Sustainable Pearl Millet Cultivation: Choices in a Changing Climate

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Abstract

Unprecedented changes are occurring to the Earth's climate, with temperatures rising quickly, precipitation patterns changing, and an upsurge in the frequency of extreme weather events. These dynamic shifts are having a significant and wide-ranging effect on agro-ecosystems. Among different food crops, pearl millet proves climate resilience with a deep root system, efficient photosynthesis, and drought tolerance, while early maturity lessens vulnerability to extreme weather and the C_4 photosynthetic pathway enhances CO_2 fixation and water use. This paper thoroughly explores the unique characteristics of pearl millet that enable it to flourish in harsh conditions. It discusses the impact of climate change on pearl millet and its assessment using crop modeling techniques and proposes robust strategies to enhance its resilience in the face of climatic challenges. These strategies encompass elevating resource use efficiencies such as water use efficiency (WUE), nitrogen use efficiency (NUE), carbon sequestration potential, radiation use efficiency (RUE), and more. Additionally, the paper explores innovative production approaches tailored for changing climates, including adjustments in planting windows, precise fertilizer application, optimal inter and intra-row spacing, efficient irrigation management, etc. To achieve a fair and sustainable global food system that benefits the world's most vulnerable populations, it is important to recognize that pearl millet is a crop that can withstand the challenges of changing climates.

Abbreviations

APSIM: Agricultural Production Systems sIMulator
CERES: Crop Environment Resource Synthesis
DSSAT: Decision Support System for Agro-technology Transfer
FAO: Food and Agriculture Organization
GCM: Global Circulation Model
GHG: Greenhouse gases
GI: Glycemic Index
IW/CPE: Irrigation Water/Cumulative Pan Evaporation
NUE: Nitrogen Use Efficiency
PAR: Photosynthetically Active Radiation
ppb: parts per billion
ppm: parts per million
RCM: Regional Circulation Model
RCP: Representative Concentration Pathways
RUE: Radiation Use Efficiency
SALUS: Systems Approach to Land Use Sustainability
SDGs: Sustainable Development Goals
SRES: Special Report on Emission Scenarios
SSP: Shared Socio-economic Pathways
SST: Sea Surface Temperature
SWAP: Soil Water Atmosphere Plant
WOFOST: WOrld FOod STudies
WUE: Water Use Efficiency

Introduction

One of the biggest problems facing the globe today is climate change. It is described as notable variations in the long-term averages of meteorological variables, such as temperature and precipitation, that have been computed and also place significant pressure on various sectors of the economy. Some parts of the world will benefit more from some aspects of climate change than others. For example, colder countries may experience temperature increases or experience carbon fertilization effects, as noted by Stokes and Howden (2010); significant negative consequences (such as water stress, increased yield variability, decreased crop yields, etc.) might befall other nations. Due to its large scale and increased susceptibility to meteorological factors, the agriculture sector is identified as being extremely vulnerable to the effects of climate change (Saravanakumar *et al.*, 2022). As a result, this vulnerability presents a serious risk with considerable financial consequences (Mendelsohn, 2009). World agriculture faces a serious decline within this century due to global warming. Overall, agricultural productivity for the entire world is projected to decline between 3-16 % by 2080 (Mahato, 2014). Generally, the total agricultural productivity of developing nations is expected to decline by 9-21% as a result of global warming (Thakur *et al.*, 2024).

India is one of the most affected nations by climate change and natural disasters because of its low amount of arable land, large population, reliance on agriculture and monsoon-dependent farming, and lack of technological and financial advancements for climate change adaptation (Birthal *et al.*, 2014). Over India, rainfall is expected to increase by 10-12% by the end of the twenty-first century, and the average annual temperature is predicted to rise by roughly 3-5°C (Vyankatrao, 2017). All seasons will see an increase in temperature, with a maximum of 4-5°C, as well as an increase in precipitation and high temperature and high precipitation extremes, according to Salunke *et al.* (2023). Different crops may be produced differently depending on the season, degree of management, and climate change (Aggarwal, 2003), whereas their yields are impacted in distinct ways by various climatic variables in India (Guntukula, 2020). Therefore, it is critical to concentrate on high-yielding, climate-resistant cereals in agricultural production systems to maximize production while minimizing resource usage. In these situations, pearl millet is a crop that can be profitable, suitable for the environment, culturally acceptable, and nutritious.

Next to sorghum, pearl millet (*Pennisetum glaucum* L.) is one of the most significant coarse grain crops farmed worldwide and viewed as food for the underprivileged. It is widely grown in tropically dry and semi-arid regions of Asia and Africa, covering an area of 30 million hectares, and serves as a staple diet for approximately 90 million people living in poverty (Gupta *et al.*, 2015), while in India, it is grown on around 6.70 million hectares, with a production of 9.62 million tons during 2021–22 (Fig. 1). It has a high nutritional value, is a climate-resilient crop, is practically devoid of severe illnesses and insect infestations, and can be grown to produce a good crop; hence, the emphasis should be on creating edible products to promote it as a future alternative crop (Satyavathi *et al.*, 2021). This paper reviews the significance of pearl millet for food and nutritional security in the current changing climate, as well as the choices in the changing climate for pearl millet production.

International Year of Millets, 2023

The Sustainable Development Goals (SDGs), which tackle environmental protection and poverty eradication, were unanimously adopted by the UN in 2015, with the objectives of ending hunger, guaranteeing food security, improving nutrition, and advancing sustainable agriculture. Because of the interdependence of

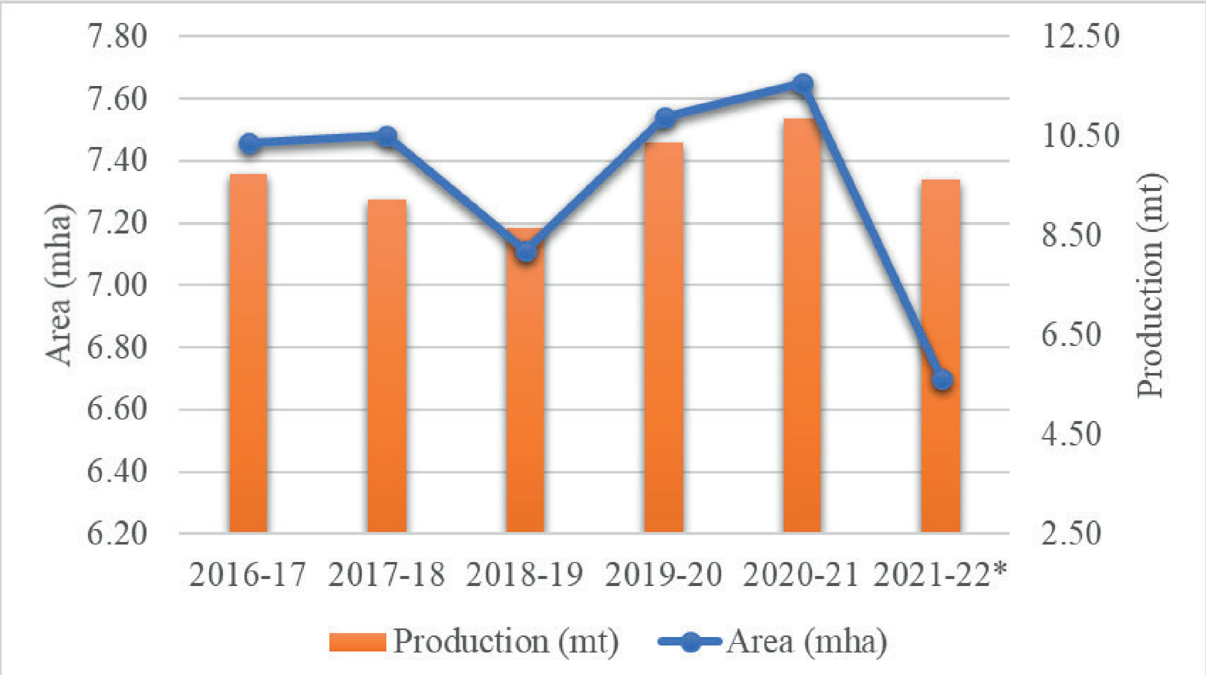

Fig. 1 - Trends in pearl millet area and production across India for past five years
(*4th Advance Estimates, Agricultural Statistics at a Glance 2022)

agriculture and climate change, quick fixes are needed to lessen the effects of the latter on food security and hunger to achieve the SDG targets by 2030. One important strategy is to gradually transition to crops that can withstand drought; millets are becoming a viable and wholesome alternative to meet the demands of the world's growing population (Nesari, 2023). Compared to traditional cereals, millets are more nutrient-dense, resilient to climate change, and require less fertilizer and pesticides (Antony Ceasar and Maharajan, 2022). The United Nations General Assembly designated 2023 as the International Year of Millets in recognition of their potential (Srivastava *et al.*, 2023). Strong agriculture, better nutrition, and healthier diets are all facilitated by the support of millets (Pradhan *et al.*, 2021); Nesari 2023).

Nutritional significance of pearl millet

Since nutrition is a long-lasting force for health, it plays a decisive role in helping people in starving areas to avoid malnutrition. Numerous studies have consistently shown that millets are an exceptional and valuable source of essential nutrients, including fundamental components like amino acids and a wide range of essential minerals and trace elements (Anitha *et al.*, 2020). Pearl millet is a highly nutritious grain that is the primary source of energy for semi-arid tropics and drought-prone regions of Asia and Africa because it contains higher concentrations of vitamins and minerals, easier-to-digest proteins, starch, soluble and insoluble dietary fibers, and antioxidants (Table 1). Due to this status, it shares a crucial position with important grains like sorghum, wheat, rice, and maize (Satyavathi *et al.* 2021; Ragaee *et al.* 2006). The glycemic index (GI) measures how food affects blood glucose levels. Pearl millet has a low GI, which can help lower insulin reactions, cholesterol, and blood pressure (Dona *et al.* 2010; Sewak *et al.* 2023).

Growth phases and phenological behaviour of pearl millet

The success of a crop is determined by how well it grows and the duration of its growth cycle. Pearl millet is a crop with small seeds, a short cycle, and monocot status, and its growth cycle comprises three main phases: the vegetative phase (GS_1) from emergence to panicle initiation, panicle development phase (GS_2) from panicle initiation to flowering, and the grain-filling phase (GS_3) from flowering to physiological maturity (Fig. 2) (Maiti and Bidinger, 1981). Under optimal conditions, pearl millet seeds germinate in 3-5 days, extending to 7 days in unfavourable weather. The flag leaf appears after 50 days, with panicle initiation and blooming at 45 and 59 days. Seed setting and grain formation begin 60–65 days post germination, concluding in 9–10 days. Physiological maturity occurs around 90–95 days post germination, influenced by weather conditions (Khairwal *et al.*, 2007). Pearl millet's root system includes seminal roots (3-4 days post radicle emergence), adventitious roots (6-7 days after seedling emergence), and crown roots (30 days after emergence) (Maiti and Bidinger, 1981).

Climate requirement of pearl millet

A crucial agricultural option for tackling environmental issues is cultivating pearl millet, which has lower water requirements, resilience to climate change, and resistance to drought. It thrives in hot, dry environments with low rainfall and poor soil fertility, where other crops often struggle to survive. The optimum air tem-

Table 1 - Nutritive value of pearl millet (gm/100gm)

Carbohydrate	50.4–63.2	Tomar *et al.* (2021)
	67.0-67.5	Amadou *et al.* (2013)
	70.0	Shukla *et al.* (2015)
Protein	8.0–18.1	Tomar *et al.* (2021)
	11.8	Shukla *et al.* (2015)
	11.6-11.8	Amadou *et al.* (2013)
Fat	4.8-5.0	Amadou *et al.* (2013)
	4.8	Shukla *et al.* (2015)
Ash	1.8	Dias-Martins *et al.* (2018)
	2.3	Shukla *et al.* (2015)
Energy (Kcal)	353	Shukla *et al.* (2015)
	360	Khairwal *et al.* (2007)
Ca (mg)	37.0	Shukla *et al.* (2015)
	42.0	Amadou *et al.* (2013)
Fe (mg)	9.8	Shukla *et al.* (2015)
	8.0	Amadou *et al.* (2013)

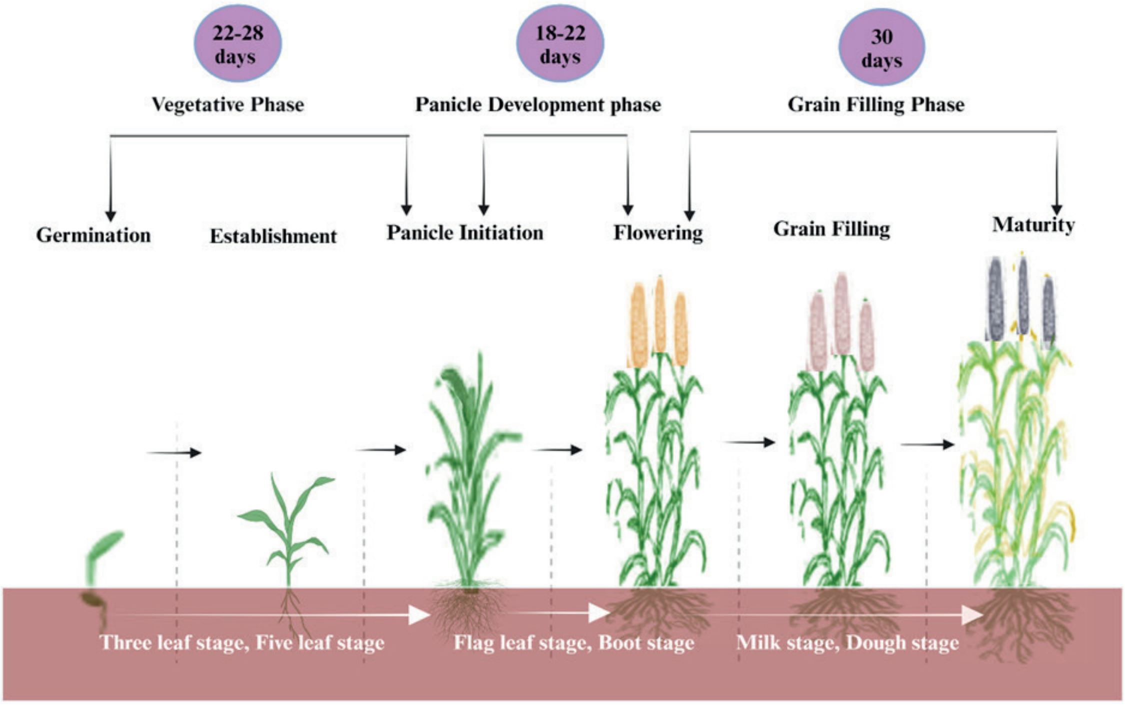

Fig. 2 - Growth Phases of pearl millet

perature range for the vegetative growth of pearl millet is 33 to 34°C (Ong and Monteith, 1985), and rainfall for optimal growth is 350 to 500 mm, while it shows poor emergence and seedling growth at soil temperatures below 23°C (Upadhyaya *et al.*, 2008). (Fussell *et al.*, 1980) found that high temperatures (33/28°C day/night) during the vegetative, stem elongation, and grain development phases negatively impact pearl millet grain yield and result in fewer grains per inflorescence, fewer basal tillers, and a decrease in the weight of individual grains. It grows best when the soil is kept sufficiently moist through irrigation, but it can also withstand erratic weather as a result of its deep, quick-growing roots.

Reported trend of climate change

Unquestionably, human activity, especially the release of greenhouse gases has, caused global warming, which has raised the average global surface temperature by 1.1°C between 2011 and 2020 when compared to the baseline of 1850–1900. Atmospheric CO_2 levels reached 410 ppm, and atmospheric CH_4 and N_2O peaked at 1866 and 332 ppb in 2019. These results indicate that greenhouse gas concentrations in the Earth's atmosphere were elevated in 2019. The warming effect was also significantly influenced by halogenated gases and tropospheric ozone (O_3) (Lee *et al.*, 2023).

Due to the harsh effects of climate change, India faces substantial challenges concerning public health, food and water security, and economic growth. The average temperature of the nation increased noticeably by about 0.7°C between 1901 and 2018. The average sea surface temperature (SST) in the tropical Indian Ocean increased by 1°C between 1951 and 2015, indicating a more noticeable warming. The Western Ghats and the Indo-Gangetic Plains have been worse hit by the roughly 6% decline in summer monsoon precipitation between 1951 and 2015. The frequency and geographic extent of droughts in India have also alarmingly increased between 1951 and 2016, sea levels in the North Indian Ocean rose historically, reaching 3.3 mm annually between 1993 and 2017 (Krishnan *et al.*, 2020). For most of India's subdivisions between 1871 and 2011, Mondal *et al.* (2015); Dash and Hunt (2007) reported declining annual and monsoon rainfall. Also, notable regional temperature variations were observed, with the winter and post-monsoon seasons showing the highest minimum, maximum, and mean temperatures. Bhargavi *et al.* (2023) reported a significant increase in the frequency of droughts between 1990 and 2019. Although the static stability of the current atmospheric conditions was cited as the cause, the primary causes of this increase are the regions of Central and Northeast India's higher surface temperatures and decreased precipitation.

Future projection of climate change

Climate projections, which typically span until 2100, employ computer simulations to forecast Earth's climate for upcoming decades based on the amounts of aerosols, greenhouse gases (GHG), and other atmospheric components essential to affecting the planet's radiative balance. Future climate change projections are typically constructed using general circulation models (GCMs), which have uncertainties due to initial conditions, GHG emission, model process, and downscaling of GCM to regional scale (Asseng *et al*., 2015; Wilby *et al*., 2004). The near future (2021–2040) is predicted to see an increase in global warming, mostly as a result of higher cumulative CO_2 emissions in nearly all scenarios and modelled pathways. Global warming is likely to reach 1.5°C even with extremely low GHG emissions (SSP1-1.9), and it's likely or very likely to surpass 1.5°C under scenarios with higher emission levels (Lee *et al*., 2023). The global surface temperature had risen by approximately 1.1°C above preindustrial levels, a phenomenon that is manifesting sooner and with greater intensity than previously anticipated (Lee *et al*., 2021).

There is a clear pattern of increasing magnitudes observed over the 21^{st} century under RCP8.5 for several climatic parameters, such as average temperature, warmest day and coldest night temperatures, frequency of warm days and nights, sea surface temperature, and ocean heat content in the tropical Indian Ocean. Together with increased daily precipitation extremes in terms of frequency, intensity, and spatial coverage, there is also a noticeable increase in monsoon precipitation variability. In addition, as reported by Krishnan *et al.* (2020) there was an obvious upward trend in the frequency and severity of tropical cyclones, sea levels in the North Indian Ocean, and droughts. Krishnan *et al.* (2020); and Das and Umamahesh (2022) anticipate a spike in the frequency and intensity of heat waves, along with extended periods of heat, indicating an increasing pattern in the upcoming thermal challenges under the RCP8.5 scenario.

Impact of climate change on pearl millet

The productivity of pearl millet is considerably influenced by meteorological variables, such as elevated temperatures during seed setting, shifting precipitation patterns that affect non-irrigated regions, and heightened levels of CO_2. A. Ullah *et al.* (2019) employed the CSM-CERES-Millet model to evaluate the ways climate change alters pearl millet. According to their research, the yield of pearl millet in Faisalabad's semi-arid climate would drop by 7% and 10% at RCPs 4.5 and 8.5, respectively. But in the same RCPs, yield losses for the arid Layyah region range from 10% to 13% by the middle of the century (2040–2069). Ullah *et al.* (2018) observed in Punjab, Pakistan, that the genetic algorithm method proved helpful in forecasting pearl millet yield in the context of future climate change scenarios and this method measured a 12% drop in pearl millet grain yield. In six locations throughout semi-arid (Jaipur, Aurangabad, and Bijapur) and arid (Hisar, Jodhpur, and Bikaner) tropical India, Singh *et al.* (2017) investigated the effects of climate change on pearl millet cultivars. As a result of projected increases in rainfall, most sites except Jodhpur and Bikaner exhibited a decline in yield variability linked to mean yields under climate change. The increased yield standard deviation suggests that climate change has increased yield uncertainty in the drier climates of Jodhpur and Bikaner. In contrast to baseline simulations from 1960–1990, Yadav *et al.* (2013) evaluated the effects of climate change on pearl millet over the projected period (2071-2100) using the DSSAT4.5 (CERES-Millet) model and found that in several districts of Gujarat, India, climate change has an impact on the anthesis date, maturity date, grain yield, and fodder yield of pearl millet.

The impact of climate variability and change on pearl millet was assessed by Rezaei *et al.* (2014) using the DSSAT CERES-Millet model, which predicted a yield decline ranging from -11% to -62% as a result of predicted climate change based on various scenarios and time periods. Using crop yield data from 1971 to 2004 and future climate projections (SRES A1B scenario) for various Indian districts, Rao *et al.* (2019) examined the susceptibility of pearl millet to climate change, and findings indicated a higher yield vulnerability between 2071 and 2098 than between 2021 and 2050, with an average yield impact of about 274 kg/ha. Sultan *et al.* (2013) found that millet yield was negatively impacted by most climate scenarios (31/35) in West Africa, with potential reductions of up to 41% at +6°C and 20% from variable rainfall in the twenty-first century. Research has shown that photoperiod-sensitive pearl millet cultivars can modify their growth cycle to mitigate the effects of climate change, specifically elevated temperatures. Because of the high temperatures that cause high potential evapotranspiration, respiration, and a shortening of the crop cycle, climate change has an impact on pearl millet yield.

Examining the impact of climate change: assessment approaches

Reducing poverty requires an emphasis on agriculture; developing nations may be particularly affected by the adverse effects of climate change on this industry (Cervantes-Godoy and Dewbre, 2010); additionally, residents of developing nations are more vulnerable to future food crises exacerbated by climate change (Nelson *et al.*, 2009). Knox *et al.* (2012) stated that there will be notable regional and crop-specific variations by the 2050s, with a mean yield variation of -8% across all crops. Considering that a large section of the population depends on farming for an income, it is imperative to assess how climate change is affecting crop productivity in India (Pattanayak and Kumar, 2014).

A thorough assessment of the effects of climate change can be carried out using an array of methods, including expert judgment, empirical research, modeling, predictions, and quantitative models (Feenstra, 1998). Of the various approaches, crop growth models, which incorporate future climate conditions derived from Regional or General Circulation Models (RCMs and GCMs, respectively), have been widely used to rigorously assess the impacts of climate change. Evaluation of crop responses in terms of development, growth, and yield is made possible by these models (Moriondo *et al.*, 2011); Zacharias *et al.*, 2015). Combining projections from climate models with process-based crop models is a useful strategy for conducting a thorough assessment of how climate change is affecting crop yields. Corbeels *et al.* (2018) have highlighted the importance of this combined methodology in providing meaningful information to support successful and accurate crop-level adaptations in the face of changing climatic conditions.

Approaches to enhance pearl millet resilience in the face of climate change

Boosting pearl millet's resilience to climate change demands a comprehensive strategy integrating agronomic and genetic approaches. Singh *et al.* (2017) suggest that improved resource use efficiency in pearl millet genotypes can lead to significantly higher yields, particularly under challenging climate conditions. Optimizing water, nutrients, and inputs stands out as a crucial aspect of enhancing resource use efficiency, aiming to maximize productivity while minimizing environmental impact.

1 *Water Use Efficiency*

One of the factors used to assess a plant's resistance to drought is its water use efficiency (WUE), or the biomass it produces per unit of water transpired. This criterion is helpful when choosing plants against drought (Ibrahim *et al.*, 1986). Millets are distinguished by their exceptional water efficiency, requiring a great deal less water for growth than a number of well-known crops, including wheat, maize, cotton, rice, and sugarcane (Fig. 3). Improving the WUE of pearl millet is crucial in the context of climate change, where water scarcity and unpredictable weather patterns pose significant challenges to agriculture. According to Sivakumar and Salaam (1999), fertilizers may have an impact on improving WUE and lowering soil evaporative losses by accelerating the early growth of leaves. When fertilizer was added, the average WUE of pearl millet increased noticeably, reaching an astounding 84%. Greater yields and WUE are possible using plant populations >20,000 hills ha^{-1} and fertilizer applications of >40 kg N ha^{-1} and >18 kg P ha^{-1} for most of the climatic zones of the West

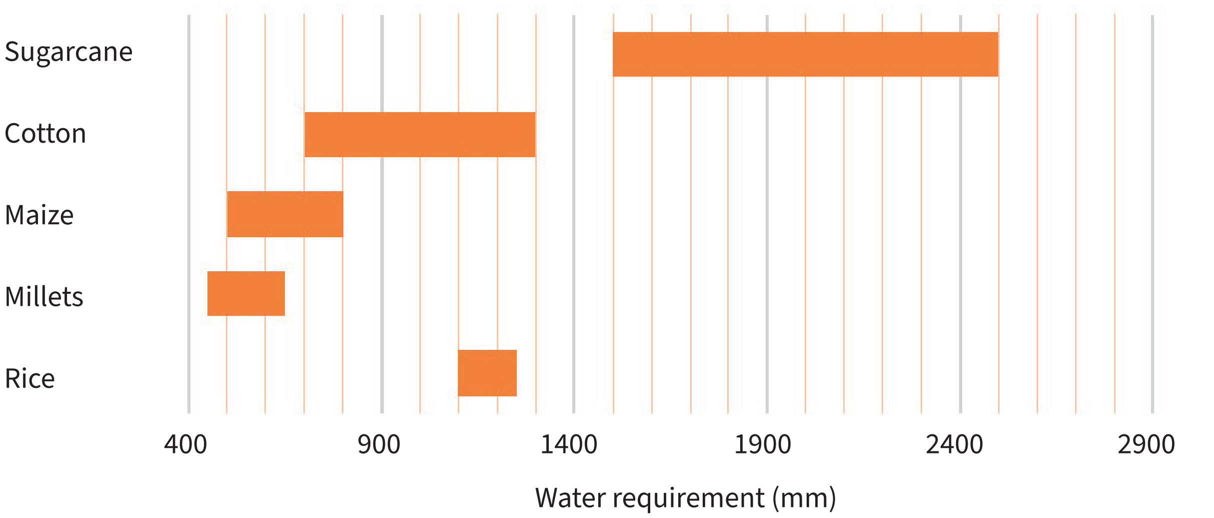

Fig. 3 - Water requirement of different crops

African Sahel (Payne, 1997). Nagaz *et al.* (2009) noted that under complete irrigation, the pearl millet crop consistently showed high yield and exceptional WUE, highlighting the crop's vulnerability to possible failure. Strategic interventions like soil management, crop husbandry, water management, genetic selection, and crop competition management can improve the WUE (Farooq *et al.*, 2019).

2 *Carbon sequestration potential*

A number of important food crops and bioenergy grasses rely on C_4 photosynthesis as their main source of carbon capture, which also boosts productivity (Vivitha and Vijayalakshmi, 2015). Kushwah *et al.* (2014) examined the carbon sequestration potential among crops such as maize, soybean, sorghum, pearl millet, finger millet, and rice by estimating carbon and nitrogen partition in root and shoots and the result showed that the carbon sequestration potential of maize and pearl millet was higher compared to other crops. Pearl millet exhibits efficient rhizodeposition, releasing carbon compounds from its roots that nourish soil microorganisms and ultimately contribute to soil organic carbon storage (Ndour *et al.*, 2022). Ali *et al.* (2021) found that one practical method for reducing gas emissions from saline, sodic soils is the sequestration of carbon using pearl millet supplemented with biochar (the total amount of organic-C sequestered by the pearl millet was 6.00–9.45 ton C ha^{-1} per season). Because pearl millet is a powerful carbon sink in the global terrestrial carbon fixation process, its effective soil carbon sequestration improves climate resilience. As a result of its high photosynthetic efficiency, pearl millet actively contributes to sustainable agriculture and lowers atmospheric CO_2 levels.

3 *Nitrogen Use Efficiency*

Nitrogen Use Efficiency or NUE for short, is a vital indicator of a crop's capacity to use nitrogen efficiently and is the ratio of nitrogen absorbed by the crop to the amount of nitrogen applied per unit (Fageria and Baligar, 2005). A complex interaction between plant physiology and environmental factors determines crop NUE. Dividing crop yield by nitrogen inputs yields the most accurate way to calculate NUE (Govindasamy *et al.*, 2023). Leaching and gaseous losses of nitrogen are increased by climate change. Under higher CO_2 levels, it is anticipated to increase nitrogen use efficiency. Higher CO_2 levels cause crop growth to intensify, necessitating the application of more nitrogen than is currently done in agriculture (Boomiraj *et al.*, 2010). When crop performance is negatively impacted by below-optimal temperature, a spike in seasonal air temperature can cause a sudden increase in crop growth and nitrogen demand, potentially leading to a rise in NUE (An *et al.*, 2005). Govindasamy *et al.* (2023) prophesied that NUE can be greatly increased by strategic management practices that involve careful consideration of fertilizer application timing, rate, source, and placement. Mosier *et al.* (2013) observed that crucial environmental determinants influencing agronomic NUE include photosynthetic active radiation (PAR), temperature, and rainfall. In a descending hierarchy of impact, temperature takes precedence, followed by rainfall and irradiance

4 *Radiation Use Efficiency*

Radiation Use Efficiency (RUE), a crucial indicator of the plant's photosynthetic productivity, describes how well the crop transforms absorbed PAR into dry matter (H. Ullah *et al.*, 2019). A variety of factors, including soil heterogeneity, climate, crop management techniques, and a range of abiotic stressors like water deficits and temperature fluctuations, are primarily responsible for the variability in RUE (Rouphael and Colla, 2005). In favourable circumstances, the conversion efficiency of pearl millet surpasses that of C_3 plants, standing at an impressive 2.9 g MJ^{-1} PAR over the entire growth cycle. However, this efficiency diminishes with the extension of the cropping cycle and decreases notably when the crop is cultivated under suboptimal conditions (Begue *et al.*, 1991). In irrigated arid conditions, Ahmad *et al.* (2016) recommend raising the RUE for C_4 summer cereal crops such as maize, millet, and sorghum by following a three-split nitrogen application strategy instead of a single application. According to Niwas *et al.* (1997), the implementation of a north-south sowing orientation resulted in a noteworthy increase of 0.21 g MJ^{-1}, which is significantly higher than the results observed in crops sown in an east-west direction. This indicates a substantial enhancement in radiation-use efficiency.

Production strategies under changing climate

In order to minimize the negative effects of climate change, adaptation is an essential component in reducing its possible negative effects (Fig. 4) (Ahmed *et al.*, 2019; Yang *et al.*, 2019). A more resilient and dynamic agricultural landscape is the result of improvements in crop varieties, modifications to ideal planting dates and rates, nitrogen levels, intra-row spacing, creative cropping sequences, changes to the required fallow years for soil-water replenishment in rainfed systems, and the addition of alternative or novel crops (White *et al.*, 2011). The components reported below are critical and essential:

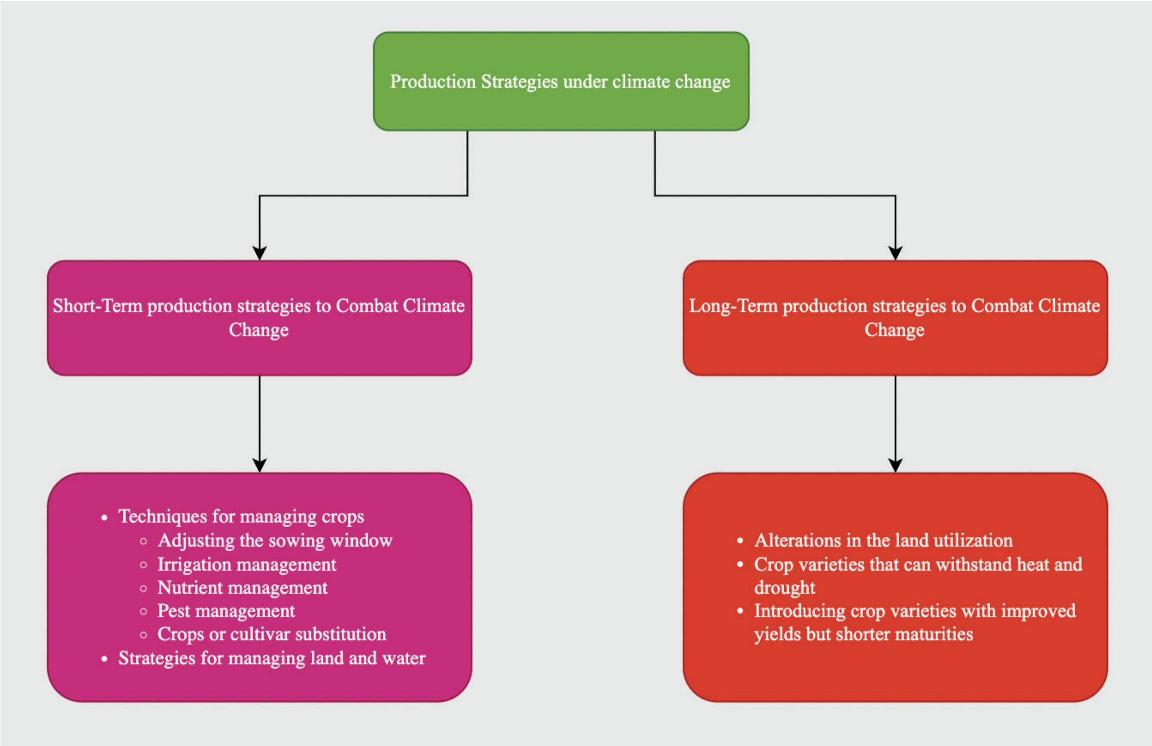

Fig. 4 - Sustainable production tactics in a changing climate

1 *Adjusting the planting window*

According to Jalota *et al.* (2012); Lashkari *et al.* (2012), aligning planting dates with optimal temperatures is a realistic and environmentally friendly approach to sustaining yields in the face of rising temperatures. Effective shifts in planting dates can significantly mitigate the probable negative impacts of drought, making future cultivation more resilient to climate challenges. Drastic droughts have a negative impact on crop productivity, but they can be mitigated by planting when flowering occurs during times when the risk of drought is lowest (Lu *et al.*, 2017). Traore *et al.* (2022); Nwajei *et al.* (2019) demonstrate that delayed planting considerably drops millet yield, which points out the decisive role of timely planting as a crucial strategy for securely fixing challenges linked to rainfall variability. Day length appears to be a major factor affecting pearl millet's final yield, regardless of whether it is sown in an environment with enough moisture or insufficient moisture, according to Maas *et al.* (2007). Singh *et al.* (1998) observed that a crop's need for thermal time is greatly impacted by the timing of sowing because it affects the crop's phytoclimate conditions as well as temperature, radiation, and photoperiod. It is clear from comparing normal and late sowing that the early-planted crop requires more thermal time to reach the flowering stage. The prolonged availability of a longer photoperiod during the crop's vegetative stage is thought to be the cause of this flowering delay. Junior *et al.* (2023) noticed that the number of days that pearl millet was subjected to water stress was reduced by carefully planning the planting schedule to more closely match patterns of precipitation during times of increased water demand, i.e., it is essential to modify the planting date to match crop requirements with water availability.

2 *Fertilizer application*

Porter *et al.* (1995) stated that changes in climate have the ability to cause either greater or smaller losses of nitrogen through gaseous emissions and leaching, or changes in the demand for fertilizer. According to Sivakumar and Salaam (1999), there was a massive 7–14% increase in water consumption when pearl millet was fertilized with 30 kg P_2O_5 and 45 kg N ha^{-1}. Increased yields and better water use efficiency are outcomes of the fertilizer because it encourages early leaf growth, less water goes out through soil evaporation, and more water gets used efficiently. For enhancing crop quality, efficient nitrogen management is essential for preventing possible degradation brought on by different climate change scenarios. It is expected that crops will show higher levels of carbohydrates, lower levels of protein, and an elevated C:N ratio due to the rising concentration of CO_2 in the atmosphere and the decreased availability of N in the soil under changing conditions (Pathak *et al.*, 2016). Under current environmental conditions as well as in the face of projected future climate change scenarios, pearl millet's total dry matter production could be significantly increased by implementing an optimized fertilization management strategy (Rezaei *et al.*, 2014). Arya *et al.* (2022) observed that applying nitrogen fertilizer dramatically increased pearl millet yields, exhibiting a distinct curvilinear response, especially considering the climate conditions of the mid-century (2040-2069). Shukla and Panda (2023) noticed that in drought conditions, adding nitrogen had a significant physiological impact on different varieties of pearl millet's growth, biomass accumulation, relative water content, etc.

3 *Intra and inter row spacing*

Mtambanengwe *et al.* (2012) observed that increasing the intra and inter-row spacing is a coping strategy for climate change, which reduces the competition for soil moisture. Legwaila *et al.* (2014) reported that plants spaced further apart showed a notable improvement over those spaced closer together in terms of leaf area, number of leaves, and number of tillers because, with wider spacing, effective utilization of increased solar radiation and nutrient resources was observed. Grain yield and total biomass are significantly and statistically affected by the adjustment of intra-row spacing. Pearl millet grain yield increased by 28.7% when the intra-row spacing was increased from 15 to 25 cm, and the grain yield increased by 6.7% when the inter-row spacing was adjusted from 40 to 60 cm (Yoseph, 2014).

4 *Irrigation management*

Globally, there is an increasing need for irrigation water in light of climate change, so farmers must employ more effective irrigation techniques to conserve water and optimize its use due to inefficient water usage and increasing competition for scarce water resources (Belay *et al.*, 2019). It is projected that by 2080, the extensive effects of climate change on irrigation water needs will result in a 20% increase in the world's irrigation water demand and a notable 10% decrease in agricultural output (Esteve *et al.*, 2015). Improving irrigation management is a crucial step toward mitigating the negative consequences of climate change (Nandan *et al.*, 2021). Arya *et al.* (2022) stated that, if compared to rainfed farming, the application of irrigation significantly increased millet yield, and this development holds special significance in areas where water stress will likely drastically influence millet yield. Kumar and Kumar (2021) claimed that effective irrigation management is vital during critical growth stages, and the recommended irrigation in the *Kharif* season is 150–200 mm, while the crop can tolerate a 75% reduction in available soil water. The preferred method for irrigation scheduling is the climatological approach, utilizing the IW/CPE ratio, which integrates weather parameters naturally. Ausiku *et al.* (2020) suggest that adjusting nitrogen and water requirements together can enhance pearl millet's yield and water use efficiency while reducing the need for high irrigation and nitrogen levels. Precision irrigation scheduling, considering factors like soil type, growth stage, and climate, proves crucial for sustainable pearl millet cultivation, contributing to improved crop resilience amid climate change challenges.

5 *Crop insurance*

Agriculture's immense reliance on erratic weather and environmental factors makes it incredibly dangerous. Insurance, however, is a crucial instrument for significantly reducing and minimizing these risks (Aryal *et al.*, 2020) like crop failure along with strategies like reduced tillage, irrigation, and new crop varieties, etc. (Madaki *et al.*, 2023) and Intergovernmental organizations strongly advocate and actively endorse agricultural insurance as a foremost strategy for effectively adapting to climate change, emphasizing its considerable and impactful benefits.

Crop modelling: dealing with the climate change and adaptation

Crop models are being used to simulate crop responses to current weather variability with the goal of identifying crop management strategies for adjusting to climate variability (Corbeels *et al.*, 2018). The inability to perform experiments in every environmental condition is one of the problems that crop modeling solves in agricultural research. It is an essential tool for hypothesis testing and scenario analysis across a range of environmental scenarios because of the unknown or non-existent nature of certain future environmental conditions, and this aids in developing strategies for genetic improvement and adaptive management in agriculture (Peng *et al.*, 2020). Crop simulation models are now essential tools for expanding the scope of climate change impact assessments from small-scale experimental data to a variety of conditions and also helping agriculture adapt to the complexities of climate change (Asseng *et al.*, 2015). The models are a handy tool for determining when to plant, how far apart to space plants, and how much fertilizer is best, and this analysis proceeds without wasting time or resources by running seasonal simulations with different dates, intra-row spacings, and fertilizer levels.

DSSAT is unique in that it not only forecasts how climate change will affect crop productivity but also thoroughly evaluates the best management practices and genetic alternatives for a range of climate scenarios. Its diverse range of capabilities makes it an effective tool for comprehensive research on climate change, facilitating the evaluation of successful adaptation plans. By addressing important factors like sowing date, row spacing, plant density, irrigation, and fertilization, it proved invaluable in mitigating the potential negative effects of climate variability (Ventrella *et al.*, 2012). Anser *et al.* (2020) assessed the effects of climate change on the agricultural production system and suggested adaptation measures using the APSIM and DSSAT models. The suggested adaptation techniques include increasing the sowing density, fertigation, developing better crop cultivars and adjusting the best times to sow (Zeleke, 2021). The APSIM model simulates both biological and physical processes having different modules like a biophysical module, a management module, various modules for input and output of data and a simulation engine (Keating *et al.*, 2003) and it is widely used by researchers for climate change adaptation strategies (Holzworth *et al.*, 2014). The FAO crop model AquaCrop facilitates planning and decision-making for crop production. It models the yield response to water while accounting for a range of crop and field management situations. Because of the model's versatility, crop production simulations can incorporate salinity, fertility, and climate change factors like global warming and elevated carbon dioxide concentrations (Steduto *et al.*, 2009). The SALUS (Systems Approach to Land Use Sustainability) model was used by Liu and Basso (2020) to study the effects of climate change and assess the efficacy of climate adaptation strategies. This model has proven to be a useful tool in determining how cereal and non-cereal crop production will respond globally, particularly in the face of changing climate conditions. Similarly, other models are also available like WOFOST (Supit, 1994), SWAP (Kroes *et al.*, 1999), and CropSyst (Stöckle *et al.*, 2003).

Conclusions

Sustainable pearl millet cultivation is a highly promising approach to ensuring resilience and food security in the face of climate change, especially in areas where the crop is a staple diet. It is one of the best crops that can withstand and adapt to climate change when climate-smart agricultural practices are used, such as improved seed varieties, enhanced resource use efficiency like increasing the WUE, NUE, RUE, and carbon sequestration potential, using adaptation strategies like adjusting the sowing window, efficient fertilizer application, intra and inter-row spacing, irrigation management, crop insurance, and adoption of conservation agriculture, which will not only increase output but also significantly reduce greenhouse gas emissions and preserve priceless natural resources. The impact of climate change on pearl millet across different climatic zones, soil types, management practices, and scenarios is largely predicted by using physiology-based crop simulation models, which examine the effects of various climate scenarios and individual climate elements on crop productivity and assist agriculture in adapting to climate change. These models are employed by researchers to evaluate management options and, to a lesser degree, trait options for breeding to mitigate adverse effects. Hence, there is a need to validate the crop models for millets to assess the climate change impacts precisely, identifying suitable adaptation strategies and delineating new areas for higher productivity in millets for sustaining food and nutritional security.

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