussain et al., 2006). Among the various factors contributing to low per hectare yields worldwide and particularly in Pakistan, climate change is the leading cause. Although Pakistan contributes little to global greenhouse gas emissions, it is among the most vulnerable countries to climate change impacts. Climate change can cause an increase in the volume and flow of rivers and oceans, frequent droughts, coastal flooding, tornadoes and various forms of abiotic stress, including frequent droughts. The increase in mean annual temperature worldwide mediated by an increase in greenhouse gas emissions is another aspect of climate change (Noroz et al., 2021; Omokhafe et al., 2024). It has been reported that the average temperature in Pakistan has risen from 0.3 to 0.8 °C during the past century (Jahangir et al., 2016). The sustainability of sugarcane cultivation is increasingly at risk due to changing climatic conditions. Pakistan is among the top ten most climate-vulnerable countries, experiencing rising temperatures, irregular monsoon patterns, declining water availability, and increased frequency of heatwaves and droughts. These climatic stresses adversely influence sugarcane germination, tillering, sucrose accumulation, and overall productivity. Prolonged dry spells and reduced canal flows have intensified irrigation challenges, particularly in southern Punjab and Sindh. In response, research efforts are focusing on developing drought- and heat-tolerant sugarcane varieties, improving irrigation efficiency through drip and sprinkler systems, optimizing planting time, and enhancing resource-use efficiency. Understanding these adaptive strategies is essential for sustaining sugarcane productivity under changing climate scenarios in Pakistan. Keeping in view of the above picture, the cultivation and production options for sugarcane in Pakistan are under investigation. The current review is an effort to explain the production options for sugarcane in Pakistan and the reactions of sugarcane crops under changing climate patterns.

Sugarcane production areas in Pakistan

In Pakistan, sugarcane is cultivated on more than 1.2 million hectares, and the climate of Pakistan has a diverse physiographical nature. The country stands on the 5th spot as far as sugarcane yield is concerned with a total yield of 63.75 million tons (Khan et al., 2019). However, Pakistan is producing very low per hectare yields—approximately 56.48 tons which puts Pakistan at the 51st spot in terms of per hectare yields. The decrease in per hectare yield will increase further from the perspective of future climates (Farooq and Gheewala, 2019). Although the cultivation area of Punjab province of the country is greater than that of Sindh, the Sindh province of Pakistan is comparatively better in terms of per hectare yield, as is the case for Punjab and KPK Provinces, which is why the share of total sugarcane production by Sindh province is highest, i.e., 40 % (Solangi et al., 2025). The highest per hectare yield of Sindh may be attributed to better agricultural practices, better planting techniques, better land management and cultivation in the optimum season for sugarcane (Chandio et al., 2021). The sugarcane crop is planted in the autumn season and stays in the soil for a longer duration approximately 14 to 18 months and thus, the planting season of the crop serves as a catalyst for providing better agricultural output in terms of yields. In Punjab and other provinces, sugarcane is cultivated during spring; thus, little time is available for approximately 12 to 14 months to stand in fields, affecting the overall yield parameters (Chohan, 2019).

Nourishing and medicinal value of sugarcane

Sugarcane (*Saccharum officinarum* L.) is a giant perennial grass that comes from the family Poaceae and is highly nutritious and medicinal worth consuming. Sugarcane is a rich and inexpensive source of carbohydrates such as fructose and glucose (Singh, 2019). Sugarcane is a rich source of phenolics and flavonoids, which are major metabolites and are thus known for their antioxidant potential (Freitas et al., 2021). Approximately 70 % of the world's white sugar demand is met through sugarcane (Singh and Rao, 2021). Sugarcane yields a variety of products, such as molasses, brown sugar and jiggery, and thus serves as an important candidate for providing sugar (Iqbal et al., 2020). Vegetative parts of sugarcane are important sources of phytochemicals and have ethno-pharmacological applications in treating various maladies, such as cardiovascular diseases, skin problems, urinary system issues and respiratory diseases (Ji et al., 2020). The sugarcane culms are processed and crushed to yield sugarcane juice. In Pakistan, sugarcane juice is commonly known as a "row", which is reported to contain nutritionally important raw sugars, minerals, starch and organic metabolites (Malviya et al., 2021). The caloric value is 40 kcal/100 mL of sugarcane juice. The nutritional elements per 100 ml of sugarcane juice were 1.1 mg of iron, 6 µg of carotenes and 10 mg of calcium. Sugarcane juice has been proven to be useful for treating a number of diseases, such as constipation, haemorrhage, anaemia and jaundice (Bispo et al., 2022; Prakash, 2022). Sugarcane juice is also an important cooling candidate and mitigates aphrodisiac issues (Flórez-Martínez et al., 2023).

Correlation of temperature with sugarcane phenology

Phenology is the study of seasonal changes in plants, and all of these parameters are highly regulated by environmental factors such as temperature (Pipitpukdee et al., 2020). In sugarcane, the first phenological stage relates to germination or shoot initiation, which takes place either from true seeds or from vegetative buds. The germination of seeds requires a base temperature or a minimum temperature of approximately 12 °C. The optimum temperature for the initiation of new shoots is 36 °C, while the maximum temperature above which germination stops is approximately 48 °C (de Medeiros Silva et al., 2019). The seeds of sugarcane are not preferred as planting material due to their smaller size; instead, the crop is planted from culms with auxiliary buds. Surging from auxiliary buds is restricted by high temperature, and salt stress also acts as a limiting factor in germination (Ruiz Corrêa et al., 2019).

Germination is usually followed by leaf initiation and development. Leaves continue to form following the open growth pattern; however, leaf initiation and development rate followed by sugarcane development are temperature driven and cultivar dependent (Stegen & Kaparaju, 2020). The minimum temperature for leaf initiation varies from 8-11 °C (Linnenluecke et al., 2020). The optimum temperature for leaf development is 32 °C, and the maximum temperature beyond which leaf development ceases is 42 °C, as reported by some researchers (Verma et al., 2020; Fioranelli and Bizzo, 2023). Leaf development is followed by another important phenological state called tillering, which refers to the process in which auxiliary buds of existing culms from new side shoots develop into additional culms later on. The tillers that arise from the principal culm are referred to as primary tillers, and the tillers that arise from the primary tillers are known as secondary tillers (Singh et al., 2019). The tillering of sugarcane plants is related to environmental signs and cues, and temperature is the most important factor. The minimum temperature for tillering is 16° C, and below this temperature, sugarcane fails to develop new tillers. The optimum temperature ranges between 23 and 30 °C for the formation of new tillers (Boonruksa et al., 2020; Pacheco-Zenteno et al., 2021). The internode elongation starts after full expansion of leaves at lower nodes. The elongation of internodes occurs as the four newly formed leaves expand fully in succession. The internode elongation depends upon the temperature. A temperature above 36 °C reduces the length of internodes (Pacheco-Zenteno et al., 2021).

Another seasonal change in the life cycle of sugarcane plants is the development of harvestable culms, which are directly linked to the concentration of sucrose near the intermodal portion. Temperature also influences the concentration of sucrose and acts as a crucial factor in sucrose accumulation. A temperature lower than 21 °C for 3 months stops the ripening of culms (Boonruksa et al., 2020; Pacheco-Zenteno et al., 2021). The spikelet initiation stage follows the development of harvestable culms. At maturity, the vegetative culms reach the spikelet initiation stage, which lasts several months. Environmental factors, including temperature and humidity, influence the emergence of spikelet's, and the various regions of the planet experience differential durations of spikelet initiation due to variations in climate. A temperature less than 21 °C can affect the pattern of inflorescence development in sugarcane crops, and a temperature of 18.3 °C is the base temperature for the initiation of spikelet formation, whereas the maximum temperature is 32 °C (Lucas et al., 2023). The inflorescence follows the fruit formation process, and the incidence of fleshy fruit around sugarcane seeds has not been reported; however, the fruit is a caryopsis and is considered an adherent mass of dry bracts reminiscent of the inflorescence (Flack-Prain et al., 2021). The maturity of sugarcane spikelet starts to increase irrespective of the level of seed maturity. The seed development process occurs at 10 days' post pollination, and after 20-30 days' post pollination, the ripened ovules reach their maximum size (Hansson et al., 2020). Sugarcane is a perennial plant that does not seem to experience any dormancy because the whole plant is considered to be dormant. Crops are generally hand harvested, and suckers and tiny culms are allowed to stand in the field area (Coelho et al., 2019). The rate of leaf shedding is generally enhanced by low nitrogen and moisture contents, and crops are more sensitive to drought and temperature variation than are many other perennial grasses, such as sorghum. Considering the perspectives of future frequent droughts and high temperatures, the phenology of sugarcane will be highly affected. Therefore, a strategy to mitigate the negative impacts of climate change is necessary, and the main focus should be harvesting and postharvest sprouting of sugarcane (Ali et al., 2021).

Constraints in sugarcane cultivation and poor yields across Pakistan

Irrigation water constraints

In Pakistan, the mean annual rainfall is approximately 250 mm, and the country receives the maximum rainfall (approximately 67 %) in the months of July and August (Ahmad et al., 2019). A growth climate with a rainfall of 600 mm is required for sugarcane. Due to poor rainfall, irrigation water in the form of rainfall is unavailable to farmers throughout the year, and this water is extracted from underground reserves, which have pumping costs (Pacheco-Zenteno et al., 2021). The average rainfall in the province of Punjab is approximately 335 mm in a year, and the other provinces receive relatively less rainfall per year; thus, the climate in most of the country is of the scrub type. Drought is a productivity-limiting constraint faced by C4 crops (Ali et al., 2021). Sugarcane requires more water than other cereal and millet plants (Ahmad et al., 2019). The Indus River water and tributaries serve as major surface water reservoirs in Pakistan, contributing approximately 138 million acre feet of water per year. Due to a defective canal system and poor irrigation practices, approximately 33 % of the water is lost annually in Pakistan (Ahmed et al., 2022). Water availability is strongly correlated with crop productivity, and water shortages are the main culprit behind average yield losses (Aslam et al., 2021). In Pakistan, the lower temperature scenarios account for the months from November to April, and the surface water becomes shorter due to slow glacial melt and poor rainfall. All of these scenarios are yield limiting in the case of sugarcane. The lack of available water leads to poor stalk growth and stalk development, thus accounting for a 30-50 % decrease in yield (Javed et al., 2022).

Genetic potential of sugarcane cultivars

In Pakistan, high-yielding varieties and cultivars are lacking, and farmers are unable to obtain genotypes with high agronomic potential due to their poor economic conditions. There are three cultivation zones for sugarcane crops in Pakistan (Farooq and Gheewala, 2019), namely, the north western, central and southern areas. Provincial data suggest that the sugarcane is cultivated in the KPK, Sindh and Punjab provinces. In Punjab SPSG-26, CP77-400, CPF-237, SPF-213, HSF-240, SPF-234, and CPF-243 are widely cultivated. In Sindh Province, Thatta-326, Thatta-10, Thatta-300, SPSG-326, NIA-98, Lark-2001, BL-4, and SPF-234 are cultivated. In the KPK Province, Mardan-93, S87US-1873, SPSG-326 and CP77-400 are cultivated on croplands. The varieties of sugarcane are being developed on the basis of germplasm and fuzz characteristics imported from Brazil, Barbados, South Africa and the USA. Research institutes are being administered these development programs under the practice of plant tissue culture and molecular biology principles; however, from the perspective of climate change and population growth, much effort is needed to increase the yield potential of sugarcane and sugarcane cultivars (Afghan et al., 2024).

Soil characteristics for sugarcane cultivation in perspective of climate change

Crop yield is strongly regulated by nutrient uptake and availability patterns. Mostly, the cultivated 22 million hectares across Pakistan face constraints such as soil erosion, waterlogging and salinity. Alkaline soils deficient in important minerals, such as N, P, and K, have also been widely reported (Qureshi and Afghan, 2020; Elahi et al., 2020). The southern part of the country produces higher sugarcane yields than other zones due to favourable soil characteristics. The central and south-western areas of Pakistan have yield-limiting soil attributes with a pH ranging from 7-9.2 and salinity ranging from approximately 2.73 dSm^{-1}(Chandio et al., 2021).

Policy Matters

Policy constraints have been a traditional issue for Pakistan. There is a high per hectare cost of sugarcane in Pakistan, and the farmers mostly have a humble background and poor financial conditions. Moreover, the lower rewards in terms of financial gains to the farmer are also a major constraint in limiting the production of sugarcane and other crops (Ali et al., 2021). The production of sugarcane in Sindh is 150-200 tons per hectare, that in Punjab has 100-150 tons yield potential, and that in KPK Province yields approximately 75-100 tons of sugarcane per hectare, which is far lower than international standards. The country is still awaiting a committed effort in the development of sugarcane cultivation (Shar et al., 2021).

Responses of sugarcane to climate change

High-temperature stress

The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) predicted heat stress, frequent droughts and extreme weather events. All crops are susceptible and vulnerable to being affected by the environmental stresses posed by climate change impacts. As a C4 crop, sugarcane yield increases with increasing temperature in the range of 8-34 °C (Coelho et al., 2019). In winter, frost formation negatively affects the growth and productivity of sugarcane plants. Due to climate change-mediated elevated temperatures, the incidence of frost formation will decrease; however, elevated temperatures affect the germination of sugarcane seeds and sprouting of auxiliary buds (Sanghera et al., 2019).. Increased temperature and heat stress are also responsible for the decreased accumulation of sucrose and the shortening of internodes, leading to rosette structure and dwarfism in plants (Boonruksa et al., 2020). Elevated night temperatures lead to the formation of more flowers; however, increased flowering leads to poor elongation of internodes, and ultimately, yield is affected because climate change is thought to risk global food security. A higher transpiration leads to more transpiration-mediated water loss; thus, more irrigation water will be required by the sugarcane crop. As projected by the IPCC, future climates will accompany more droughts; thus, the vegetative growth of sugarcane will suffer. Sugarcane ripening is also monitored by temperature, and ripening is directly correlated with the concentration of glucose. Under elevated temperature, the concentration of glucose is reportedly reduced, affecting yield parameters negatively (Dharshini et al., 2020). Plants exhibit innate defence mechanisms under heat stress and high temperatures; however, the mechanism of action is cultivar dependent. The degree of heat stress and duration of stress are also important factors in activating innate defence mechanisms. The generation of cooling products by the evaporation of water from the aerial parts of plants, particularly from the lamina surface, is practiced by all plants under varying degrees of temperature stress. Similarly, plants respond to high temperature-mediated evaporative loss of water by closing their stomata, which is stimulated by the production of a hormone, namely, Abscisic acid (Valarmathi et al., 2023). Some plants respond by changing lamina characteristics through changes in leaf orientation and lamina rolling (Manimekalai et al., 2023).

Increased atmospheric levels of CO_2 and weed proliferation status

The leaf anatomy of a C_4 plant such as sugarcane is different with respect to cell orientation and arrangement, and this characteristic enables these plants to efficiently utilize atmospheric CO_2 (Valarmathi et al., 2023). However, elevated levels of CO_2 are equally helpful for the growth of crop weeds and their wild relatives. An increased population of weeds (e.g., *Parthenium hysterophorus)* competes with crop plants for the purpose of obtaining fertilizers, nutrients and soil resources, thus limiting crop yields and growth (Manimekalai et al., 2023). In the year 2007, the atmospheric CO_2 concentrations were approximately 387 ppm, and the expected levels in the year 2050 were 600 ppm. Increased weeds cause a 24 %, 19 % and 15 % reduction in sugarcane stalk density, biomass, and commercial sugar production, respectively (Valarmathi et al., 2023). A higher weed density decreases crop performance. Elevated levels of atmospheric carbon dioxide are also responsible for reductions in herbicide performance, and the introduction of exotic species is also facilitated by abundant carbon dioxide concentrations. These exotic and alien species also become invasive for local flora and cause pests and insects of their own types to threaten cultivated crops such as sugarcane (Naz et al., 2021). Elevated concentrations of CO_2 lead to a 30-40 % reduction in the stomatal aperture, and the leaf area is also reported to decrease under these circumstances. Higher CO_2 levels also decrease the available nitrogen content for plants (Terrer et al., 2019).

Climate change and pests of sugarcane

Climate change-induced risks to planet temperature have challenged food crops in various ways. More instances of pest-induced diseases and fungal pathogens are being reported under elevated levels of CO_2 and temperature. Along with physical stressors such as water scarcity and nutrient deficiency, biotic stressors are the main limiting factors in the production of sugarcane and other crops. Climate change-induced disease and pest attacks have decreased yields and have made global food security a challenge for people ever exceeding the population (Heeb et al., 2019). Under elevated temperature, more instances of smut borne diseases caused by fungal pathogens are observed. The dry leaves of sugarcane (as a result of heat stress and drought) become vulnerable to attack by the pest Eoreuma loftini (Solis et al., 2020). In Pakistan, climate change has induced increased weed flora, and more instances of fungal diseases of sugarcane (e.g., red rot of sugarcane) are expected to cause serious challenges for sugarcane farmers (Rahman, 2025).

Sugarcane production options under changing climates

Changing climates have forced worldwide agriculture to adopt mitigation options, and various practices to mitigate climate change have also been part of agricultural systems in Pakistan. Some of the cultivation options for sugarcane in Pakistan can be practiced as follows:

Climate change resistance

Planting material is key for success in agricultural units, and better planting material is planted worldwide in croplands for better productivity and yield traits (Solis et al., 2020). There are agricultural sectors and institutes working on plant breeding and genetics in Pakistan, and there is a need to accelerate this process. Climate change-resistant cultivars need experimentation under diverse agro climatic conditions. Successful cultivars show a wide range of mitigation effects in various climates and adapt well to native adaptive crop counterparts (Renzi et al., 2022). The active participation of local farmers in the cultivar development process increases the chances of success for that cultivar due to active reporting after experimentation (Renzi et al., 2022). To mitigate climate change impacts in Pakistan, there is a need to practice climate change resilient varieties of sugarcane as a production option; similar suggestions have been reported for maize and other millet varieties (Singh et al., 2021). The locally cultivated plant species of sugarcane in Pakistan are best suited to local ethno practices; however, the changing climate will create serious challenges for these locally adapted cultivars, and cultivation options must be optimized (Ameen et al., 2023). The introduction of exotic varieties is a compromise option for crop farmers and will carry risk; therefore, the development of local cultivars through random hybridization, selection and breeding experiments followed by rigorous testing should be included in the development of resilient climate change cultivars. Genetically engineering sugarcane cultivars to make them better adapted to climatic variations should be the focus of related research; however, the introduction of GMOs is still debatable. The availability of climate-resistant and resilient varieties of sugarcane and other food crops to farmers is also of prime importance, and a proper system should be developed for this purpose (Amir et al., 2023).

Changing the dynamics of cropping systems

The cultivation of climate change-resistant cultivars that are appropriate for farming work-outs and that deliver improved agronomic trait information should be part of a strategy for mitigating climate change. There are 22 million hectares (Mha) of total croplands in Pakistan, and sugarcane is cultivated on 5.18 % of the cultivated land (Syed et al., 2023). The cropping system included wheat–maize in Khyber Pakhtunkhwa, rice–wheat, mixed-wheat, cotton–wheat, and sugarcane-wheat in Punjab Province. The cotton–wheat and rice–wheat cropping systems are part of agricultural practices in Sindh Province (Shah et al., 2021). The yield of sugarcane is approximately 48.06 tons/ha, which is quite low due to the use of orthodox cropping systems. By adopting better crop diversification systems, the research potential yields of sugarcane crops in Pakistan can reach 300 tons per hectare. The resilience and better outputs from cropping systems lie behind the focus on diverse cropping systems. Crop rotation should be part of agricultural practices to better handle climate change scenarios; additionally, land management becomes easier. The diversified agro-cropping system serves as a better candidate for integrated pest management. Moreover, society and the general public benefit from diverse cultivation practices. In future climates, the challenges of increasing crop production by increasing the population size will become easier by increasing the flexibility of cropping systems (Yu et al., 2022). Several crop system diversification options are being practiced worldwide, including seasonal variation in the planting times of crops and intraspecific or interspecific variability options for cultivation within individual fields, farms or landscapes. Such practices are suggested for cropping sugarcane in Pakistan to attain better yield outcomes per international standards, and at the same time, these practices increase the options available for developing resilience in response to climate change. Sugarcane, in particular, is a perennial crop and a better option for crop diversification, and perennial crop cultivars are also sources of fuel, medicine and food for the human population (Yu et al., 2022). The strategy to develop climate resilience in food crops will increase over time; however, better cropping systems, such as those involving the planting of better cultivars and variable cultivars under various climates, will force this issue to occur on better grounds in Pakistan. The different cropping systems and better cultivars, both intraspecific and interspecific, with variability and variety will help increase production options.

Sustainable water resource management

Crop yield is widely affected by water deficit conditions, and both qualitative and quantitative characteristics are affected by improper irrigation water management. There is need for an advanced set of tools and irrigation technologies to optimize yields with financial support and planning. Under climate change, frequent droughts occur on cards, and in Pakistan, where water resources are depleting and freshwater is being polluted, the abovementioned effects of climate change will be more pronounced, limiting the yield of sugarcane and other crops; thus, there is an increasing need for sustainable water resource management. The resilience and adaptability of crops to climate change under water shortage conditions demand principles such as conservation agriculture (Mehmood et al., 2019).

There is need of conservation agriculture, highlighting the importance of zero tillage practices and the retention of crop residue mulch. Such practices are recommended for the cultivation of sugarcane crops in Pakistan and for the conservation of water resources. The conservation agriculture and deficit irrigation techniques for checking transpiration losses are highly recommended under changing climates (Ali et al., 2015). The synergistic application of irrigation water conservation and management techniques along with the cultivation of drought-resistant varieties will increase sugarcane production under changing climatic scenarios. Similarly, there is a need to evaluate soil erosion to determine its cause.

The integrated approach will help to improve the cultivation options for sugarcane under changing climatic scenarios. Irrigation technologies based on advancements in agriculture involving properly managed water allocation strategies and farmer education regarding irrigation time and management are extremely important and are needed (Yu et al., 2022). Similarly, there is a need for better weather forecasting tools and technologies that can better predict the nature and duration of precipitation. Weather prediction and forecasting tools are limited in their ability to predict weather conditions for a few days; thus, under changing climatic patterns, there is a need for an efficient forecasting system. Efficient wastewater reuse systems can play a crucial role in mitigating freshwater shortages in agricultural regions, especially in countries facing severe water stress. In addition to technological advancements, encouraging community-based water management programs can enhance local participation and promote sustainable practices.

Improved management of soil under sugarcane cultivation

Climate change is forcing farmers across the globe to increase the soil carbon stock by efficiently managing the area under cultivation (Pepitpukdee et al., 2020). Agricultural lands are involved in greenhouse gas emissions, and wider agricultural lands will result in greater greenhouse gas production. By efficiently utilizing the soil and proper management, better yields of sugarcane and other crops can be acquired under limited land usage; thus, the chances of increased greenhouse gas emissions will also decrease due to the limited area under cultivation. Together with climate-smart agriculture systems, better nutrient recycling is needed in the current era (Lucas et al., 2023). The principles of conservation agriculture, such as zero tillage and the retention of crop residues in the soil, are better soil management options available to sugarcane farmers. Similarly, crop rotation and improved resource use efficiency leading to minimum disturbance in soil structure should be implemented to prevent the adverse impacts of climate change (Afghan et al., 2024). The influence of soil microorganisms on the performance of natural ploughing and tillage has its own value for improving soil texture, structure and porosity. The humus formed by decomposition by soil organisms helps improve the moisture retention capacity and water holding ability of cultivated soil (Pepitpukdee et al., 2020). Maintaining soil nitrogen contents in equilibrium is also helpful for improving soil carbon stocks under changing climates. The best method for maintaining a positive balance of soil nitrogen contents is crop rotation (de Medeiros Silva et al., 2019). In Pakistan, sugarcane is cultivated with wheat and cotton, and in some areas, sugarcane is cultivated with maize and rice; this approach is a better option under a changing climate. However, crop rotation needs to be considered on proper lines in all areas to attain better yield outcomes under changing climates. Table 1 presents overview of the available options for sugarcane cultivation under the changing climate (Table 1).

Modelling sugarcane crops from the perspective of climate change

In Pakistan, various crop models for the cultivation of sugarcane have been established to understand the projections of future climate change scenarios. Crop modelling enables strategy makers to develop policies in response to changing climatic patterns. Crop modelling involves developing a cost effect plan for crop plantations, fertilizer use requirements and tillage. Mehmood et al. (2019) applied Box-Janken’s methodology to determine the production of sugarcane in Pakistan for the years 2018-2030. The forecasting data were obtained from the Pakistan Bureau of Statistics (PBS) and Pakistan Economic Survey reports. The autoregressive integrated moving average (ARIMA) was used to forecast sugarcane crop attributes and cultivation patterns in Pakistan under a changing climate. The model forecasted an increase of 6.56 % in sugarcane production from 2018–2030. A similar study using the ARIMA modelling approach was performed by Ali et al. (2015) for forecasting the yields of sugarcane and cotton through the year 2030 in Pakistan. The forecasted amount of sugarcane production will reach 71414 tons in the year 2030. Shah et al. (2017) used time series data from 1984-1985 to 2013-2014 and applied ARIMA modelling for the prediction of sugarcane in the KPK Province of Pakistan. According to the KPK, the predicted yield for the year 2023 is 5781 tons compared to 5402 tons for the year 2014. Various crop models are being applied worldwide for modelling sugarcane crops that might be used in the country for better sugarcane productions. Baez-Gonzalez et al., (2017) performed a sugarcane modelling study in rain-fed areas of Mexico. The Agricultural Land Management Alternatives with Numerical Assessment Criteria model was used for the simulation of crop productivity in their research. Hu et al., (2019) utilized the Soil Water Atmosphere Plant (SWAP) World Food Study (WOFOST) model to determine the phenology of sugarcane under predicted climate change-induced temperature changes.

Hammer et al., (2020) employed the Data Mining Technique to predict sugarcane yields. Crop modelling is a new area of research and study in Pakistan, and for efficient analysis of planting time, plant spacing and resource requirements, crop modelling is necessary.

Table 1 Sugarcane cultivation options and their benefits under changing climate conditions in Pakistan

Category	Cultivation/ Management options	Key benefits/ Impact
Varietal improvement	Development of drought- and heat-tolerant varieties (e.g., CP-77-400, Thatta-10, HSF-240)	Enhances yield stability under temperature and water stress conditions
Water management	Adoption of drip and sprinkler irrigation systems	Reduces water use by 30–40 % and improves water-use efficiency
	Laser land leveling	Ensures uniform water distribution and minimizes runoff losses
	Scheduling irrigation based on soil moisture and crop stage	Optimizes water application and prevents waterlogging
Nutrient management	Integrated nutrient management (INM) combining organic and inorganic sources	Improves soil fertility and enhances nutrient uptake efficiency
	Use of biofertilizers and compost	Reduces chemical input dependency and supports soil health
Crop and field management	Adjustment of sowing and harvesting times according to regional temperature trends	Aligns crop growth with favorable climatic windows
	Improved ratoon management and trash mulching	Enhances ratoon yield and conserves soil moisture
Pest and disease Control	Integrated pest management (IPM) using biological controls and resistant cultivars	Minimizes yield loss and reduces pesticide reliance
Technological Interventions	Use of remote sensing and GIS for crop monitoring	Supports decision-making and early stress detection
	Climate-smart crop modeling (DSSAT, APSIM)	Predicts yield responses under future climate scenarios
Policy and Institutional Support	Implementation of National Climate Change Policy (NCCP) and provincial agricultural reforms	Promotes climate-resilient and water-efficient agriculture
	Strengthening research–extension linkages	Facilitates farmer training and technology transfer

Conclusion

Sugarcane has a long life cycle of more than months and requires a large amount of water and cultivation resources. Several stages are part of the phenology of sugarcane. Although cultivated on a large area in Pakistan, its yield per hectare is very low compared to international standards. From a production perspective, several options have shown promise in mitigating climate-induced stresses. The development and dissemination of drought- and heat-tolerant sugarcane varieties are crucial for maintaining yield stability in semi-arid and water-limited regions. Efficient irrigation methods, such as drip and sprinkler systems, can reduce water use by up to 40 % compared to traditional flood irrigation. Integrated nutrient management, use of organic amendments, and precision agriculture tools can enhance soil health, fertilizer efficiency, and carbon sequestration. Adjusting planting schedules and adopting short-duration cultivars also help align crop cycles with shifting climatic windows. On the policy front, Pakistan's National Climate Change Policy and Agricultural Policy Framework emphasize improving water governance, promoting climate-smart agriculture, and supporting public–private partnerships for technology transfer. Incentives for efficient water use, renewable energy-based tube wells, and climate-resilient seed systems are needed to accelerate adoption at the farmer level. Strengthening research-extension linkages, improving data-driven climate forecasting, and enhancing farmer awareness programs will ensure that adaptation measures reach end users effectively. Future climates are going to limit the cultivation and production options of sugarcane in Pakistan. There is a need for good policy and the development of climate-resilient and climate-smart varieties of sugarcane to mitigate climate change-related expected yield losses in Pakistan. There is need for fuel-efficient agricultural equipment, residue management and conservation agriculture techniques to make cultivation and production easier nationwide. There is a need to increase the carbon stocks of soils to lower carbon dioxide levels in the atmosphere. The demand for sugarcane is increasing in Pakistan, so it is necessary to manage the cultivation and production of sugarcane in Pakistan by developing strong relationships among research workers, agricultural forces and academics.

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