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Review Article

# Sugarcane Cultivation Amidst Climate Change Challenges: An in-depth Review of Mitigation Strategies and Environmental Resilience

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**Abstract:** The sugarcane (*Saccharum officinarum* L.) holds global significance for sugar and bioenergy production, contributing to the gross domestic product of Pakistan and generating employment. However, environmental degradation resulting from global warming, climate change, and high greenhouse gas emissions pose a critical threat to the sugarcane as well as the sugarcane industry worldwide. Developing countries, like Pakistan, India, and Bangladesh are likely to be more affected because of poor adaptability and forecasting systems, high vulnerability to disasters/extreme events, and insufficient mitigation strategies. Sugarcane production is affected by shifts in climatic conditions, such as temperature, rainfall, and $CO_2$ level, and will continue to be affected by the onset of such events, which are directly linked to geographical areas and the capacity to adapt to such changes. This paper gives a brief description of the challenges and behavior of sugarcane crops to climate change, and the future trend of climate change with respect to sugarcane production to better quantify, comprehend, and counteract the potential negative impact by enhancing the sugarcane production on a sustainable and economically viable basis.

**Keywords**: Sugarcane, Sustainability, Climate Change, Circular Economy.



## 1. INTRODUCTION

Sugarcane, a tall perennial grass of the genus Saccharum belongs to the family Poaceae(Srivastava & Rai, 2012). It is represented by a stout, jointed, fibrous stalk of 2-6 m with high sucrose content. Sugarcane is mainly grown in tropical and subtropical countries and has a C4 mechanism that fixes carbon. Sucrose is the main essence of this crop, which makes it economically important (Verma *et al*., 2019). This crop is widely affected by weather, viz. temperature, precipitation, atmospheric $CO_2$ concentration, and extreme weather events (Hongyan *et al*., 2018; Hussain *et al*., 2018; Mall *et al*., 2016). Sugarcane is a major and economically important cash crop in the world in terms of production, contributing approximately 75% of sugar production in the world(Kumar *et al*., 2021). Global sugar production is expected to grow from 175 MMT during the base period to 198 MMT by 2032, 23% of which will be sourced in Brazil which is expected to meet the growing needs of the international market, especially in the second half of the decade. Asia will remain the leading producing region producing about 42% of the world's global output. Brazil, the world's largest sugar producer makes Latin America the second-largest sugar-producing region. Considering the profitability of international sugar markets, sugar production is expected to increase by 5.2 MMT over the next decade. According to the Pakistan economic survey, the production of sugarcane in 2022-2023 reached a total of 91.1 million tons, which was 2.8% higher over the last season despite 2022 monsoon rains followed by floods which damaged around 1.7 million hectares of crop (Economics survey, 2023; FAO, 2023).

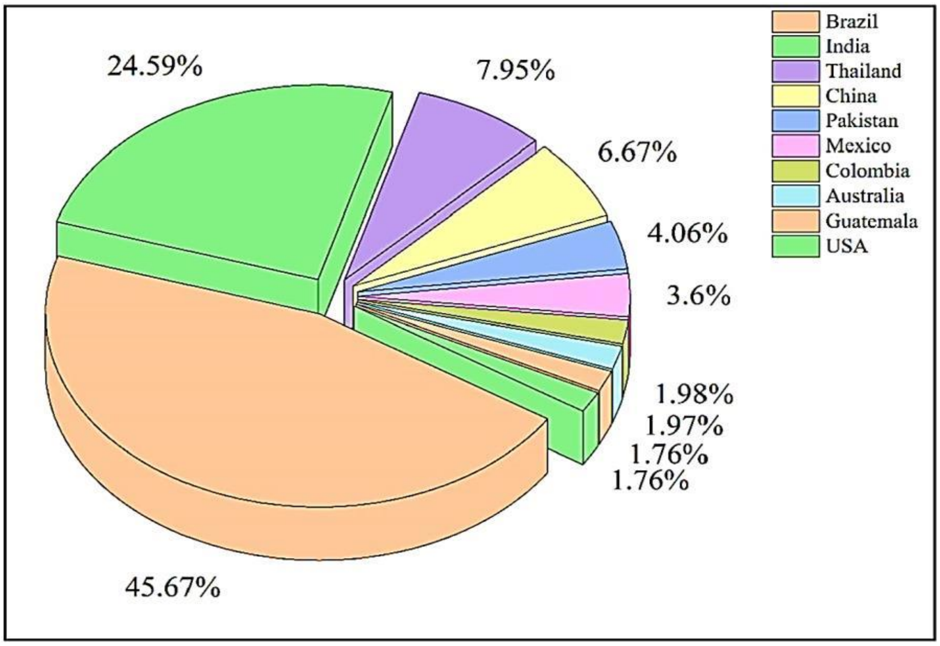


**Figure 1: Percentage of sugarcane crop area harvested. Source: (FAO, 2019)**
**Source article:** (Ali *et al*., 2021)

Pakistan is facing the adverse effects of climate change and has been listed as the 12th most vulnerable country due to climate change, which impacts its agriculture and land resources. A massive gain in the utilization of fossil fuels results in an increase of greenhouse gas emissions which trap the heat in the upper atmosphere. Elevation in global temperature enhances global warming phenomena and sparks the effect of climate change worldwide(Awan & Yaseen, 2017). Carbon dioxide concentration has increased to 47% (from 280 ppm to 412 ppm) in the atmosphere since the industrial era began(Alan, 2019). An increase in greenhouse gases, specifically atmospheric carbon dioxide ($CO_2$), is mainly linked with global warming. Worldwide earth surface temperature was 1.09$^{O}$C higher in 2011-2020 compared to 1850-1900 and is projected to increase from 2.1$^{O}$C – 2.7 $^{O}$C (low emission) and 3.3$^{O}$C -5.7$^{O}$C (high emission), which is directly associated with the level of greenhouse gases emissions and cause massive climate change(Calvin *et al*., 2023).

Some studies have shown that the high level of atmospheric $CO_2$ can be favorable for some plants (especially C3 plants)(Wang *et al*., 2020). High temperature and water stress in sugarcane may cause a drastic impact during the growth stages (germination, flowering, and maturity) of the crop(Sanghera *et al*., 2019; Verma *et al*., 2019). It is a very important crop for sugar, bioenergy, and other valuable byproducts. The average cane and sugar yield is much lower than the achievable potential of the crop. Climatic changes affect agriculture directly [through abiotic stresses such as changes in rainfall and/or temperature] as well as indirectly [through biotic stresses like changes in pest pressure, diseases, and other ecological services] that directly impact agricultural productivity. Crop production is globally reported as reducing due to climatic change affecting their productivity *(Lobell et al*., 2008). Climate change and global warming are widespread events that contribute to abrupt alterations in rainfall patterns, which are majorly linked with agricultural production and water resources. Drastic changes in rainfall patterns and intensity are largely evidenced to damage the fertile land and crops as extreme droughts and floods. A change in precipitation pattern resulting from climate change is likely to anticipate alteration of disease, insect pest, and weed occurrence that affect sugarcane cultivation. Certain weed species like Cyperus spp. are projected to decrease as drought becomes more frequent. Conversely, the population of termites and nematodes under warmer and drier conditions linked to climate change is expected to rise (Clowes & Breakwell, 1998). Many countries rely on arable lands in semiarid regions for food production, and under climate changing scenarios, there's a need to develop climate-smart management and mitigation strategies to achieve food security, while adoptive action will be helpful to counter the effect of climate change and its negative cost.

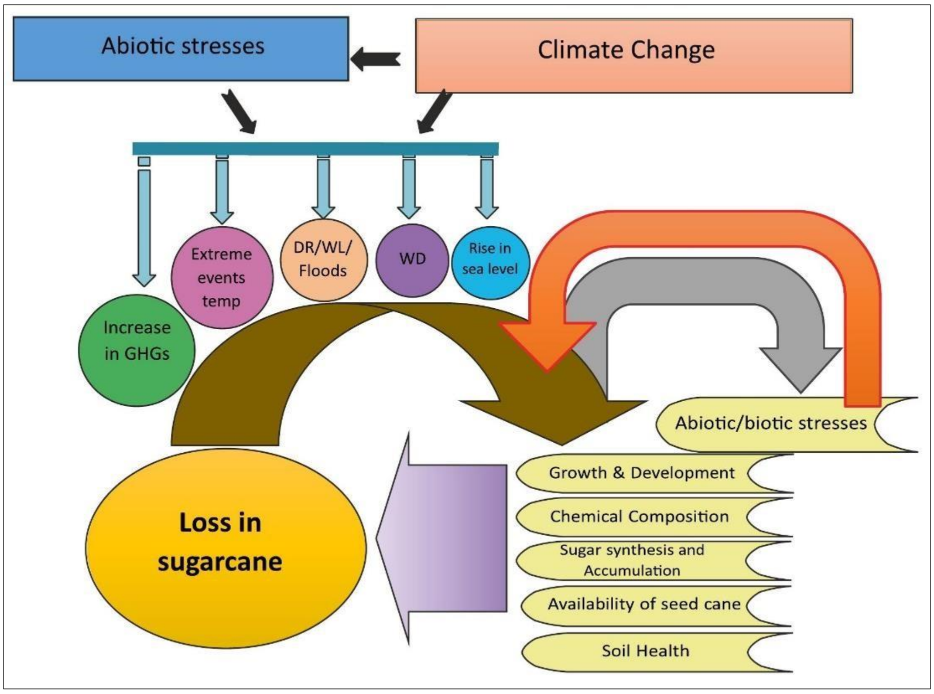


**Figure 2: Influence of abiotic stresses and climate change-induced abiotic stresses on sugarcane**
**Source:** (Shrivastava *et al*., 2016)

**2. Sugarcane Production and Challenges:**

Developing countries share the major sugarcane production in the world. Global production of sugarcane was ~1.9 billion tons in 2020 with a total share of >60 % of the top 2 producers, Brazil and India(FAO, 2022). In a broader context, huge variation in the yield of sugarcane exists all over the under developing countries with different patterns of biotic and abiotic stresses because of less adaptive capacity, more natural hazards susceptibility, inefficient forecast systems and lack of mitigation strategies(Gawander, 2007). Some major challenges in the production of sugarcane are described below:

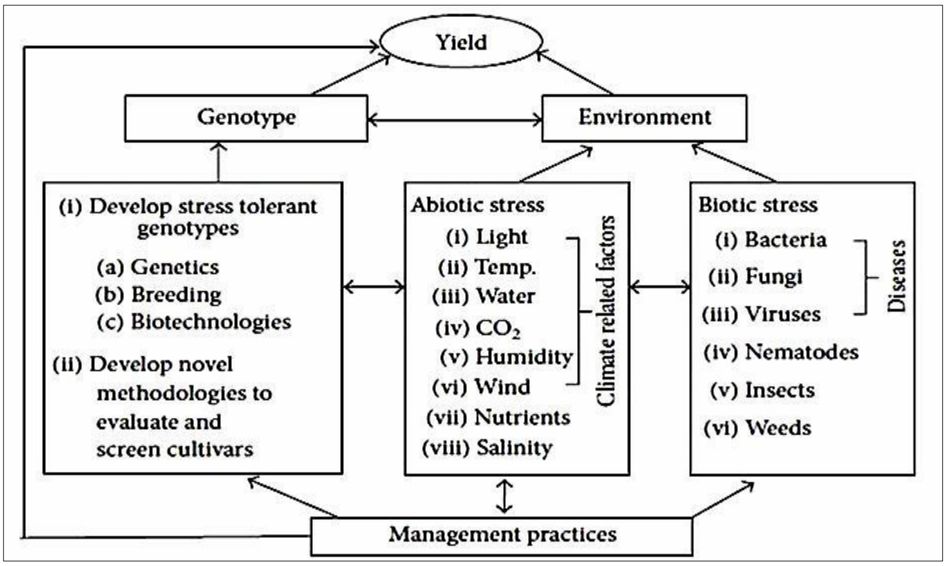


**Figure 3: A flow chart with major factors (genotype, environment, and management practices) and their interactions influencing sugarcane yield**
**Source:** (Sanghera *et al*., 2019)

**Water:**

Water is a main factor for sugarcane production as it requires a large amount of irrigation water compared with the other crops to reach maturity. Abiotic stresses, mainly drought, affect sugarcane productivity, and its affect can be observed on crop(Begcy *et al.*, 2012). During drought, crop growth slows down, and as a result, cane yield reduces(Barnes, 1974). As the number of stacks and their growth cut down, 30%-50% reduction in the yield can be observed(Silva *et al.*, 2008). It becomes evident that effective water management practices are essential for sugarcane cultivation, particularly in regions where water resources are constrained or unreliable. The graph provides valuable insights into how varying water resources impact the growth and yield of sugarcane. It becomes clear that these practices play a crucial role in optimizing water use in sugarcane farming, with a focus on enhancing water productivity, which measures the amount of sugarcane produced per unit of water used. In this context, water availability is a critical factor. It refers to the actual amount of water accessible for sugarcane crops, considering factors like evaporation, runoff, and drainage. Additionally, storage variation, which reflects changes in soil water content over time, can be either positive or negative. Understanding these dynamics is key to making informed decisions about water management in sugarcane cultivation.

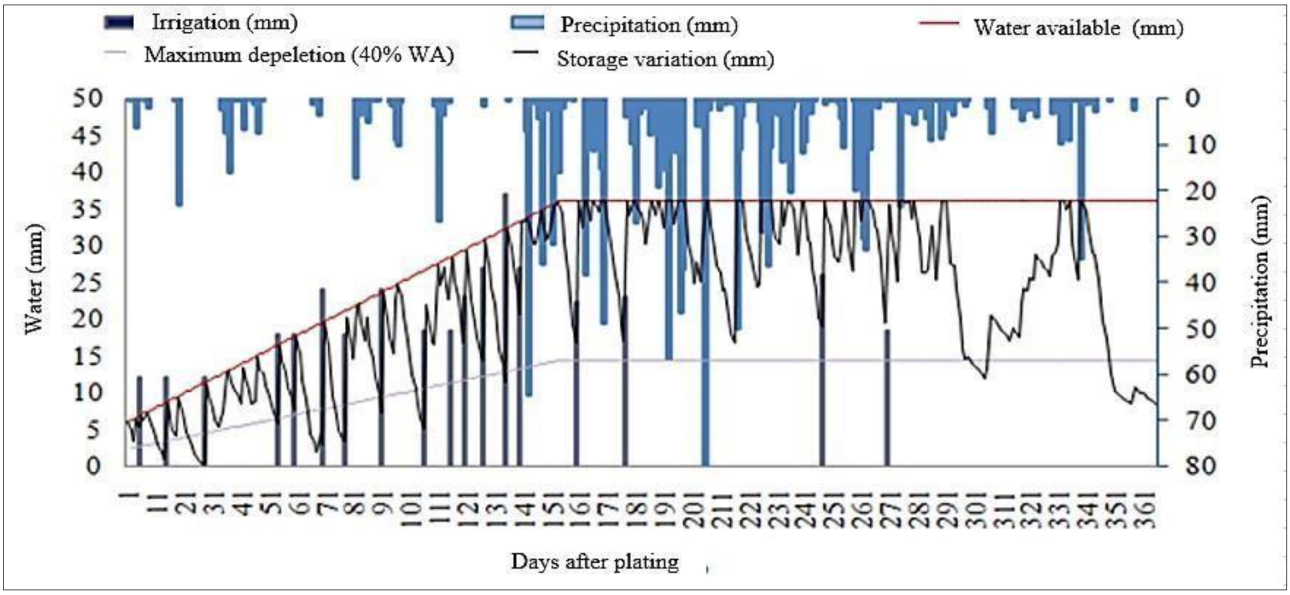


**Figure 4: Water balance during the sugarcane crop cycle (plant crop)**
**Source:** (Costa *et al.*, 2022)

**Temperature:**

Over the past few decades, a rise in temperature has been recorded in the majority of Asian territories. Nearly 27% of greenhouse gases (GHG) in this region are attributable to agricultural activities (Fahim, 2011). As indicated by the global climate risk index report of 2020, Pakistan ranked 5th among nations most susceptible to being impacted by global warming, and climate shifting patterns (Garg, 2021). Stability of major crops including sugarcane is under great threat due to changing scenarios of climate both in space, and irrigated cropping systems. A projection indicated that by 2040, the increase in temperature of $3^0$C and till the end of 21st century temperature surge 5-$6^0$C (Ghanem, 2010). It is predicted that by 2040, a substantial reduction of 8-10% in agricultural yield may occur resulting from rise in temperature(Cradock-Henry *et al.*, 2020). The escalation in temperature is likely to influence the physiological mechanism of sugarcane plants. Sugarcane since classified as C4 plant that starts to increase $CO_2$ assimilation through the photosynthetic pathway when the temperature surges within a range of 8-$34^0$C (Gawander, 2007; Sage & Kubien, 2007). Temperatures above $38^0$C not only hinder germination but also impact vegetative growth resulting from a decrease in photosynthetic and an increase in the respiration rate. Plants complete their life cycle faster under higher temperatures resulting in a shortening of the reproduction period and leads to significant loses in overall crop yield(Taylor *et al.*, 2022).

When evaluating crop production systems and the effects of climate change on them, an inclusive examination of different social, economic, and environmental factors become mandatory. It may include 1) Balancing long-term and short-term goals, 2) Enhancing Productivity, Per-Capita Income/Profitability and Sustainability, 3) Adoption of Integrated Management Practices, 4) Modern Technology Transfer 5) Climate change and crop production policies, 6) Optimizing food and energy resources. Certainly, these challenges are also affecting the sugarcane production system.

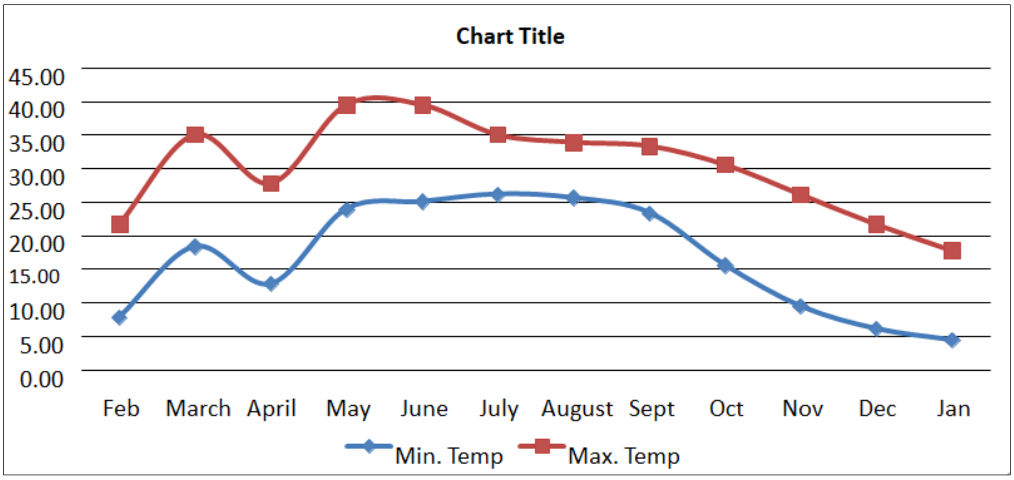


**Figure 5: Mean monthly temperature (max. and min.) during 2019-20 crop seasons in Punjab.**
**Source:**(Sanghera *et al*., 2019)

**2. Climatic Shifts and Sugarcane Crop Behavior:**

Sugarcane is a major agro-industrial crop used for the production of sugar and contributes to 80% global sugar production(Murphy, 2017). Over the past few decades, it has become evident that anthropogenic activities, particularly the combustion of fossil fuels and deforestation, greatly contribute to the shifting of climatic events, including extreme temperatures and precipitation pattern(Intergovernmental Panel On Climate Change, 2014). Among numerous economic sectors, agriculture is the most susceptible to such changes, and over the last 30 years, a number of studies have been conducted to analyze the potential effect of these climate shifts on agricultural yield and production(Adams *et al*., 1990; Attavanich & McCarl, 2014; Mendelsohn *et al*., 1994; Miao *et al*., 2016; Schlenker & Roberts, 2009). Investigations have shown that the variability in temperature, precipitation, and their relationship has affected crop yield, while the impact of climate change is likely to be variable based on geological position, crop type, farmer adoption, and specific scenario(Attavanich *et al*., 2013; Cammarano *et al*., 2019; Lobell *et al*., 2011; Raymundo *et al*., 2018; Zhao *et al*., 2017).

For sugarcane crop, Prior studies measured the yield potential under climate changing Scenarios. By using the Caregro model (Singels *et al*., 2014) it was shown that at fixed composition of 360 ppm of $CO_2$, Sugarcane yield was estimated to reduce at 2 sites, in piracicabal (Brazil) and in Ayrl (Australia), with a ratio of 4.15% and 4.65% for rainfed and irrigated crops, respectively, from the 1980-2010 baseline. Considering the effect of $CO_2$ fertilization, (Marin *et al*., 2013) revealed that there might be a remarkable increase of 24% in sugarcane yield in São Paulo, Brazil in 2050. Furthermore, (de Medeiros Silva *et al*., 2019) founded a positive correlation between precipitation and sugarcane yield, whereas production is negatively associated with temperature in Paraiba municipalities of Brazil. In Mexico, the agriculture land management alternative model used by (Baez-Gonzalez *et al*., 2018) documented that sugarcane yield will increase 1-13% under positive outcomes of climate change in the future when compared to $A_2$ scenario with the baseline. Meanwhile, (Hongyan *et al*., 2018) used the agriculture production system stimulator (APSIM)-Sugarcane model and projected that higher altitude will contribute the greatest percentage change in sugarcane yield with an increase in mean value of 44.2% and 23.5% for Representative concentration pathway (RCP) 4.5 and 8.5, respectively, in 2060.

Shifting in climatic patterns results in drought, which effects the sugarcane crop, and severity will impact the crop according to the growth and developmental stage of the plant, intensity, and duration of water scarcity stress. Normally, at the early and middle growth stages, drought predominantly reduces cane yield, which results in an overall loss of sucrose yield. During the late growth stage, moderate drought stress leads to increased sucrose concentration in the stacks. In China (Globally 3rd top sugarcane producer), drought is a dominant stress factor in the production of sugarcane crop, and over 80% of the crop thrive under rainfed condition *(Gilbert et al*., 2008). Waterlogging, another stress factor for sugarcane production, impacts the growth and challenges the survival of crop, leading to 18-64% loss of yield (Gilbert *et al*., 2008)mainly depending upon the variety, period of waterlogging, and growth stage of crop (Gilbert *et al*., 2008; Glaz & Lingle, 2012). In sugarcane production, certain diseases, weeds, and insects are also influenced by a shift in temperature resulting from climate change (Chandiposha, 2013).

Currently, under climate-changing scenarios, effective adoptability of farming systems for sugarcane production is required by maximizing the potential benefits and mitigating the potential adversities. Therefore, understanding the climatic patterns and their potential impact will be helpful in designing the new prototypes that have better adoptability to climatic shifts and will meet human needs by enhancing the profitability.

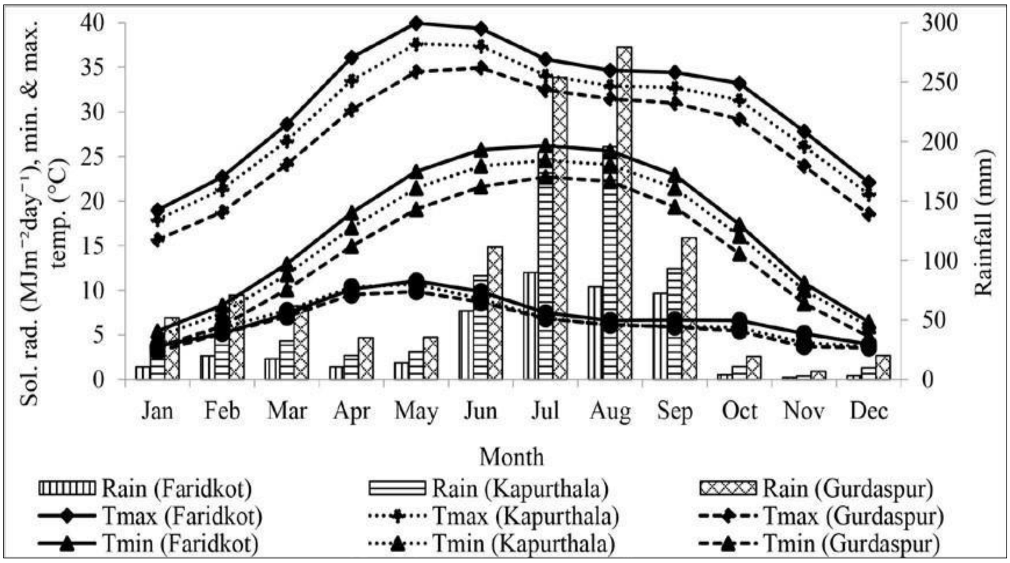


**Figure 6: Monthly weather conditions at different locations in India during 2000-2017**
**Source:** (Singh *et al*., 2021)

### 3. Mitigation Strategies for Climate-Resilient Sugarcane Production:

More frequent and extreme weather events resulting from shifts in climate change lead to a vulnerable and has adverse effects on agriculture (Calvin *et al*., 2023; Dhillon & von Wuehlisch, 2013; Gawander, 2007; Thornton *et al*., 2009), even though over the past 56 years from 1965-2021, global sugarcane production increased four times(*Global Sugar Cane Production 2021*, n.d.). This change in sugarcane production is because of the surge in both yield and hectarage.

However, there is a dire need to double the efforts to enhance yield and maximize profitability under the growing world population and climate-shifting scenario. Factors that majorly contribute to sugarcane production are genotypes (cultivars), management practices, biotic and abiotic growth conditions.

Mitigation and adaptation strategies against climate change, including cultivation of drought resistant genotypes, investment in irrigation infrastructure improvement, enhancing the efficiency of irrigation and drainage systems, and improvement in cultural and management practices have been proposed in Zimbabwe (Chandiposha, 2013). Deresssa *et al*., highlighted the need for adaptation strategies based on the long-term data collected in South Africa and suggested that focus on technologies and management approaches will help in tolerance of warm temperatures, specifically during the harvesting stage of sugarcane in winter (Deressa *et al*., 2005). Therefore, a key aspect for adaptation against climate change is to develop stress tolerance and high yielding cultivars, and for this purpose plant scientists can build databases to facilitate hybridization program for achieving specific objectives in breeding programs like different parameters includes growth and physiological traits can be used for screening elite lines against biotic and abiotic stresses (Inman-Bamber *et al*., 2012) and advanced technologies (tissue culture, molecular breeding, double haploid and CRISPR CAS) can enhance the efficiencies of breeding and selection processes. Anotonell mentioned that gene editing and genomic sequencing techniques are crucial for enhancing crop production by resisting climate change, pests and diseases without harming the environment (Antonelli, 2023). Ali *et al*., found that to counter the impact of climate change, there is a dire need to develop different varieties(Ali *et al*., 2017).

Diversifying cropping systems and cultivars within a crop is important to mitigate the effects of extreme climatic events because among cultivars, plant species and cropping system there is a considerable difference in adapting to such extreme stresses. For this season, it is suggested that each dominant sugarcane cultivar should not cover more than 25% of its total area in the region to mitigate the negative impacts and minimize the risk of crop failure due to unexpected pests and diseases. Additionally, adaptation of the best management practices (BMPS) for increasing input efficiencies and control of pests and diseases is key to overcome the climatic challenges and enhance the sugarcane yields. These practices include tillage operations, irrigation methods and scheduling, drainage systems, nutrient monitoring and fertilizers, mulching, and carbon sequestration. To summarize, the application of mitigation strategies through a comprehensive and interdisciplinary approach will be useful to save the future agroecosystem.

**4. Understand Sustainability in Sugarcane Production:**

Sugarcane as a bio-factory has the potential solution to address the problems of global sustainable development such as climate change, poverty reduction, green energy, water scarcity, and technological innovations. To achieve this, agribusinesses and stakeholders have to adapt the 21st centuries need of sustainability, circular bioeconomy and economic variability including modern factors of competitiveness, diversified production, Agriculture 5.0, Industry 4.0, and authentic methodology structure methodological structure which are vital for systematic and transdisciplinary evaluation of sugarcane bio-factory across these dimensions. At the farm level, two major constraints farmers have faced are low quality production and yield of sugarcane resulting from overuse/improper use of agrochemicals and trash burning. Aligned to it, the challenges like climate impact, biodiversity loss, water scarcity and resource depletion, sugarcane industry is currently facing as an Agri food sector (Hamam *et al*., 2021). Defining sustainability, Palmeres-parada *et al*., elaborated that the recognition of issues within the social economy and environmental aspects of crop field, public policies etc. to assess the impact of sustainability policies through stakeholder alignment within the pre-structured framework of 2023 sustainability agenda including goals, objectives and indicators(Palmeros Parada *et al*., 2021).

For the sugarcane industry, several different sustainability certification schemes and indicators have been formed by both scientists(Aguilar-Rivera, 2019) and organizations like Bonsucro. In 2008, the Bonsucro production standard was formulated to uplift and enhance sustainability in the sugarcane sector both at the farm level and at mills, through which operators can measure sustainability through defined indicators to produce sugarcane and its derived products. This metric-based production standard Provides the quantifiable sustainability goals to the operator with a set of standard production data define according to the geographical locality to gauge the performance based on three pillars of sustainability: social, environmental and economic (Viart *et al*., 2016).

**Concept of Circular Economy (CE) in Sustainability of Sugarcane:**

Circular economy aims to reduce waste to minimum through strategies such as sharing, reducing, reusing, and recycling. This shift from a linear economy to a CE demands efforts to enhance sustainable practices by managing complex changes in existing systems like technologies, costs, resources, and reliable policies are aligned with sustainability indicators. Hence, the sugarcane industry can take it as an opportunity to shift from conventional to sustainable bases (Geissdoerfer *et al*., 2017). Kirchherr *et al*., connected circular economy with sustainable goal by altering the concept "end of life" with material reduction, reuse, recycling and recovery at several levels (micro, meso and macro) of production and consumption, with an objective of increasing the performance of sustainability pillars by enriching the social equity, environmental quality and economic prosperity for present day and future generations(Kirchherr *et al*., 2017). Circular economy relies on the following key principles; 1). Safeguard natural and renewable resources 2). Improve resource efficiency through material recycling and renewable energy production and 3). Optimize available resources by value addition without exerting negative impacts. These fundamental principles are often referred as 3Rs "Reduce, Reuse, and Recycle"(Pourahmadi *et al*., 2016).

## 4. CONCLUSION

It is evident that sugarcane crop is directly or indirectly affected by climate change, especially due to the onset of extreme events like drought and high temperature. To an extent, current adopted strategies may be able to overcome the adverse effect of such climatic conditions by overuse of available resources however, in long-run it might not be sufficient in resource depression scenario. If emissions of GHG remain high, there are possibilities that the era of post 2050 will exert an adverse impact on the quality and yield of sugarcane. Therefore, there is a dire need for collaboration between the scientific communities and organizations to come up and align the businesses and stakeholders to broaden the agenda of sustainability to its new horizons by minimizing the resource wastage and maximizing the outcome across all stakeholders to counter the potential negative consequences of climate change. This could be achieved by adapting multidisciplinary approaches including introgression of new cultivars specific to locality, sustainable and measurable management practices, technologies transfer, enhancing production and profitability by safeguarding natural resources and improving efficiencies through value addition to sugarcane byproducts including sugar ethanol and biofuel to ensure economic gain.

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**Authors Contributions:** All the authors contributed equally in the manuscript.

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