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Crop yield resilience in marginal environments and climate change

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Abstract
Due to climatic changes, food safety became a big problem to fulfil the needs of increasing global communities. To overcome this, suitable crop predictions under various meteorological and agricultural factors are necessary. Many studies have been done on the effect of temperature and adaptations in agricultural productions. However, they often failed to understand the uncertainty of the yield, the timing of impact and the effectiveness of the adaptation strategy. Increase in temperature by 2^0 C in tropical and temperate regions resulted in decreased yields of Corn, rice and wheat. Even though maize is less reactive than rice and wheat, crop level adaptations increased the yield by 7-15% that partially helped to overcome these losses. By the end of 21^{st} century, climate related yield losses are expected to increase in tropical regions. High CO_2 content can improve C3 crop yields under certain conditions. C4 crops benefit mainly in drought stress conditions. However, these effects vary within the region. They are limited to occurring at lower latitudes. Integrated approaches using process- and data-driven models, biotic stress simulations, and multifactorial field experiments are important to effectively assess and respond to these challenges. Such methods are vital to us if we better adapt our strategies and ensure that food is globally safe when the climate changes.

Keywords: Climate change, CO2 effects, crop yields, food security, sustainable agricultural practices, SDG 2, SDG 12, SDG 13

Introduction
Due to increase in temperatures and global food requirements, farmers are tasked to maximize production per acre by using less water and also to enhance soil quality by minimizing the agricultural inputs. (Adhikari, Prabhakar, *et al.*, 2018) [5]. In food-insecure areas, particularly in Asian nations, climate change poses a danger to agricultural production. Several climatic conditions like drought, heatwaves, heavy rainfall, storm, flood, and many insect pests had a greater impact on farmer's livelihood (Habib-your-Rahman, Muhammad, *et al.*, 2022) [57]. In agriculture, climate change involves two forms of exposures: sensitivity to weather variability and vulnerability, exposure to change in average climate (O'Brien *et al.*, 2004). Climate change also alters agriculture production by directly influencing the biological factors such as growth of plants and animals, as well as on the different sectors involved in food distribution and processing (Satyavathi, C. Tara, *et al.*, 2021) [140]. According to crop yield projections based on mean changes, tropical regions are more affected by climatic trends in terms of production than temperate regions (Challinor *et al.*, 2014) [24]. According to Food and Agriculture Organization (FAO), the production should be increased by 60% in order to fulfill the requirement of increasing global population to 9 billion by 2050 (Porter *et al.*, 2014; Bailey *et al.*, 2015; Wani *et al.*, 2020). It is calculated that an annual rate of yield increase of 2.4% is necessary to meet the demand of population growth in order to achieve this goal (Ray, Deepak K., *et al.*, 2013; Kim, Sunghwan, *et al.*, 2019) [77, 126].
For the next Green Revolution, all levels of organization need to adopt a much more comprehensive, systems-based approach that considers the environment, the economy, and society (Nüsslein & Dhankher, 2016) [37]. In addition to incorporating major radical changes in existing knowledge and supporting technology, the agriculture of the future requires customized

solutions that also take into account the need to safeguard the environment and meet social expectations. The global agricultural production already got affected by climatic changes and it impacted on soil fertility and carbon sequestration, microbial variety and activity, plant development and productivity. Low variety and high intensity in contemporary cropping systems worsen negative environmental consequences, with broadleaf crops and grain legumes such as soybeans experiencing greater climate-associated yield instabilities than cereals sown in autumn (Reckling *et al.*, 2018).

Increase in global temperatures and extreme weather conditions resulted in increase of pest incidence (Bale, J. S. 2002; Lehmann, Johannes, *et al.*, 2020), and also decreased crop yields (Raseduzzaman, M. D., & Jensen, E. S., 2017) [12, 84, 125]. Extreme weather and drought are now the main delicacies of tropical rainwater agriculture (Dilley 2005). Global agricultural production is damaged by extreme heat and drought (Lesk, C., Rowhani, P., & Ramankutty, N., 2016) [85]. In sub-Saharan Africa (SSA), recurrent droughts led to severe food insecurity, the need for humanitarian assistance (Haile, 2005). In addition, the ability of agroecological systems to function and the resilience of society can be affected in the long term by consecutive or extended extremes. Higher investments in food production are associated with new innovations which are considered to be essential for climatic change adaptations in agriculture (Ainsworth *et al.*, 2008).

Environmental changes such as deforestation and dryland degradation are exacerbated by marginalization and lack of economic growth (Najam, A., Ribot, J. C., & Watson, G. 1996) [132]. Various cropping systems help in increase the resilience of an agroecosystem by controlling the disease, insect and weed incidence, also by reducing the impact of extreme weather conditions on crop. Integrated crop farming systems (ICLS) are more dependable, productive, sustainable and climate resilient than intensive and specialized agricultural systems (Sekaran, Udayakumar, *et al.*, 2021) [142]. Climate change and agrobiodiversity interact in two ways. Rapid changes in local climatic circumstances could lead to species loss, endangering agrobiodiversity. However, it is also an essential resource for climate change adaptation (Wu, J., Fisher, M., & Pascual, U., 2011) [118, 177]. The global food supply has shifted to animal proteins from grains over the last 50 years, which also increased livestock production. Inadequate agricultural management techniques, short crop rotations, extensive grazing, specialized intensive cropping systems, and overuse of machinery caused by industrialization can lead to off-site contamination, loss of pollinator habitat, soil erosion, and water pollution.

Understanding marginal environments

Climatic changes have shown a major impact on plants and animals at boundaries of their ranges of terrestrial, limbic and marine ecosystems (Kolzenburg, R., 2022). According to Haberzettl (Haberzettl, Robert, *et al.*, 2013) [56, 80], environmental restrictions related to marginal farmland result in lower yields than ideal circumstances. Numerous abiotic (climatic and geographical) problems, including excessive salinity, drought, flooding and unfavourable soil types, can limit plant development and, consequently, contribute to the marginalisation of agricultural areas. Abiotic factors such as unfavourable weather conditions impacts growth and yield, which also affects the quality and quantity of biomass produced by plants (Hilgert, P., Von Cossel, M., & Reinhardt, J. 2022) [130].

In dry and semi-arid regions, small landholdings, poor productivity, less water availability, with unpredictable climatic changes lead to environmental degradation, lower agricultural production, and increases risk of rural communities (Singh, P. K., & Chudasama, H. 2021) [151]. More than 48% of total land in India is under arid and semi-arid regions which consists over 700 million people. Droughts and heatwaves are expected to increase in India during 2020-2100, along with rising temperatures, rainfall variability, and heavy rainfall events (Gupta and Jain, 2018). Changes in temperature and humidity regimes caused by global climatic changes have a greater effect on marginalized populations in arid regions (El-Beltagy A, Madkour M., 2012). The dryland vulnerability has five factors: poverty, water stress, land degradation, remoteness, and natural agricultural limitations (Sterzel, Till, *et al.*, 2020) [160]. The growing pattern of dryland agriculture explains the issues of livelihood and their sustainable development by examining various environmental factors such as poverty, desertification, vulnerability and community development (Reynolds *et al.*, 2007) [45].

In arid regions, the soil, vegetation and water resources are mainly influenced by its climate, soil, water and temperature (Hupp, C. R., & Osterkamp, W. R. 1985; Moore, Ian D., *et al.*, 1993) [69, 103]. The environmental conditions and functions of its ecosystems together provide varying degrees of vulnerability and diversity. Several studies are conducted in recent years on desert region's susceptibility response to global warming (Held, I. M., & Soden, B. J. 2006) [61]. According to Intergovernmental Panel on Climate Change (IPCC), the tropical and sub-tropical dry zones will continue to increase (Parry, R., 2007) [117]. The hydrological and biological environment faced many problems due to over exploitation of water and soil resources, also affected population growth and social wellness (Stern, D. I., Common, M. S., & Barbier, E. B. 1996; Evans, G. W., & Kantrowitz, E., 2002). Solving the problems that affect the sustainable development in arid regions is one of the main challenges (Liu, Hai-Long, *et al.*, 2016) [46, 87].

The lives of small landholders in southern regions are in danger due to climatic change. Food insecurity caused by climatic changes was a serious problem in Ghana's semi-arid north, where small-scale agriculture employs more than 73% of the population (Mohammed, Kamaldeen, *et al.*, 2021) [102]. In general, resilience to climatic changes means the ability of social, economic and environmental systems to withstand and recover from the impact of climate changes and stress (Adzawla, William, *et al.*, 2019; Holling, C. S., 1973; Folke, C., 2006) [6]. In semi-arid north of Ghana, smallholder farmers rely primarily on rainfed farming practices (Kuuire, Vincent, *et al.* 2013; Dapilah, F., Nielsen, J. Ø., & Akongbangre, J. N. 2019). About 30% of households experiencing food insecurity, due to increasing temperatures, hence this region is susceptible to climate related food insecurity (Nyantakyi-Frimpong, H., 2013; Biederlack, L., & Rivers, J., 2009) [17, 34, 53, 65, 81, 108].

Climatic changes and its impact on crop yields

Over the past decade, a number of scientific studies have examined climate variability and climate change (Hulme, Mike, *et al.* 1999; Alexandrov, V. A., & Hoogenboom, G. 2000) [66, 10]. Climate change hampers efforts to maintain and improve food production in many regions (Ehsan Eyshio, Rezaei *et al.*, 2023). Global food security may be at risk due to the impact of climate change on agricultural productivity (Wheeler, T., & Von Braun, J., 2013; Wei, Taoyuan, *et al.*, 2014) [131, 172, 173].

Climate change situation made this difficulty much worse and an urgent problem. All available conventional and unconventional water resources should be used to combat drought, which is a significant aspect of the climate change scenario (Setter, T. L., & Waters, I., 2003) [143]. Globally, salinity is a major problem that affects agricultural production, degrades soil and disrupts ecosystem functioning (Flowers, Timothy J., and Timothy D. Colmer. 2008; Hussain, Karishma, *et al.*, 2015) [52, 71]. The driver-pressures-state-impact-response (DPSIR) paradigm is used in Figure to demonstrate climatic problems in agricultural production and possible remedies.

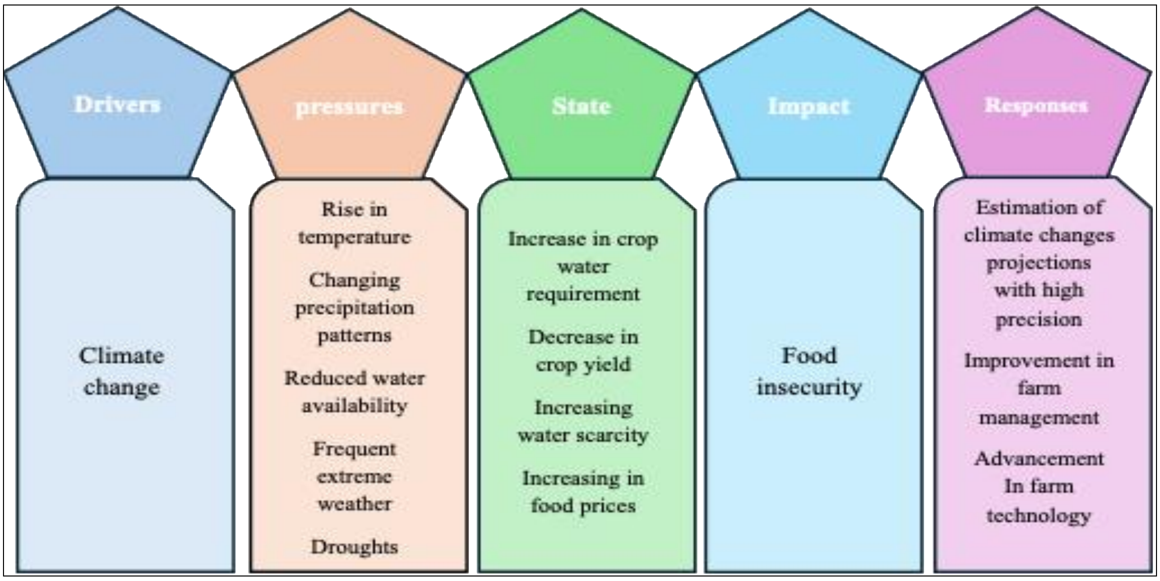

Fig 1: DPSIR framework to study the climatic change effect on agricultural production (Farooq, Ahsan, *et al.*, 2023) [49].

In arid, semi-arid and coastal regions a considerable part of the land is affected by salt, the situation is worse (Pitman, M. G., & Läuchli, A. 2002) [120]. The main cause of the images is that farmers are irrigating their crops with more saltwater in these degraded marginal lands, and most of these places are receiving much less rainfall (Malash *et al.*, 2008). Due to waterlogging and the continuous usage of low-quality, highly saline sodium irrigation water, more than 50% of the land in Central Asian states has already been transformed into non-fertile marginal land (Kijne 2005; Qadir *et al.*, 2008, Hussain, Muhammad Iftikhar, *et al.* 2020). This indicates that the soil degradation situation is extremely severe (Skendžić, Sandra, *et al.*, 2021) [72, 153].

Impact of Drought

Drought, a recurrent and complex natural hazard (Wilhite, D. A., & Buchanan-Smith, M. 2005) which can be an abstract natural disaster (Johnson, C., Lewis, C., & Hagman, J., 1984; Wilhite, D. A., 1996) [74, 174, 175]. Drought is one of the biggest limits to crop expansion outside of current agricultural areas. readable, due to recognized changes in the global climate. Drought can lead to unfavorable natural and social phenomena (Shen, Juwen, *et al.*, 2007) [147], such as exacerbated land desertification, significant crop yield losses, increased social violence, and fire disasters in a natural ecosystem (Bruins, H. J., & Berliner, P. R. 1998; McDonald, C. V., & Abd-El-Khalick, F. 2017; Routledge.; Pausas, J. G. 2004; Quiring, S. M., & Papakryiakou, T. N. 2003) [21, 96, 119, 122]. At present, the concern is to improve the cultivation practices and crop genotypes for drought-prone areas. Hence, to understand the mechanisms behind drought resistance and the efficient use of water by plants is crucial for achieving these goals. Oxidative stress which is crucial for crops, experience drought periods. The role of detoxification system in prevention of irreversible damage to photosynthetic machinery and redox molecules as local or systemic signals was reviewed (Chaves, M. M., & Oliveira, M. M. 2004) [25]. There are three common drought indices that help to monitor agricultural drought and soil water balance, the standardized rainfall evapotranspiration index (SPEI) (López-Moreno, J. I., Vicente Serrano, S. M., Angulo-Martínez, M., Beguería, S., & El Kenawy, A. M. 2010; Wang, Yi, *et al.*, 2014) [171], the standardized precipitation index (SPI) (McKee, T. B., Doesken, N. J., & Kleist, J. (1993) and the Palmer drought severity index (PDSI) (Palmer, W. C., 1965) [112]. The PES used with multi-scale characteristics monitored different types of droughts, including meteorological drought, agricultural drought, hydrological drought, and socio-economic drought (Guttman, N. B. 1998; Hayes, Michael J., *et al.* 1999). However, SPI only consider rainfall as a drought factor and does not monitor drought caused by higher temperatures. The influence of temperature on drought can be characterized using PDSI (Dubrovsky, Martin, *et al.* 2009) [41, 55, 60, 89, 97, 168].

Impact of Temperature

In crops, biomass stimulation and productivity of some species decreased due to temperature rise compared when temperature is optimum. In temperate cereals, the optimal average temperature range for maximum grain yields are 14 to 18 °C (Chowdhury, S. I., & Wardlaw, I. F. 1978; Högy, P., Poll, C., Marhan, S., Kandeler, E., & Fangmeier, A. 2013) [28]. On the other hand, since cereal ripening processes are linked to specific temperatures, moderate increase in average temperature of 1-2 °C resulted in short grain filling periods in cereals and negatively affected yield characters in some regions (Barnabás, B., Jäger, K., & Fehér, A. 2008; Savin, Roxana, *et al.*, 1997; Högy, Petra, *et al.*, 2013). Previous studies had shown that cereal grain yield decreased from 4.1% to 10.0% due to temperature rise of 1 °C in seasonal average temperature (Hatfield, Jerry L., *et al.* 2011; Högy, Petra, *et al.*, 2013) [13, 59, 64, 141].

Impact of rise in temperature

Temperature is a key element that influence plant habitat and growing patterns due to physiological limitations of living organisms (Parmesan, C., & Yohe, G., 2003) [115]. It is a factor limited to the geographical areas in which various crops are grown, also a factor that impacted the rate of growth and maturity of crops (Rehman, Munib your, *et al.*, 2015) [129]. Agricultural crops require base temperature to complete its particular phenophase and their entire life cycle. Furthermore, particularly during phenocritical stages (at anthesis), extremely low and high temperatures had a higher influence on crop development, growth, and yield (Luo, Q., 2011) [91]. The spring-summer season was expected to have high air temperatures, which is beneficial for agricultural production in northern locations where the length of the growing season is currently a limiting factor (Tubiello, F. N., *et al.*, 2002) [163]. The effect of increase in temperature generally associated with other environmental factors like water availability, strong winds, and the intensity and duration of sunlight (Rehman, Inayat Ur, *et al.*, 2018) [128]. The direct negative influence of temperature on yield is further influenced by the indirect influence of temperature on these environmental factors. Increase in temperatures also increased the demand of atmospheric water, which led to additional water stress due to high evaporation rate, which eventually reduced soil moisture and ultimately decreased yield (Zhao, Chuang, *et al.*, 2017). Indirect effect of raised temperatures are increased intensity of heat waves and impact on pest, weed, and plant diseases (Field, Christopher B., *et al.*, 2015) [50, 179].

Impact of a high concentration of CO2

CO2 is a chemical, compound essential for photosynthesis, which is a process in which water and CO2 are converted into sugars and starch, by solar energy. Photosynthesis occurs in green pigments of the leaves, and CO2 enter through the stomatal openings (Rötter, R., & Van de Geijn, S. C. 1999) [136]. Since carbon is an essential nutrient in plant metabolism, the increase in CO2 concentration resulted in better growth due to carbon assimilation (Woodward, F. I., 1990) [176]. The main effect of higher CO2 content on plants is transpiration reduction and conductivity of stomata, an improvement in the efficiency of water and sunlight, that resulted an increased photosynthetic rate. Due to higher concentrations of CO2, the plant growth and development get disturbed that impacts entire ecosystem (Drake, B. G., Gonzàlez-Meler, M. A., & Long, S. P. 1997) [40]. Although higher concentrations of CO2 increase yield, its extent of effect is still unknown. CO2 also shown different effects on C3 and C4 plants due to less sensitivity of C4 plants to an increased concentration of atmospheric CO2 than C3 plants (Tubiello, F. N., *et al.* 2002; Rosenzweig, C., & Hillel, D., 1998) [135, 163].

However, both C3 and C4 plants got benefited due to increased atmospheric CO2 concentration (Rötter, R., & Van de Geijn, S. C. 1999) [136]. Most of the cultivated plants used oldest method among carbon fixation pathways i.e. C3 carboxylation pathway (Calvin cycle), which was found in plants of all taxonomies (Bloom, Arnold J., *et al.* 2012; Ehleringer, J. R., Cerling, T. E., & Dearing, M. D. 2002) [18, 44]. The C3 photosynthesis concept was given that the first product of photosynthesis is a 3-carbon molecule, while it is a 4-carbon molecule in C4. C4 photosynthesis occur in the most developed plant taxa, and the main C4 plant species include maize, sorghum and sugar cane, all of tropical origin (Rötter, R., & Van de Geijn, S. C. 1999) [136]. C4 plants accounts only 3% of all flowering plant species, still they contribute about 50% of the 10,000 grass species (Leakey, Andrew DB, *et al.*, 2006) [83]. C4 plants had about 50% higher photosynthetic efficiency than C3 plants (e.g., rice, wheat, soybeans, potatoes, etc.), indicating their high productivity, due to their different mechanisms of carbon fixation. The Calvin cycle is only used by C3 plants for the fixation of CO2, which is catalyzed by the enzyme called Rubisco, that occurred within the chloroplast in the mesophyll cell. In C4 plants, photosynthetic activities are divided between mesophyll cells and bundle sheath (BS) cells, which are biochemically and anatomically different. Primary carbon fixation gets catalysed by the enzyme PEPC (phosphoenolpyruvate carboxylase), which forms OAA (oxaloacetate) from CO2 and PEP (phosphoenolpyruvate). OAA is converted into the salt of malic acid (malate) and then dispersed into BS cell where it is decarboxylated and results in high concentration of CO2 around the Rubisco enzyme.

Subsequently, PPDK (pyruvate orthophosphate dikinase) enzyme regenerated PEP, the first substrate of the C4 cycle, in the mesophyll cell (Wang, Chuanli, *et al.* 2012.) [169]. The of CO2 concentration mechanism decreased the oxygenation reaction by Rubisco and the subsequent energy-wasting process of photorespiration, resulted in increased photosynthetic yield and improved water use efficiency and nitrogen content compared to C3 plants (Majeran, Wojciech, *et al.*, 2010). C4 plants adapt warm climates, such as tropical grasslands, where photorespiration rates are very high, not suitable for C3 plants (Leakey, Andrew DB, *et al.*, 2006). Hence, the efficiency of C3 photosynthesis is less compared to C4 photosynthesis (Ehleringer, J. R., Cerling, T. E., & Dearing, M. D. 2002). Plants with nitrogen-fixing symbionts (e.g., soybeans, alfalfa, lupine, etc.) are expected to have high CO2 resources than other plant species under favorable environmental conditions for both the plant and the symbiont. (Cure, J. D., Israel, D. W., & Rufty Jr, T. W. 1988) [33, 44, 83, 94].

Impact of the Variable Precipitation Model

Agricultural production was firmly impacted by the availability of water. Climate change resulted changes in rainfall patterns, soil moisture storage, evaporation and runoff. It is estimated that more than 80% of total global agricultural production is provided by rainfall and therefore change in total seasonal precipitation or its patterns are very important (Olesen, J. E., & Bindi, M., 2002) [109]. Strong evidence of an amplification of the global hydrological cycle, which is strongly influenced by temperature variations. However, its effect on agricultural production is still unpredicted as it depended on other climatic parameters such as the intensity and frequency of extreme weather events (Huntington, T. G., 2010) [68]. Change in precipitation patterns had greater importance to agriculture than change in temperature, especially in regions where dry seasons are limiting factor for agricultural production (Parry, M., 1990) [116]. According to Lickley and Solomon (Lickley, M., & Solomon, S., 2018) [86, 154] a drying trend is emerging in southern and northern Africa, parts of Latin America, Australia, and southern Europe. In addition, the models predicted significant drying for these regions and southern parts of North America by mid-century, with an increased drought of more than 10% and a moisture deficit of more than 200 mm per year. In Mediterranean countries, yields of cereal crops are decreased by less water availability, heat stress, and shorter grain filling duration (Skendžić, Sandra, *et al.*, 2021) [153]. Hence, permanent crops such as olive, vine, and citrus fruits have greater importance in this region. These crops got affected heavily by extreme weather events such as hail and storms, which subsequently reduce or completely destroy yield (Olesen, J. E., & Bindi, M., 2002) [109].

High evapotranspiration and low rainfall resulted in higher attention to the development of irrigation techniques that allow efficient and effective use of available water resources, as well as good agronomic practices that emphasize moisture conservation and thus improved crop productivity (Kirda, C., *et al.*, 2007) [78]. Less water in soil can cause plants to lose their biological functions and become even more susceptible to pests and diseases (Zayan, S.A., 2019) [178]. On the other hand, the world had become wetter in large areas such as northern Europe and eastern parts of the Americas, with extreme precipitation events contributing strongly to increasing global precipitation (Pachauri, Rajendra K., *et al.*, 2014) [111]. Direct analysis of precipitation extremes (largest annual accumulation of precipitation in 1 day/largest annual accumulation of precipitation in 5 days) shows that extreme precipitation has increased in much of the world, with an increase in the potential of a typical 2-year event of about 7% in the period from 1951 to 1999 (Alexander, Lisa Victoria, *et al.*, 2006, Min, Seung-Ki, *et al.*, 2011) [9]. Due to humid climatic conditions, the Atlantic coast and mountains of European regions have cold and rainy summers that lead to yield and quality losses in various annual field crops (Olesen, J. E., & Bindi, M., 2002) [109]. Excess moisture also affected soil fertility and reduced the number of working days of agricultural machinery (Brignall, A. P., & Rounsevel, M. D. A. 1995) [20]. However, the impact of climatic change is still unknown completely, but current scenarios indicate the severe impact on crops in future (Skendžić, Sandra, *et al.*, 2021) [50, 153].

Physiological and genetic basis of crop resilience

Agricultural production around the world is significantly being affected by many environmental challenges that crops face in the field. Plants use different molecular, transcriptional, physiological and morphological processes to reduce the negative impacts of these stimuli. Roots are primarily responsible for detecting most abiotic stressors, including waterlogging, salt, drought, and nutrient deprivation, which cause changes in root architecture and biomass (Choudhary, P., Muthamilarasan, M., 2022) [27].

With its essential functions in anchoring and acquiring earth-based supplies, the root of plant is a pertinent organ for stress adaptation. In order to improve production and sustainability under drought and stress conditions, it should be possible to analyze root system changes and select traits that will help to future global food security (Siddiqui, Md Nurealam, *et al.* 2021) [148]. Due to increase in climate unpredictability and consequent deterioration of agricultural land, the negative effects of abiotic stressors are becoming more pronounced. This has a detrimental effect on overall plant homeostasis, which results in limited crop growth and, ultimately, global food production (Bray, T. M. 2000; Checker, Rahul, *et al.* 2012; Fahad, Shah, *et al.* 2017) [19, 26]. Abiotic stressors are directly responsible for between 50 and 70% of the decrease in agricultural production (Francini and Sebastiani, 2019). Due to its detrimental effects on plant growth, physiology, and its reproduction, drought is a severe abiotic stressor that reduces agricultural yields (Fahad, Shah, *et al.* 2017; Lamaoui, Mouna, *et al.* 2018) [47, 82, 144].

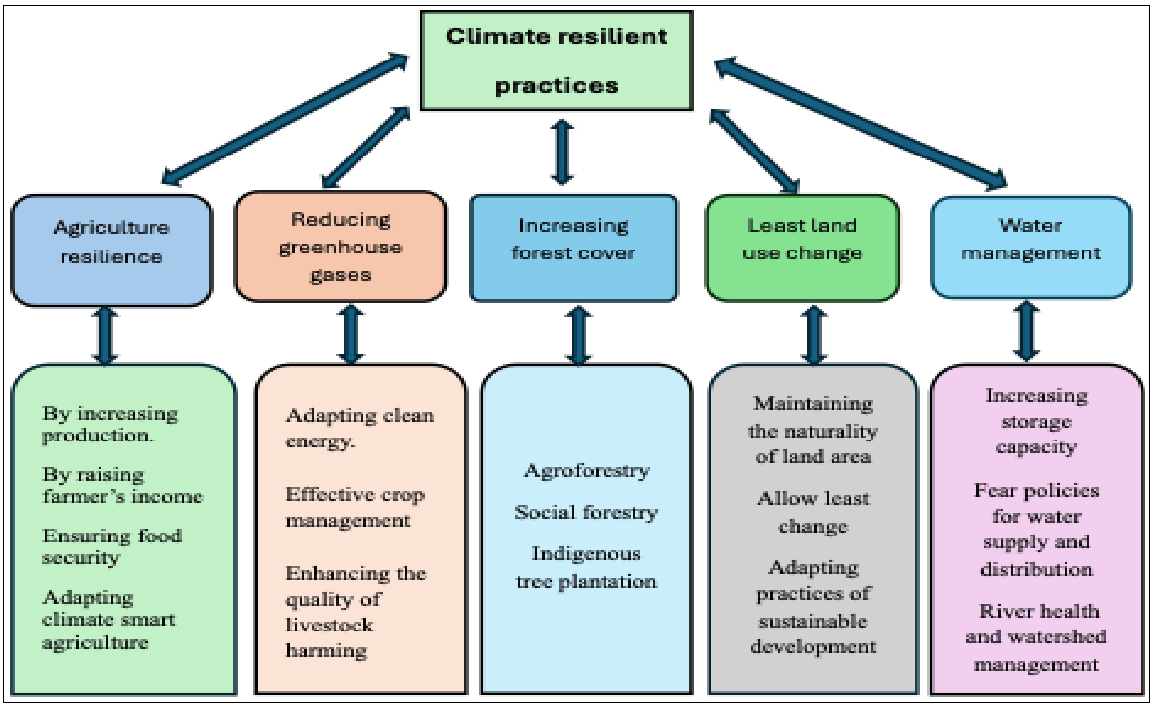

Fig 2: Climate resilient practices (Srivastav, Arun Lal, *et al.*, 2021) [157]

In situations where water is scarce, the root of a plant is the primary organ essential for the extraction of soil resources. According to Maeght (Maeght, J. L., Rewald, B., & Pierret, A. 2013.; Koevoets, Iko T., *et al.*, 2016; Fan, Peilei, *et al.* 2017; Van de Vyver, Hélène, *et al.* 2017) [48, 79, 93], plant roots continue to develop and penetrate deep soil layers when they perceive a lack of water. In order to prevent dehydration through effective water and nutrient uptake and beneficial gaseous exchange that increases carbon assimilation and yield productivity in drought stress conditions, root architecture and morphological characteristics are essential (Gewin, V., 2010; Kell, D. B., 2011; Lopes, Marta S., *et al.*, 2011; Palta, Priya, *et al.*, 2014) [54, 76, 88, 113].

In order to conserve water and prevent drought, plants always lower their stomatal conductance, which can slow down their rate of C02 fixation and growth. Under extreme drought stress conditions, plants react physiologically by enhancing osmotic adjustments, increasing cell wall flexibility to preserve tissue turgidity, and modifying metabolic pathways (Mitra, 2001). Mechanisms to escape and avoid drought are often related to plant moisture content, water uptake and water use efficiency. Location, climate, and soil type have a significant impact on this. Plants should be screened in multi-locality pathways to examine the differential response of genotypes at various locations/seasons in order to describe them for drought escape or avoidance strategies.

Globally, agricultural systems are becoming more efficient through the use of diversified crop rotation (DCR). Improving soil quality and increasing system production are two possible outcomes. In crop rotation, improved soil quality, include more beneficial soil microbes, and improved soil water uptake and storage, can improve drought tolerance and other challenging growing circumstances (shah, Kabita Kumari, *et al.*, 2021) [144].

In general, soil management by tillage-based implements for continuous crop production results in soil deterioration that ultimately reduced crop yields. In addition, the high costs of labor, fuel, agricultural chemicals, and other inputs needed for intensive crops burden farmers. In addition to reducing soil productivity, intensive tillage increases greenhouse gas emissions, mainly CO2, and produces a greater loss of carbon in the soil (Stangnari, F., Ramazzotti, S., and Pisante, M., 2010).

Three guiding concepts underpin conservation farming systems, which aim to maximize land cover, minimize soil disturbance, and promote biological activity in order to improve ecosystem services. In this study, we look at the concept of variety and its applications at farm and field level to optimize ecosystem conditions from managed grasslands and integrated agricultural systems (sometimes called integrated crop-livestock-forage systems) (Sanderson, Matt A., *et al.*, 2013) [139]. Because some benefits of employing no-till practices, such as improved soil organic matter and increased soil water availability, could present opportunities to expand the producer's crop portfolio, conservation agriculture can promote crop diversification (Hendrickson, J., & Colazo, J. C., 2019) [62]. Compared to conservation agriculture (CA) techniques, conventional agricultural technologies are less profitable (Jat, Raj Kumar, *et al.* 2014), ineffective (Bhushan, Lav, *et al.* 2007) and result in a loss of soil health (Bhushan, Lav, *et al.* 2007; Mehla, Mukesh Kumar, *et al.* 2022) [15, 73, 98].

Case studies

Case 1: Adaptation of maize production to climate change in sub-Saharan Africa

Tropical and subtropical regions especially sub-Saharan Africa are expected to be the most affected by the effect of climate change on agricultural production, due to the region's wide range of projected effects, numerous pressures and lower adaptive capacity (IPCC 2007). Increased seasonal events and high temperatures, as well as the severity of droughts, are among the climate change predictions for SSA. (IPCC, 2007) and may lead to change in the production and suitability of present crops. Africa is getting warmed faster than the global average (Collier, P., Collier, P., Conway, G., & Venables, T. 2008) [30], and by this century end, increasing seasonal temperatures are expected to exceed the most extreme seasonal temperatures recorded in the last century (Battisti, D. S., & Naylor, R. L. 2009) [14]. In much of SSA, maize is main staple crop, that covers a total area of around 27 million hectares (Cairns, Jill E., *et al.*, 2013) [22]. According to FAO (2010), maize accounted for about 30 percent of the total area used for wheat production in this region, with 19 percent going to West Africa, 61 percent to Central Africa, 29 percent to East Africa and 65 percent to Southern Africa. Most of the corn in SSA is produced by rain-fed and small-scale farming methods with few inputs.

Drought stress, low soil fertility, weed, pest, diseases, limited availability of inputs, low input utilization, and incorrect seeds are the main causes of low yields in this area (Cairns, Jill E., *et al.*, 2013) [22]. Dependence on rainfall makes maize systems more susceptible to climate change. Although land holders have a long history of adapting to the effects of climate variations, the challenges created by present and future climate change are more significant as the likely effects go beyond their previous experience. As a result, farmers' ability to adapt and be inventive will be challenged by climatic change (Adger, W. N. 2007) [1].

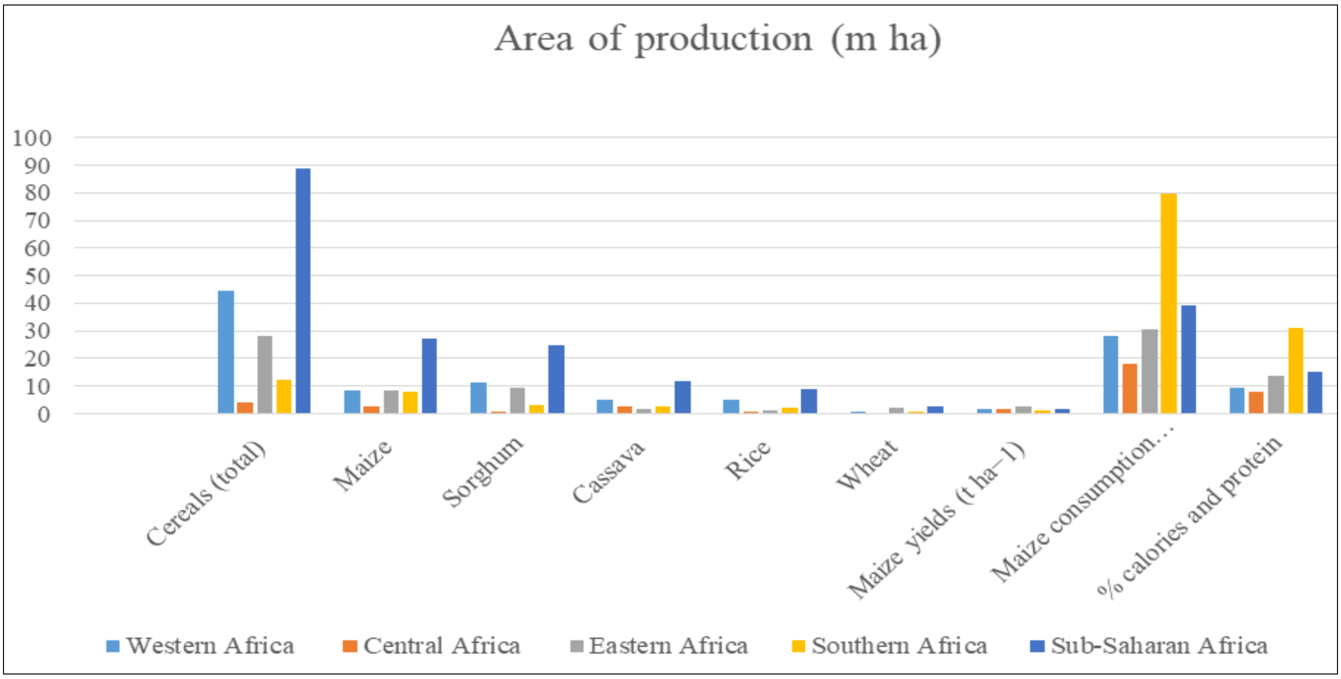

Fig 3: Production of major food crops and the importance of maize in sub-Saharan Africa (data from FAO 2010)

Expected climate scenarios for maize cultivation

Regions of sub-Saharan Africa increased at an average rate of 0.5°C per century during the last century (Hulme *et al.*, 2001) [4]. With a maximum limit of 2°C per century increased temperature in the Mediterranean basin of northwest Africa and throughout the interior of southern Africa, analysis of spatial models showed significant heterogeneity in warming within sub-Saharan Africa. The rate of increase in day and night temperatures remained constant (Solomon, Susan, ed. 2007) [154]. Previous projections of climate change indicated that by 2050, the southern African land and Sahara regions of will be warmed up to 1.6°C (Hernes, Peter J., *et al.* 1996; Ringius, Lasse, *et al.* 1996).). Hulme (Hulme, M. 2001) [4, 63, 133] used the greenhouse gas emission situations and created third Assessment Report for the Intergovernmental Panel on Climate Change (IPCC) to predict that African subcontinent would warm by 0.2°C per each ten years (Special Report on Emissions Scenarios (SRES) to more than 0.5°C per each ten years. The semi-arid tropical boundaries of the Sahara, middle and lower Africa are expected to see the most warming. Using the SRES A1F1 emissions scenario, Ruosteenoja (Ruosteenoja, Kimmo, *et al.* 2003) demonstrated that temperature got increased in southern Africa from September to November, reaching up to 7°C [77, 138].

Mitigation of effects of climatic changes on maize systems

It is estimated that 20% of global greenhouse gas emissions are attributed to agriculture (IPCC 2007). According to Cairns (Cairns *et al.*, 2012) [23], the use of fertilizers and agricultural equipment for irrigation and tillage operations is linked to higher CO2 emissions due to fuel use. By decreasing the emissions of greenhouse gaseous and increasing carbon sequestration, better agronomic techniques such as conservation agriculture can help slow global warming. However, most maize production methods in SSA are sprinkler-fed, use manual soil preparation or animal traction, and use very little fertilizer: small land holders in SSA used less than 10 kg/ha (Morris, Amanda Sheffield, *et al.* 2007). In addition, SSA only accounts 3.6% of global CO2 emission (Collier, P., Conway, G., & Venables, T. 2008) [30, 104].

Therefore, in this area, climatic change adaptations are more crucial than mitigation. Although corn yields in SSA are now lowest in the world, new corn varieties with greater resistance to heat and drought will be crucial to adapt maize systems to climatic changes. On the scale requirement of simultaneous increase in existing production levels and counteract future yield losses related to climate change and increased climatic variability, maize selection alone will not be sufficient (Cairns, Jill E., *et al.*, 2013) [22]. As mentioned above, higher temperatures in the growing season increases plant transpiration, which will increase water usage in plants, decrease the soil water availability to plants, although they may not exceed threshold temperatures for subtropical and tropical corn by 2050. According to Thierfelder and Wall (2010) [161], improving soil water status can both reduce the effect of a drought conditions and protect plants from the possible impacts of drought stress in the event of intermittent rainfall. Agronomic practices such as crop rotation, residual management, and ploughing minimize soil disturbance in conservation agriculture (Hobbs 2007). By improving water infiltration, agricultural conservation techniques reduce evapotranspiration and water runoff, while increasing water stored in the soil (Verhulst, Nele, *et al.* 2010; Thierfelder, C., & Wall, P. C. 2012) [162, 167].

Conservation agricultural practices have been linked to higher soil moisture content, according to a number of studies (Ussiri, D. A., & Lal, R. 2009; Dendooven, Luc, *et al.* 2012) [36, 164]. According to Verhulst (Verhulst, Niels O., *et al.* 2011) [166], conservation agriculture produced corn yields 1.8-2.7 times higher than those produced by traditional management techniques during a mild drought. Maize production can be protected from brief droughts in its growing season due to higher soil water content of conservation agriculture (Fischer, R. A., F. Santiveri, and I. R. Vidal. 2002; Thierfelder, C., & Wall, P. C. 2012) [51, 162]. Because landholders are active "agents" whose interactions and strategies shape development within the limits of the information and resources available to them, the effects of climate change and increased climate variability on farmers' livelihoods are less evident (Long 1992). Farmers have developed coping mechanisms over time to protect themselves from uncertainties caused by annual fluctuations in rainfall (Cooper, M. J., Gulen, H., & Schill, M. J. 2008) [31]. Numerous decisions made by farmers, including those on crop production and management, are expected to be affected by changing temperatures. Farmers use a variety of livelihood development techniques to reduce or eliminate poverty, according to Dixon *et al.*, 2001).

Using this concept, farmers may be able to implement livelihood development techniques. Both ex-ante and ex-post risk management methods are part of livelihoods improvement initiatives (Cooper, M. J., Gulen, H., & Schill, M. J. 2008) [31]. & Intensification: households increase the material or financial production of current production models. For example, farmers are using external inputs such as irrigation, better types of crops they are currently growing, and water adoption to increase yields. Maintaining land management practices, such as diversification and conservation agriculture, where farmers enter new or current markets to boost revenue or reduce income instability. This could involve growing new goods or processing an old product on the farm to increase its value. This would entail giving up maize in southern Africa and switching to more heat- and drought-resistant crops like sorghum and millet (Burke *et al.*, 2009). Farmers choose to produce corn even though both crops are fast growing and require less water. & Expansion: Farmers use their fields or herd size to increase resources or income. Expansion can be achieved by clearing previously unused land, distributing additional land through land reform, or accumulating land left behind by migrant farmers in fewer hands. In order to increase farm incomes, farmers turn to temporary or permanent non-farm jobs. Reinvesting the earnings in agriculture or other family needs is one possible use. When farmers choose to live a non-agricultural lifestyle or work in another agricultural system, they are said to be leaving the agricultural industry. According to Adger *et al.*, 2003) [3], Migration serves as a coping strategy for climatic changes. While the above-mentioned livelihood measures are expected in reduction of negative effects of climate change, plant breeding will remain an important component of farmers' adaptation plans.

Climate change creates a serious threat to maize production inSSA, with crops threatened by rising temperatures and erratic rainfall, particularly in southern Africa. Creating heat- and drought-tolerant maize varieties and improving seed infrastructure to make it accessible to farmers are two crucial initiatives for adaptation. In order to choose types that can withstand future circumstances, breeding programs must incorporate high-temperature habitats. At the same time, in order to expand adoption, bottlenecks in seed production, distribution, and policy need to be addressed. Increasing soil moisture and reducing climate risk are two other ways in which conservation agriculture and improved farming techniques can be beneficial.

Research, seed systems and policy must work together in concert, with climate models and local data acting as a guide. Climate-resilient corn could not reach the farmers who need it most if timely funding and delivery were not provided.

Case 2: Climate Resilient Agriculture among Indigenous Communities in India: All agricultural techniques around the world are currently really and profoundly altered by climate change. This shift indicates that food security also supports rural livelihoods, which in turn affects ecological sustainability in nations such as India, where agriculture employs two-thirds of the population and accounts for more than 30% of GDP. Indian agriculture is extremely vulnerable to climate shocks related to unpredictable rainfall, extreme temperatures, pest invasions, and rainwater irrigation. (Aich, A., Dey, D., & Roy, A. 2022) [8].
Indian indigenous groups have promoted integrated, secular ecological farming methods in the face of adversity. These customs use local resources sustainably because they are firmly rooted in environmental consciousness. Important lessons on how to improve resilience to climate change can be learned from customs. Based on peer-reviewed research, this case study examines how four indigenous communities - Irulars, Lahaulas, Dongria Kondhs, and Apatanis - modified their farming methods to resist environmental changes (Mijatović, Dunja, *et al.*, 2013) [99].

Indigenous knowledge in agricultural systems

Traditional agricultural systems can be complex socio-ecological systems that are often overlooked by contemporary industrial frameworks. Cohesive land use mosaics combine soil, water, plant and animal management, preserving biodiversity and supporting livelihoods. The capabilities of these systems make them resilient. These skills include self-organization, shock absorption, and learning to adapt. The Indigenous Customary Knowledge (ITK) has a wealth of information in India, where 700 tribal tribes have been documented. The tribes in this study live in ecologically varied regions of the Eastern and Western Himalayas, the Eastern Ghats, and the Western Ghats, ranging from highlands and tropical dry forests to frigid deserts and rainforests. Each created adaptive landscape methods in response to unique climate risks (Aich, A., Dey, D., & Roy, A. 2022) [8].

Climate-resilient indigenous practices

Eastern Himalaya (Arunachal Pradesh) Apatanis

The advanced method of integrated agriculture for the production of rice and fish is practiced by the Apatani, who reside in the Ziro valley (Ramakrishnan, P. S., 1992) [124]. Millet grown on the reservoirs is used to supplement crops, and water is delivered from a complex system of bamboo channels. Rice husks, kitchen scraps and livestock manure are used to replenish the soil in this completely organic approach (Rai, S. C., 2005) [123]. Agriculture in the community is essential. The village elders supervise and divide the work and water management. Because they grow more than 100 species of plants, including 16 native varieties of rice, Apatani are an essential component of agro-biodiversity. Climate resilience is high due to scheduled irrigation, crop diversification and maintenance of soil fertility. Risks include droughts, cloudbursts, and flash floods, which can affect water-intensive paddy systems (Mishra, S., Choudhury, S. S., & Nambi, V. A. 2018) [101].

Western Himalaya (Himachal Pradesh) Lahaulas

The Lahaula only grow in the snowless months, as they live in a freezing desert in the Lahaul Valley. They rotate cash crops, vegetables, and medicinal herbs as part of their agro-livestock and agro-forestry practices. Even on high slopes, terraced farms are irrigated with their own technique of collecting ice water, which uses earth channels called kuhi or nullah (Singh, G. S., Ram, S. C., & Kuniyal, J. C. 1997.) [150]. Compost consists of night-time soil, animal manure, and forest litter to compensate for nutrient loss due to snow leaching (Di, H. J., & Cameron, K. C. 2002). Local cows are crossed with yaks to create a sturdy livestock. For the fixation of fuel, fodder and nitrogen, sea buckthorn trees are grown. Climate resilience is moderate due to a number of productions and composting. The risks are climate change, glacier retreat, and increased landslides that make farming less practical (Aich, A., Dey, D., & Roy, A. 2022) [8].

Eastern Ghat (Odisha): Dongria Kondhs

On the "dongor", or hillsides, the Dongria Kondh grow 80 different types of crops, including vegetables, oilseeds, legumes, millet, and legumes (Singh, S., Purohit, J. K., & Bhaduri, A. 2016) [152]. This system is naturally maintained and adapted to the steep and drought-prone terrain in the area. Their types of millet and mountain paddy can withstand drought and can be harvested in 60 to 90 days. As they provide 18 non-wood forest products, forests are essential. In order to balance livelihood and economic sustainability, tribes sell the remaining products after consuming 70% of them (Dash, S. S., & Misra, M. K., 2001). Due to agricultural diversity and minimal reliance on water, climate resilience is high. Risks include deforestation and mining that endanger ecosystem services and food security (Aich, A., Dey, D., & Roy, A. 2022) [8, 35].

Western Ghats of Tamil Nadu, or Irulars

Irulars place a strong emphasis on weather forecasting, pest control, and seed preservation. 11 native techniques are used to preserve seeds, including combining them with plants such as Vitex negundo and storing them in underground tanks. They employ natural insect repellents based on tobacco, chili pepper and neem. Irulais use astronomical cues (such as halos from the moon) and wildlife activity (such as ants and dragonflies) to predict rainfall. This facilitates timely harvesting and planting. Their resilience and agro-diversity are preserved by genetic selection and mixed farming. Climate resilience is very effective in managing pests and seeds. Hazards include Water stress can occur due to dry weather and unpredictable rainfall (Aich, A., Dey, D., & Roy, A. 2022) [8].

Climatic resilience heatmap

Four major stressors - heat stress, water shortages, severe events and insect attacks - are compared on a heat map to illustrate the resilience of the four tribes.

Table 1: Heatmap representing relative climate resilience across four indigenous tribes

Tribe	Temperature resilience	Water resilience	Event resilience	Resilience to pests
Apatanis	moderate	high	high	moderate
Lahaulas	low	moderate	low	moderate
Dongria Kondhs	high	high	moderate	high
Irular	high	low	moderate	Very high

Implications for more comprehensive studies and policies

Despite being often marginalized, this study shows that ITK-based systems offer valuable models for sustainable agriculture in climate-sensitive regions. There are three main elements:

1. Biodiversity as a buffer: native varieties and multi-crop systems diversify risk and improve food security.
2. Ecological infrastructure Forest systems (Dongrias), glacier harvesting (Lahaulas) and natural irrigation (Apatanis) increase resilience with minimal external help.
3. Community knowledge systems: Adaptive learning systems are demonstrated in shared work, ecological forecasting, and pest control.

At a time when climate instability is on the rise, India's traditional farming communities are particularly noteworthy for their resilience. These communities have developed a variety of decentralized tactics that adapt to natural cycles, from the rain-shaded Nilgiris to the ice-covered Lahaul Valley (Bhutiyani, M. R., Kale, V. S., & Pawar, N. J. 2007) [16]. As pillars of contemporary climate agriculture, these methods improve adaptation, increase biodiversity, and reduce reliance on inputs (Dimri, A. P., & Dash, S. K. 2012) [35, 39]. However, these systems are undervalued, poorly documented, and less and less threatened by ecological deterioration, market forces, and government indifference. As a guiding framework for sustainable agriculture in twenty-first century, this case study highlights the critical need to include indigenous knowledge in national and international efforts for climate resilience.

Conclusion

The resilience of crop yields in marginalized places is necessary to preserving global food security from the aspect of climate change. Yield losses induced by climate change occurs in these regions due to their poor soil, water scarcity and high temperatures. To solve these problems, precision agronomy, genetic advances and climate-smart technologies need to be integrated. By developing crop varieties that can tolerate stress through breeding, genetic engineering, and CRISPR-based modifications, resilience to heat, drought, and salinity has improved. Precision nutrient management, conservation agriculture, intercropping and the use of nano-fertilisers such as nano-urea and nano-DAP improve soil health and resource efficiency. Water conserving irrigation techniques, such as drip and deficit irrigation, also promote sustainable agriculture.

Real-time monitoring of weather and crop conditions, made possible by digital farming, including AI-based predictive modeling and remote sensing, optimizes decision-making. Biostimulants and microbial inoculants increase the stress tolerance of plants, improving yield stability. Barriers to widespread adoption include limited availability of reliable technologies, inadequate government support, and budgetary constraints. To successfully implement resilience solutions, it is necessary to strengthen research, service expansion and targeted policies. In summary, technological innovation and genetic agronomy must be combined to provide crop resilience under marginal conditions. Farmers' acceptance, supportive legislation and research-driven solutions will be essential to support production, also to secure food supply from the climatic change scenario.

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