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Climate Resilient Agriculture: Enhancing Agricultural Sustainability in the Face of Climate Change Scenario

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The increasing demands of a growing population pose a serious danger to global food and nutritional security due to the detrimental impacts of climate change on crop growth and agricultural production, both in terms of quantity and quality. Climate change impacts on income, livelihoods, and population health are directly related to factors including increasing temperatures, erratic rainfall, and extreme weather events. Agronomic practices that are robust to climate change have the potential to improve the current state of matters, maintain agricultural productivity globally, especially in a sustainable way, and accomplish the Sustainable Development Goals (SDGs). Agricultural scientists are anticipated to be crucial in this scenario in advancing the shift to climate-resilient agriculture (CRA), enhancing the conversion of conventional to sustainable food systems, and serving as liaisons between farmer practices and technological developments. In this study, we offer a road map for increased agricultural sustainability that includes the efficient application of technological advancement, policies and plan that will support the intensification of sustainable agriculture and climate resilience.

Keywords: Climate resilient agriculture; climate change impacts; climate-related agricultural productivity; sustainable farming practices; sustainable agriculture.

1. INTRODUCTION

Global issues such as food security, human health, water availability, and general social advancement are all impacted by climate change (CC) [1,2]. Due to the fact that agriculture depends on temperature, rainfall, and soil conditions, climate change can cause droughts, floods, and irregular monsoons, which can have an impact on agricultural output and farmers' income [3,4]. With each degree increase in mean temperature, the detrimental effects of climate change may cause a 3.7–7% decrease in agricultural output [4,5], raising the possibility of famine and undernourishment [6,7,8]. Roughly 86% of all farmers in India are small and marginal farmers [9]. It is critical to comprehend and put into execution strategies for climate-resilient and sustainable farming practices in an era where climate unpredictability and its effects on agriculture are irrefutable [10]. For nations whose economies and way of life are largely dependent on agriculture, climate resilient agriculture is essential to maintaining global food security.

The Recent decades have demonstrated that increased human activity has changed the composition of the global atmosphere, leading to notable changes in the global climate [11]. Since 1750, there has been a 150% rise in the concentration of greenhouse gases such as methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O), respectively [12]. The largest amount of greenhouse gases, carbon dioxide emissions, increased from 22.15 billion metric tonnes in 1990 to 36.14 billion metric tonnes in 2014 [13,14]. Global temperatures have risen by 0.15 to 0.20 degrees Celsius on average every ten years since 1975 [15], and rising by 2021 by 1.4 to 5.8 degrees Celsius [16]. The atmospheric CO_2 concentration changed from 315.98 ppm in 1959 to 411.43 ppm in 2019 (Fig. 1) [17] and before 1750, CO_2 emissions from fossil fuels were negligible, but it increased rapidly with industrialization. Fig. 2 Shows the increase in CO_2 emissions over the years (1850–2020) [18]. The primary greenhouse gas in the atmosphere is CO_2, which is produced by 65% of industrial operations and fossil fuels, 11% by forestry, and the remaining 2% by other land uses. Methane, at 16%, nitrous oxide, at 6%, and fluorinated gases, at 2%, round out the top three contributors [13,19]. Fossil fuel emissions contributed very little to CO_2 emissions before 1750, but when industrialization progressed, it did so quickly. It is anticipated that climate change will get worse in the near future.

Meeting the world's food demand and sustaining rural lives depend heavily on the agrifood industry [20,21]. On the other hand, climate change presents an unparalleled challenge for industry right now. Significant effects are being felt by agricultural production systems and producer incomes as a result of the changing climate patterns marked by extreme weather events and shifting seasons. To maintain the long-term health and financial sustainability of the agrifood industry, it is now essential to address climate change [22,23]. Enhancing the resilience of communities dependent on agriculture requires strategies to mitigate and adapt to the effects of climate change [24,25]. It is imperative to put policies in place that lessen the negative consequences of climate change since its influence on agricultural output cannot be understated. Crop yields and quality are directly impacted by factors such as rising temperatures, unpredictable rainfall patterns, and a rise in pests and diseases. It is becoming more difficult for farmers to sustain steady revenues as a result of these changes to conventional farming techniques [26-28]. Governments are incorporating resilience into agricultural systems as a result of the realisation that climate change may have a detrimental impact on agricultural productivity. Every day, the number of people on Earth increases, placing pressure on the land to generate more fuel, food, and fibre to sustain the growing population. Improved soil health and associated ecosystem services would result from more productive, climate-resilient agronomic techniques. Thus, sustainable agricultural output and related amenities may be guaranteed by combining a scientific approach with excellent technological solutions. With a primary focus on climate resilient agriculture for ensuring agricultural productivity, this study thoroughly

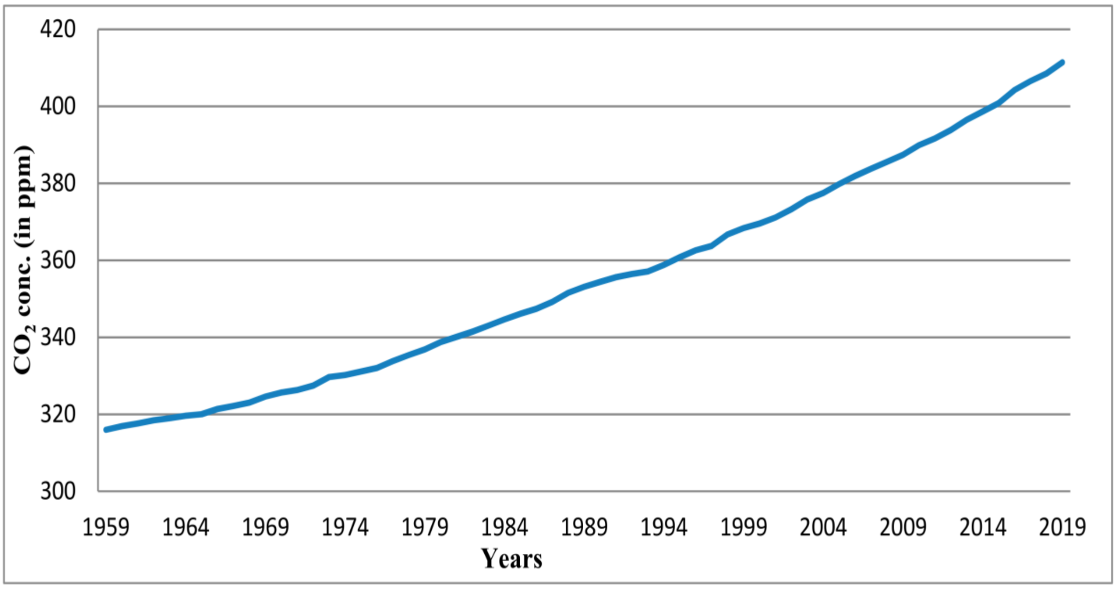

Fig. 1. Increase in CO_2 concentration in the atmosphere (Source: [18])

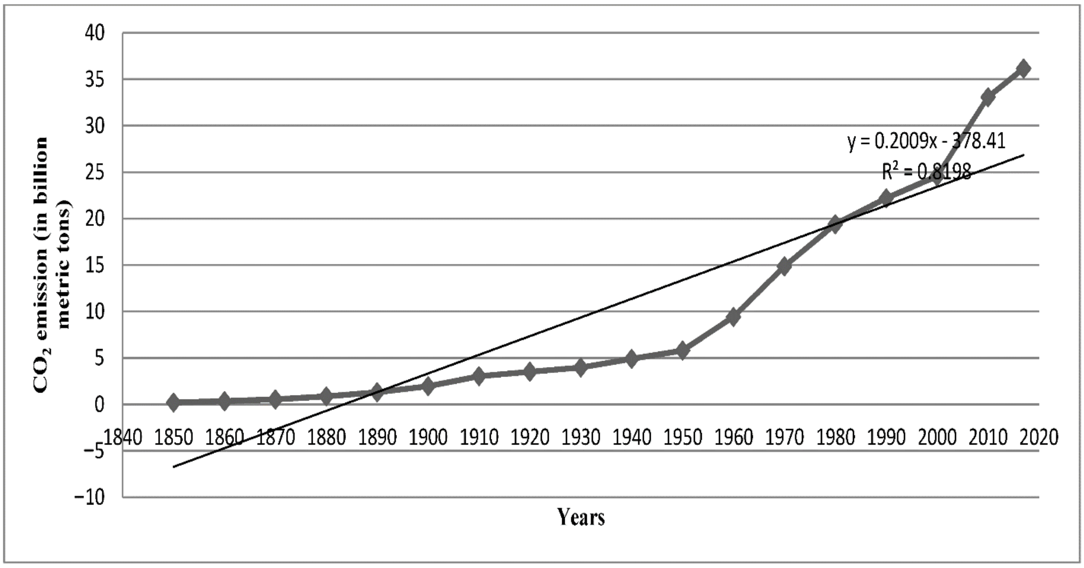

Fig. 2. CO_2 emission in the atmosphere over the years (1850–2020) (Source: 18)

examines the far-reaching implications of climate change on the agrifood system. It also aims to make a significant contribution to the body of literature by outlining the potential for sustainable solutions within the agrifood ecosystem.

2. GLOBAL SCENARIO OF CLIMATE CHANGE

There have been forecasts for higher minimum and maximum temperatures throughout the *Kharif* and *Rabi* seasons in Punjab region. Based on models conducted for the mid-century (2040–2069), the average maximum and minimum temperatures in *Kharif* are expected to climb by 1-3 ºC and 2-4 ºC, respectively. In *Rabi*, on the other hand, the average temperature is forecast to rise by 2.1–3.5 ºC and 2-4 ºC, respectively. Additionally, predictions have shown that the areas' rainfall will vary, with the *Kharif* season seeing the most fluctuations (25–35%) and the *Rabi* season seeing the least differences [29]. According to PRECIS (Providing Regional Climates for Impact Studies) projections, Punjab, India is expected to have an increase in both minimum and maximum temperatures by the middle and end of the twenty-first century. Furthermore, it is expected that there will be extremely rare instances of high temperatures (hot waves) from March to June and cold temperatures (frost) from December to January [30]. With an extra 0.5 ºC of warming predicted, it is also predicted that extremes in meteorological parameters—primarily minimum, maximum, and precipitation—will be experienced more frequently and with greater severity in China. Moreover, weather extremes will decrease if global warming is contained at 1.5 ºC [31].

The worldwide precipitation anomalies during the base period (1901–2000) indicate a positive trend in precipitation change (Fig. 3) [32]. The terrain of an area determines the occurrence of extreme precipitation occurrences, such as drought or excessive rainfall. While southern Africa and South America will see fewer severe droughts, South and East Asia are more likely to see increased average river flows as a result of extended periods of strong rainfall. The Indus River basin's rainfall pattern is expected to exhibit irregular seasonal and geographical fluctuations. In the future, the northeastern United States is likely to see more warm extremes, fewer cold extremes, and stronger precipitation extremes. These changes will become more intense with higher emissions [33]. Soil erosion is impacted by increased precipitation intensity and frequency, which would have greater negative effects in northeast China if greenhouse gas emissions rise [34]. It has a major impact on farmland areas in addition to crop production. Research points to dry anomalies as the cause of the developing world's farmland growth rate of about 9% over the past 20 years, as farmers increase their acreage to offset production losses [35]. The world's food security would be severely threatened by global warming, but if it stays below 1.5 °C, poor nations will be less vulnerable than those in similar locations at 2 °C, which would affect 76% of them [36,37]. Climate change has a significant influence on agriculture productivity, making it difficult to ensure food for the world's population [38]. Global cereal output of wheat and maize is expected to decrease by 5.5% and 3.8%, respectively, due to climate change, which is known to harm agricultural productivity [39-41].

3. IMPACT OF CLIMATE CHANGE ON AGRICULTURE

Natural disasters are causing an increase in economic losses globally, with the agriculture sector being especially vulnerable to these occurrences. Countries impacted by catastrophes suffered direct economic losses of US$ 2908 billion between 1998 and 2017, according to the United Nations Office for Disaster Risk Reduction (UNISDR) in 2018. Disasters linked to climate change were responsible for a significant 77% of these losses. Climate change's effects on the agriculture industry have become more noticeable recently (Fig. 4). Between 2010 and 2039, there is expected to be a nine percent fall in key crop yields in India as a result of climate change, with more declines expected over time [42]. Depending on the exact area and future climatic scenarios, losses might be as high as 35 percent for rice, 20 percent for wheat, 50 percent for sorghum, 13 percent for barley, and 60 percent for maize [43]. The agriculture industry in India has been severely impacted by a slew of climate-related disasters that have occurred in recent years. Increased frequency and severity of heatwaves, droughts, floods, and landslides have led to considerable crop losses, lower yields, and disruptions to food production systems. The Indian Council of Agricultural Research (ICAR) projects that by 2050, food output may fall by 6–10% as a result of climate change. The most vulnerable areas are predicted to include the Western Ghats, eastern and north-eastern India, and the Indo-Gangetic plains. Since these extreme weather occurrences are inextricably related to climate change, it is anticipated that their effects would grow in the years to come, presenting serious obstacles to India's food security and agricultural output [44].

3.1 Increased Drought Frequency and Intensity

The increased frequency and severity of droughts in India is one of the biggest effects of climate change on agriculture. Reduced soil moisture content from droughts has an impact on crop viability and growth. Extended durations of water shortage can lead to crop failure, farmers losing their livelihoods, and a decrease in food output. Severe droughts have already had disastrous effects on areas like Maharashtra, Rajasthan, and portions of South India, greatly reducing agricultural production.

3.2 Changes in Temperature and Rainfall Patterns

The conventional patterns of temperature and rainfall are disrupted by climate change, which has an impact on crop growth cycles and agricultural operations. Increased temperatures have the potential to cause heat stress, which can lower crop yields and lower agricultural output as a whole. Furthermore, variations in rainfall patterns lead to erratic precipitation; certain regions endure extended dry spells, while others get more frequent and powerful rainfall events. Crop growth, soil moisture levels, and agricultural water management are all adversely affected by these changes in rainfall.

3.3 Pest and Disease Outbreaks

The distribution and behaviour of pests and diseases are altered by climate change, which presents new difficulties for agricultural yield and health. Increased temperatures and altered precipitation patterns foster an environment that is conducive to the growth of pests and the dissemination of illnesses. In many regions of India, invasive pests like the Autumn Armyworm have already seriously harmed crops like maize. In addition to lowering crop yields, increased insect pressure also raises the cost of agricultural output overall and affects farmers' livelihoods by requiring more funding for crop protection and pest management techniques.

3.4 Coastal Vulnerability and Salinity Intrusion

Agricultural lands in coastal locations are particularly vulnerable to rising sea levels and coastal erosion. Low-lying coastal areas run the danger of having seawater seep into their agricultural holdings as sea levels rise. Farmland that has had salinity intrusion is unfit for farming because it reduces crop growth and soil fertility. Coastal regions are also more vulnerable to storm surges and cyclones, which can cause severe crop loss, soil erosion, and the uprooting of farming populations.

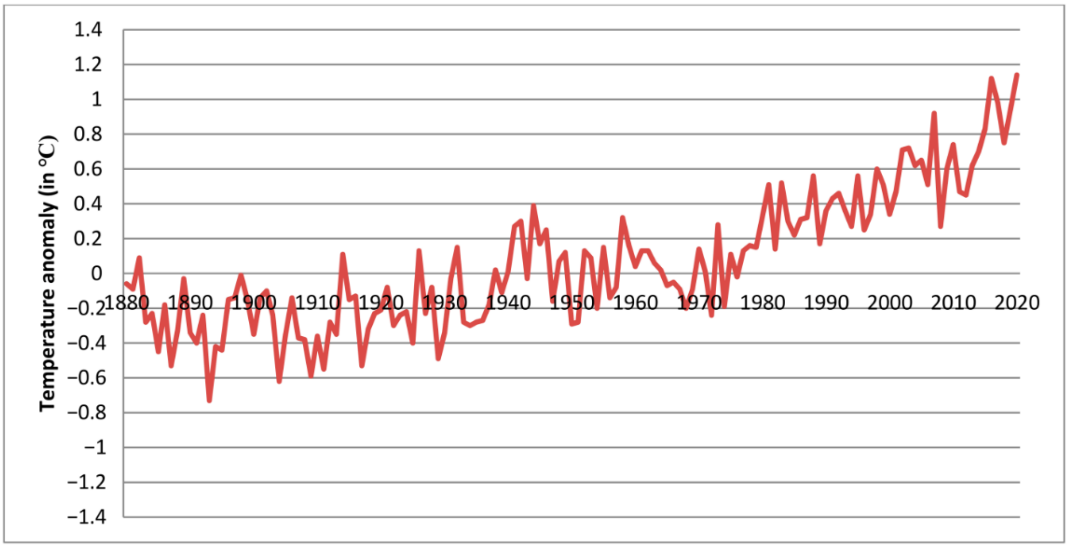

Fig. 3. Global precipitation anomalies over the base period (1901–2000)
(Source: 30)

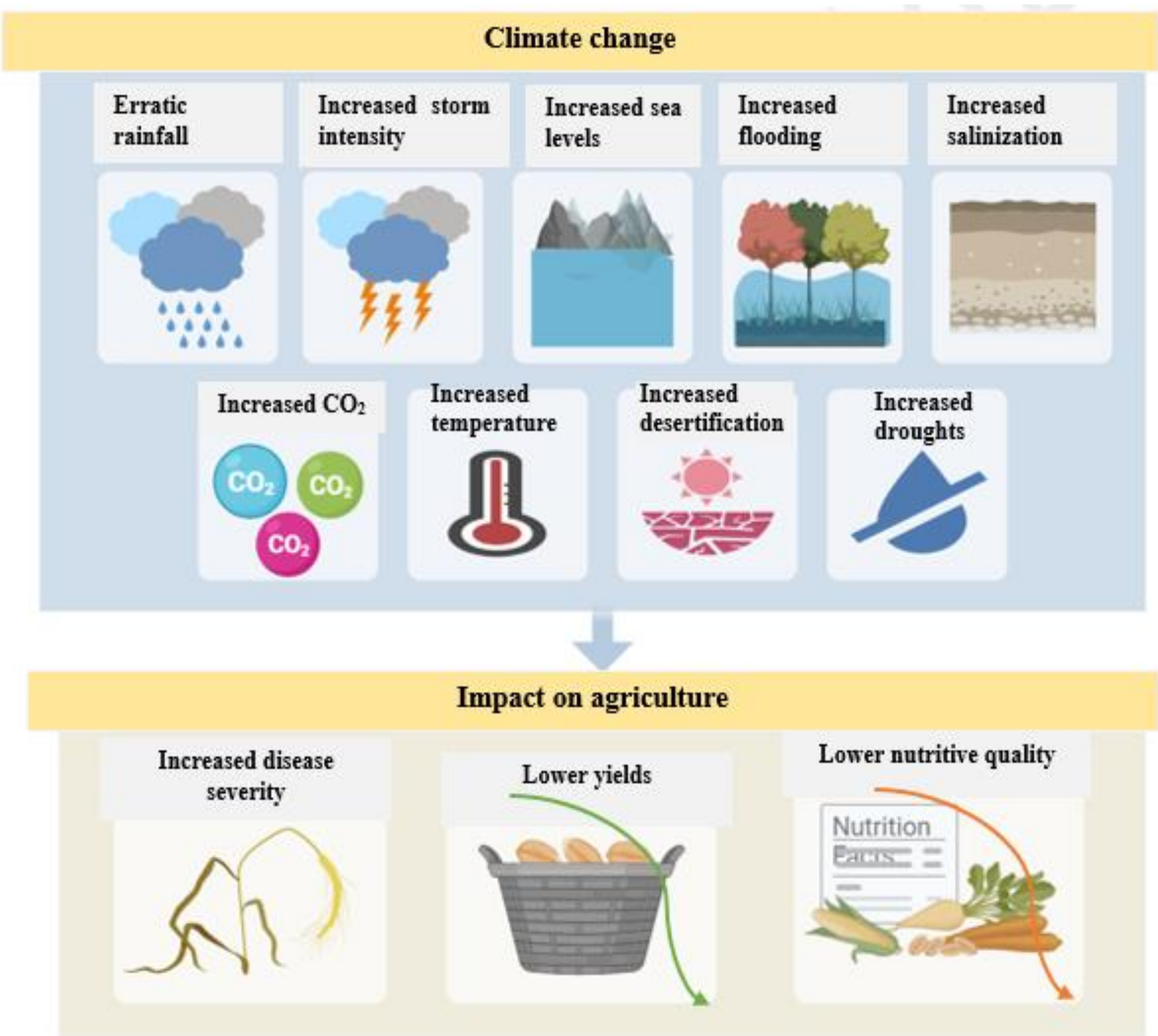

Fig. 4. Environmental outcome of climate change

3.5 Impact on Fisheries and Livestock

As essential elements of the agricultural economy, fisheries and livestock are likewise impacted by climate change. Heat stress and rising temperatures can lower livestock productivity, which can have an impact on milk yield, meat quality, and animal health. Sea surface temperature variations, ocean acidification, and coral reef degradation affect fish populations and traditional fishing methods in coastal areas, endangering fishing communities' livelihoods and lowering the availability of protein-rich food sources.

3.6 Implications for Food Security

India's food security is seriously threatened by the combined effects of these climate change variables on agriculture. Climate change is predicted by the Indian Council of Agricultural Research (ICAR) to reduce food output by 6–10% by 2050. Particularly susceptible areas are the Western Ghats, eastern and north-eastern India, and the Indo-Gangetic plains. This fall in agricultural production makes it harder to supply the food demands of an expanding population by exacerbating pre-existing issues like population expansion, urbanisation, and shifting eating patterns.

4. CLIMATE RESILIENT AGRICULTURE (CRA)

The integration of adaptation, mitigation, and diverse agricultural practices is known as climate-resilient agriculture, or CRA. By withstanding damage and recovering quickly, it improves the system's capacity to handle a variety of climate-related disturbances (Fig. 5). Events such as droughts, floods, sharp temperature swings, erratic rainfall patterns, protracted dry spells, pest or bug outbreaks, and other possible problems brought on by climate change might all be considered disruptions. To put it simply, CRA highlights the system's quick recovery. The system's innate ability to recognise and react to threats while taking their effectiveness into account is encompassed by this. The main goal of CRA is to manage natural resources—such as soil, water, land, and genetic resources—in an excellent and improved manner by implementing the best practices that are currently accessible [45].

4.1 Characteristics of Climate Resilient Agriculture (CRA)

To meet future climate change under the action of human subjective initiative, the CRA management model is built on the original agricultural system. The whole agricultural production process is taken into account by this model, which guarantees that departmental actions are coordinated and that the total level of development stays within the limits of natural resources. This paradigm facilitates cross-border collaboration to address cross-border climate/weather monitoring, resource management, space optimisation, and scientific policy development through activities like planting, breeding, aquaculture, agro-forestry systems, etc. Because of this, the creation of CRA carried over many of the basic traits of the agroecosystem, taking into account the dynamics and multidimensionality of the process of building climate resilience. Sociality, multidimensionality, and dynamics may be used to sum up the traits of CRA.

4.2 Climate-Resilient Agriculture Technologies

To mitigate the adverse impacts of abiotic stresses and tackle the difficulties posed by climate change, an all-encompassing system biology approach had to be employed. It is now necessary to apply science-led development in a holistic system approach with the best possible utilisation of advanced research to address the rapidly increasing issues of abiotic pressures and climate change. The following technologies might be considered to improve agroecological conditions and increase the profitability of agriculture.

4.2.1 Tolerant crop and management systems for climate resilient agriculture

Selecting the appropriate crops and varieties will assist you boost cropping intensity in addition to improving single-crop output in the face of climate change crisis. Based on the research of long-term climatic data, effective agricultural seasons have been determined for various parts of the nation in relation with the likelihood of monsoon onset, withdrawal, and occurrence of dry spells. These will help identify the most productive crops and the best times to grow them. The Indian Council of Agricultural Research (ICAR) has found 35 novel crop varieties with unique traits including nutrition-rich varieties and climatic resistance in India to tackle the twin issues of hunger and climate change. These comprise drought-tolerant chickpea, pigeon pea resistant to wilt and sterility mosaic, early maturing soybeans, disease-resistant rice varieties, and bio-fortified wheat, pearl millet, mustard, maize and chickpea, quinoa, buckwheat, winged bean, and faba bean [46]. Production, profitability, and risk reduction may all be increased by intercropping with the right base and companion crop combinations, plant population, and fertiliser management [47]. The implementation of farming practices centered on cereals, specifically rice-wheat cropping systems, has been characterised by excessive exploitation. This has led to the depletion of natural resources beyond their carrying capacity, which has negatively impacted not only the crop ecosystem but the entire system that sustains life.

Crop diversification can help increase profit generation and better resilience to diverse abiotic and biotic challenges. It is a departure from traditional crops such as rice-wheat/cereal-cereal based cropping systems and agri-horticultural systems [48,49]. More agricultural area may be used for intensive cropping systems like relay cropping for double cropping thanks to contemporary agricultural technology including crop selection, rainwater management, short-duration varieties, and other agronomical techniques. Many innovative double cropping systems including oilseeds, legumes, and millet have been created for India's varied agro-climatic zones [50].

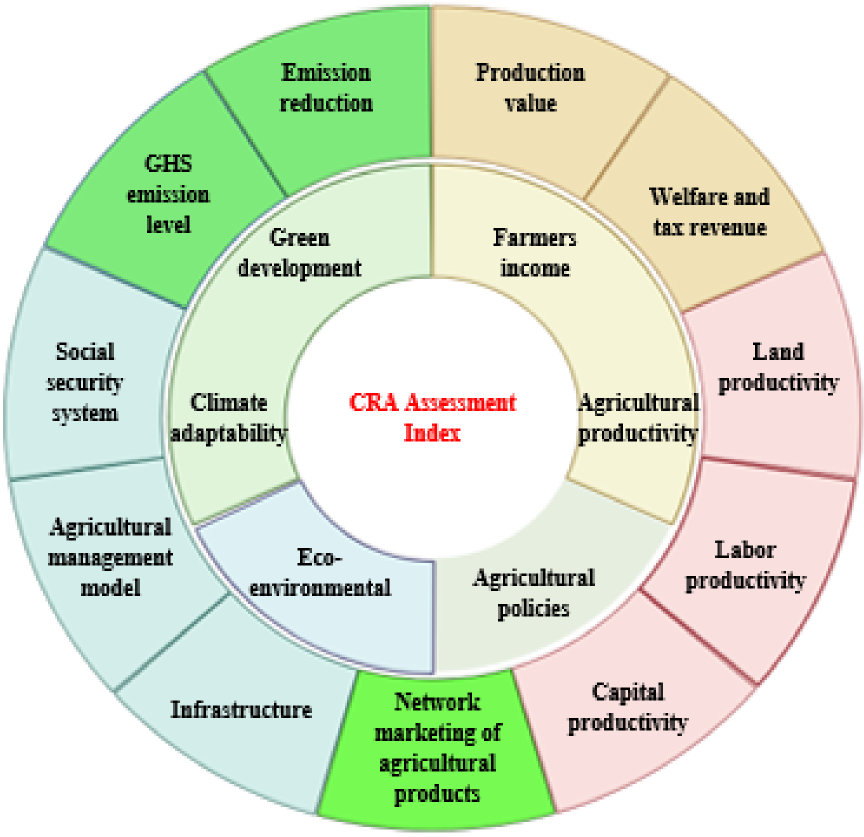

Fig. 5. Climate Resilient Agriculture (CRA) comprehensive assessment index
Source adapted from Zong et al. [45]

4.2.2 Utilising cutting-edge farming machinery

Timely operations can lead to high crop stand, maintained crop yield, increased germination and required plant population. Low agricultural yield results from huge areas of rainfed regions being left fallow or having late plantings due to lack of access to farm machinery. Therefore, one important adaptation technique for coping with climatic variabilities including late monsoon on-set, mid-season, and terminal droughts, as well as for timely sowing of post-rainy crops, is improved access to agricultural machinery for sowing, harvesting, and other activities. The optimal mixes of mechanical and biological energy were discovered after calculating the energy needs of the major dryland agricultural operations. Several effective low-cost farm implements were designed for a variety of operations; these implements result in a reduction of 20–59 percent in operation costs, a reduction of 45–64 percent in operation time, a reduction of 31–38 percent in seed and fertiliser savings, and an increase of 18–53 percent in dryland crop yield [51].

4.2.3 Planning for crops contingency

Stabilising agricultural output is the main goal of contingency crop planning in the case of late-onset monsoon, mid-season, or terminal droughts. Contingency planning covers a variety of meteorological scenarios, including late monsoon start, mid-season dryness, and terminal drought. Among the recommended drought-resilience strategies are modifications to crop/cropping systems, crop management, soil nutrient management, and moisture conservation techniques [52].

4.2.4 Rainwater harvesting and conservation

Rainwater management in arid and semiarid regions means selecting crops with short growth seasons and low water requirements and preserving as much rainwater as one can to prevent moisture stress in the crops throughout the growing season. Efforts must be made to move extra water into storage facilities in addition to conserving it in-situ. These facilities can be utilised alone or in conjunction with groundwater to satisfy significant irrigation demands. The goal in regions with heavy rainfall is to collect as much rainwater as possible and use the extra water for agricultural intensification, life-saving irrigation, and optimising returns on the water caught. To reduce different kinds of water-related losses, improving water-use efficiency should take precedence over expanding water supply through diverse means. Crops can withstand moisture stress because of better soil structure, porosity, infiltration, and hydraulic conductivity, which increase soil water storage. These methods are often more doable and acceptable even for small landholdings, as they may be carried out by a single farmer with a smaller draught [53].

4.2.5 Restoration of soil health

By 2050, there will likely be a 60% increase in the need for food, feed, and fibre due to current demographic shifts and the projected growth of the global population (about 9 billion people by that time) [54]. In addition to INM, which includes the addition of farmyard manure, crop residues, brown manuring, soil carbon sequestration, precision nutrient management, and water conservation techniques, the soils must be managed sustainably to feed the growing population. In much of India, soils are lacking not just in NPK but also in micronutrients (B, Zn, Cu, Fe, Mn, and so forth) and secondary nutrients (S, Ca, and Mg). Therefore, maintaining the health of the soil and the land is essential for both food security and the provision of several other ecosystem services [55]. The United Nations General Assembly approved the 2030 framework for sustainable development in 2015; it has seventeen Sustainable Development Goals. (SDGs). The most obvious connection between soils, food production, and healthy living is zero hunger (Goal 2: Ending hunger, guaranteeing food security and improving nutrition, and promoting sustainable agriculture). This is just one of six Sustainable Development Goals (SDGs) that have a direct bearing on agriculture. Improving soil quality is also a prerequisite for achieving other SDGs, such Goal 1: No Poverty, Objective 3: Sustaining Optimal Health and Welfare Objective 6: Sanitation and Safe Drinking Water Climate action is the focus of Goal 13, and living on land is the focus of Goal 15. To accomplish the goal of sustainable development, it is essential to scale up technologies that help improve soil health [56].

4.2.6 Brown manuring

Traditionally, brown manuring involves planting rice and Sesbania spp. side by side. Depending on the kind of weeds, a herbicide such 2,4-D/Bispyribac sodium is then used to kill the Sesbania plants until the dhaincha plants reach a height of around 25 to 30 DAS. Within 4 to 5 days of being sprayed, sesbania plants turn brown and start to die. Not rice plants; only Sesbania plants are impacted. The term "knocking down effect" describes this. For rice that is directly planted or in an aerobic state, brown manuring is typically advised in order to suppress weeds and mitigate the adverse impacts of early-season dryness since sesbania has a smothering effect [57,58].

4.2.7 Sequestration of carbon in soil and nutrient management

For agriculture to be climate-resilient, soil carbon management is essential. Daily loss of organic matter and soil organic carbon is caused by the continuous application of chemical fertilisers. Constant cropping lowers organic C levels by 50–70%, bringing them closer to the equilibrium values determined by precipitation and climate. The primary regulator of the biological, physical, and chemical characteristics of soil is the amount of organic carbon present in the soil [59]. It is essential to scale up technologies like biochar, agricultural residue recycling, agroforestry, and afforestation for boosting carbon sequestration in order to restore soil health and address the problems associated with global warming. India has the capacity to absorb three billion tonnes of CO_2 equivalent if open forests are converted to moderately thick forests and an extra five million hectares are planted. This will result in the world's forests being more densely wooded than they have ever been. The following agronomical practices can raise soil organic carbon levels: reduced tillage, crop rotations, cover crop growth and contour farming in hilly locations, appropriate crop residue management, integrated farming system, organic farming, INM, and rotation of legume crops [52]. The decline in soil health has led to a decreased trend in the principal crops' compound growth rates and total factor productivity as well as low nutrient consumption efficiency. The main reason for the decline in soil health is a widening nitrogen deficit between supply and demand. Due to a decline in the chemical, physical, and biological health of the soils, the current level of nutrient utilisation efficiency is rather poor for P (15–20%), N (30–50%), S (8–12%), Zn (2–5%), Fe (1-2%), and Cu (1-2%) [60].

4.2.8 Nutrient management through Precision agriculture

In order to assist with nutrient management choices in large agroecosystems, research is being done on the delineation and mapping of macro and micronutrient shortages using Geographic Information Systems (GIS), and Geographic Positioning Systems (GPS) technologies and simulation modelling. Accurate fertiliser prescriptions, monitoring, and assessment of soil fertility have become priorities for ensuring sustainable agricultural productivity. The development of controlled-release fertilisers and other fortified fertilisers, together with the effective use of organic wastes, locally available minerals, and industrial by-products, have all taken precedence in agriculture. The use of nanoscience and technology has led to the development of commercial Nano-urea and other formulations that will reduce cultivation expenses while simultaneously increasing fertiliser use efficiency [61]. Crops don't always use fertilisers, manures, biosolids, and other nutrient sources effectively. Integrated nutrition management (INM) and site-specific nutrition management (SSNM) can both help reduce the effects of climate change. In addition, a lot of research has been done on the usage of nitrogenous fertiliser based on LCC and Green Seeker, and this practice is presently being increased to increase NUE [62].

4.2.9 Water management

Innovative water management techniques can help farmers lessen the effects of climate change. These include laser field levelling, cover crops, rainwater gathering structures, greenhouses, micro-irrigation and furrow irrigated raised beds, and cover crops. Even in years with little rainfall and high temperatures, farmers may be able to achieve satisfactory crop yields with the use of many technologies based on accurate crop water needs estimation, adoption of scientific water conservation methods, groundwater recharge techniques, proper fertiliser and irrigation scheduling, growing less water-demanding crops, and adjusting planting [63].

4.2.10 Conservation agriculture

While soil disturbance promotes soil carbon losses through rapid decomposition and erosion, no-tillage or restricted agriculture frequently boosts the soil's capacity to absorb carbon and reduces its emissions of nitrogen dioxide. Thanks to advancements in weed control technologies and farm automation, many crops may now be grown with low tillage (reduced tillage) or no-tillage (no-till). Globally, these methods are starting to be employed more often. Moreover, burning leftovers raises aerosol and greenhouse gas emissions whereas recycling agricultural wastes enhances soil carbon [55]. It is commonly known that reducing tillage may effectively increase the amount of water stored. This is particularly important in semi-arid and dry regions, where managing agricultural residues is essential to producing crops that will last over time. Aside from the non-financial advantages of timely crop planting, conservation agriculture saves 25%–30% on irrigation water, 3% on nitrogen, 50% on labour, and 60% on fuel when compared to typical tillage. The savings stem from two factors: irrigation water moves more quickly through tillled soil than through tilled soil. Firstly, zero-tillage wheat may be planted soon after rice harvest, utilising residual moisture for germination and perhaps avoiding pre-sowing irrigation. When compared to CT, ZT with crop residue retention on the soil surface greatly reduces erosion and increases water-use efficiency [64].

4.2.11 Integrated farming system

Meeting the diverse needs of a growing global population while simultaneously preserving environmental quality, natural resources, and enough profitability for farming families has emerged as the most challenging challenge due to changing climatic conditions and declining natural resource availability. The production system for agriculture has to be robust and sustainable, with a focus on reducing risk, increasing productivity, creating jobs, conserving resources, conserving revenue, and mitigating and adapting to climate change [65]. Creating buffers and dispersing risks, or avoiding "putting all your eggs in one basket," is one of the main strategies for agricultural resilience and drought mitigation. Because location-specific Integrated Farming System (IFS) will be more robust and adaptable to climatic variability, the agricultural systems approach is anticipated to be significant and pertinent, especially for small and marginal farmers [66]. IFS has great promise in addressing these challenges, particularly in high-stress settings. Farmers in these strained regions have been utilising minimal amounts of good-quality inputs due to the high risk of growing arable crops, which has led to low crop performance and soil health [67]. In general, low-water-requirement grasses, trees, and shrubs should be encouraged in places with 500–700 mm of rainfall in order to support cattle and fulfil the farmers' demands for fuel, food, and lumber. Depending on the soil type and marketability requirements, agricultural methods centred around crops, horticulture, and livestock can all be employed in regions receiving 700 to 1,100 mm of rainfall. Runoff collection is a crucial component of the watershed-based agricultural system in this area. The IFS module that combines fisheries and paddy is best suited for areas with more than 1,100 mm of rainfall annually. IFS seems to be a vital alternative in arid and semiarid regions for ensuring environmental security, profitability, meaningful employment, and nutritional security [68]. Realising the full potential of IFS requires scaling up its implementation to the required degree.

5. ADAPTATION AND MITIGATION THROUGH TECHNOLOGICAL ADVANCEMENT

5.1 Climate-Resilient through Molecular Approach

Climate-resilient crop types that can tolerate harsh weather, fend off pests and diseases, and retain high yields have been developed thanks to plant breeding techniques [69]. Certain cultivars, such heat- or drought-tolerant crops, allow farmers to reduce the risks brought on by climate change while still generating steady profits in trying circumstances [70].

A sophisticated and novel target for modulating the crop's reaction and approaches for agronomic benefits may be found by looking into the pathways involved in enhancing other important crop species (Table 1).

5.2 Climate-Resilient through Artificial Intelligence

In light of climate change, artificial intelligence (AI) is completely changing how we approach farming. Artificial intelligence (AI) technology, such as machine learning and predictive analytics, enable farmers to anticipate changes in the environment, make data-driven choices, and maximise resource utilisation. Artificial intelligence (AI) in CSA improves sustainability and resilience across the agricultural lifecycle, from forecasting weather patterns for accurate planting to creating crop types resistant to climate change. For instance, real-time data gathering and analysis is made easier by the combination of artificial intelligence (AI) with Internet of Things (IoT) sensors. Farmers gain important insights from these data, which range from soil moisture levels to weather patterns. Farmers may use this information to plan their irrigation systems, choose crops, and manage pests with knowledge [71].

5.3 Climate-Resilient through Blockchain Technology

The agrifood supply chain may now be more transparent, traceable, and trustworthy thanks to blockchain technology. Blockchain makes it possible to store transaction and data records in an immutable, decentralised, and safe manner [72,73]. Agricultural goods may be tracked and verified using this technology from farm to fork, guaranteeing the legitimacy of certificates, provenance, and manufacturing methods.

With the use of blockchain technology, manufacturers may provide substantiated proof of their adherence to fair trade principles, sustainability requirements, and quality certificates. In the agriculture industry, this strengthens accountability and openness. In addition to enabling companies to differentiate their goods and gain access to premium markets, transparency promotes consumer and buyer confidence. Additionally, blockchain-based smart contracts can minimise payment procedures to guarantee quick and safe transactions, which lowers the financial risk for producers [74,75].

6. PRIORITIZATION AND CONVERGENCE OF PROGRAMMES AND POLICIES

Prioritise areas that are susceptible to climate change, with an emphasis on arid and semi-arid regions; create and carry out thorough district-level strategies for agriculture and livelihoods. To help rural communities benefit from new tools and technologies, integrate climate change initiatives (e.g., INCCA, NAPA, NMSA, NICRA

Table 1. Solutions to improve climate change resilience in crops

Area of study	Novel and ongoing approaches/solutions
Manipulation of candidate genes	➢ Improve phenotyping in the field to identify genes responsible for desirable traits and their environmental interactions. ➢ Improve understanding of signalling and molecular pathways. ➢ Establish efficiency in homology-directed repair (HDR) using CRISPR approaches to enable precise gene replacement. ➢ Use of crop modelling approaches and synthetic biology to design strategies for engineering multiple desirable traits.
Crop management practices	➢ Improved/widespread supplementation of crop microbiota to improve tolerance to specific stresses. ➢ Intercropping with desert plants to promote novel plant growth-promoting rhizobacteria (PGPR). ➢ Reduced reliance on monocultures and associated effect on microbial biodiversity decrease. ➢ Better understanding of practices to conserve soil moisture, temperature, organic matter, and beneficial microbiota.
Use of on-farm 'insurance crops' and preservation of genetic diversity	➢ Transition to underutilised wild and semi-domesticated crops. Progress on research of antinutrient factors. ➢ Further accessibility of genome sequencing/phenotyping data to fill the knowledge gaps in germplasm collection. ➢ Haplotype-based breeding to deploy resilient varieties/hybrids based on gene-based association analysis.
Social sciences and interdisciplinary networks	➢ Social license and harmonised governance on GMO at a global scale. ➢ Better integration/use of new technologies to assist faster decision making and policy development. ➢ Development of pathways for translation of fundamental knowledge into plant breeding and biotechnology by collaborative interdisciplinary teams. ➢ Open access to scientific information for representatives of the political world, society and stakeholders leveraging novel approaches including the arts to facilitate engagement.

NDMA, etc.) with national agricultural policies and programmes pertaining to food security, disaster management, conservation of natural resources, livelihood enhancement, etc. Promote off-farm and non-farm livelihood diversification to increase rural income; increase support for climate change adaptation initiatives under the recently established National Livelihood Mission. Assure that the most vulnerable members of society have access to government assistance and relief programmes (food security, agricultural and business subsidies, rural financing, programmes for reducing poverty, assistance for the adoption of new technologies, etc.). University curriculum should be revised and reorganised, and teaching and research facilities should be institutionalised in relevant educational institutions to produce graduates and postgraduates with the necessary training in managing climate change. To improve the local community's readiness for adaptation, promote the involvement of non-governmental organisations, civil societies, public, and philanthropic organisations. Create international and regional alliances, particularly with the FAO, CCAFS of the CGIAR, UNEP, and IPCC, to create technologies and techniques that are appropriate for local needs by combining financial and intellectual resources. Assist in the prudent implementation of international accords in reducing greenhouse gas and carbon footprint. Create effective associations, cooperatives, and community organisations to address the pressing requirements of farmers, such as resource mobilisation, custom hiring, exporting their products, and effective management of natural resources. Give Gramm Panchayats the appropriate authority to take the lead in creating and executing relevant programmes at the local level. When significant calamities like cyclones and floods destroy horticulture, livestock, and agriculture, national policies on disaster management in agriculture should be updated. Implement the National Commission on Farmers' (NCF) suggestion to create a National Agricultural Risk Management Fund and distribute funds in a timely manner depending on need.

7. CLIMATE RESILIENT AGRICULTURE: WAY FORWARD

For long-term food security and to overcome the difficulties posed by climate change, climate resilient agriculture is essential. Climate resilient agriculture, according to the Intergovernmental Panel on Climate Change (IPCC), is the management of agricultural systems to survive the effects of climate change while preserving or improving production, revenue, and the reduction of greenhouse gas emissions. Climate resilience may be attained by farmers and policymakers implementing sustainable agriculture techniques that increase yield, lower risks, and lower greenhouse gas emissions. Climate-smart solutions in the agrifood industry have a bright future. Going beyond the advancements made possible by digital technology today, the future holds the possibility of utilising quantum computing to analyse data in agriculture in a way never before possible. The application of quantum computing to agriculture might transform our knowledge of crop behaviour and allow for more precise forecasts and customised agricultural techniques. Moreover, a paradigm change in crop development may be announced by the advancement of genetic editing and bioinformatics techniques. It is possible that crops may be adapted to certain environmental circumstances, which would increase yields while requiring less inputs. Especially CRISPR-based technologies provide accurate selection tools to develop crops that are more resilient to climate-related problems. The use of cellular agriculture and insect-based proteins stands out as a significant breakthrough from the standpoint of sustainable development. The combination of these state-of-the-art technologies not only solves present problems but also creates new opportunities for agri-food systems that are sustainable. But in order to realise their full potential, multidisciplinary cooperation, regulatory awareness, and a dedication to morally and responsibly driven innovation are necessary. This all-encompassing strategy will drive the agrifood industry towards a future in which farmers prosper financially and make a substantial contribution to the aims of global sustainability.

8. CONCLUSION

In spite of the difficulties caused by climate change, climate resilient agriculture is essential for maintaining food security. Farmers may increase their production, resilience, and revenue by using science-based solutions and sustainable farming methods. Partnerships between farmers, academics, extension agencies, and policymakers are essential to facilitating the shift to climate resilient agriculture. To create resilient and sustainable agricultural systems, more money must be spent on research, capacity building, and innovation. It will be crucial to protect its food security, improve farmer livelihoods, and contribute to a sustainable future for all if climate resilience is prioritised. The agriculture industry may become more sustainable, efficient, and profitable by embracing these future orientations and encouraging joint efforts among stakeholders, governments, and research institutes. The supply of wholesome, traceable, and high-quality food is guaranteed by climate-smart technology, which benefits both farmers and consumers. Accepting these climate resilient agricultural approach is a critical first step towards building a more robust and successful agricultural sustainability in the face of changing climate.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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