CLIMATE SMART AGRICULTURE: PAVING THE WAY FOR SUSTAINABLE AND CLIMATE-RESILIENT PRACTICES

Abstract

Climate change (CC) and climate variability (CV) are causing irregular precipitation, rising sea levels, and frequent extreme weather events, which threaten global agricultural crop production through prolonged droughts, floods, and shifting agroclimatic zones. Addressing greenhouse gas emissions and ensuring food security are among the greatest challenges of this century. Climate Smart Agriculture (CSA) emerges as a global strategy to enhance food productivity amid these uncertainties. CSA aims to create climate-resilient agricultural systems that increase soil health, water, and nutrient efficiency, provide stable yields, and reduce greenhouse gas emissions. By improving farmers' incomes and resilience to climate impacts, CSA contributes to both climate change mitigation and adaptation. Future CSA development directions include leveraging advanced internet technology for secure agricultural information, optimizing cropping patterns and management, integrating "internet + weather" services, and implementing agricultural weather index-based insurance. These strategies offer new pathways for ecological protection, green agricultural development, and climate change mitigation.

Keywords: Climate change, Adaptation, Mitigation, Food security, Agricultural production, Climate Smart Agriculture, Sustainable agriculture

4.1 Introduction

Climate change is an undeniable reality supported by extensive meteorological data (IPCC, 2014). Human activities release greenhouse gases (GHGs) into the atmosphere, leading to a trapping of heat and subsequent global temperature rise, a phenomenon widely acknowledged by scientific consensus (IPCC, 2018). Over the past 150 years, global temperatures have surged by approximately 40%, with half of this increase occurring in just the last three decades (IPCC, 2014). GHG emissions originate from various sectors, including energy (57.8%), industry (21.7%), agriculture (17.6%), and waste management (3%). Notable sources within agriculture include rice cultivation (20.9%), soil management (13%), and crop residue incineration (2%), accounting for a total of 35.9% of emissions within the sector (INCCA, 2010). These emissions have far-reaching consequences, contributing to extreme weather events, lethal heat waves, and severe droughts, all of which pose significant threats to agricultural productivity (Leisner *et al*., 2020) and subsequently affect net crop income (Hossain *et al.*, 2019) and agricultural land valuation (Arshad *et al*., 2016).

Agriculture, in particular, plays a substantial role in GHG emissions, responsible for over a quarter of global anthropogenic emissions (IPCC, 2018). Key sources of emissions within agriculture include soil organic matter decomposition and the burning of crop residues, contributing to carbon dioxide (CO_2) emissions. Methane (CH_4) emissions stem from flooded rice paddies, livestock digestion, and the decomposition of organic matter in moist conditions. Nitrous oxide (N_2O) emissions primarily arise from nitrogen-rich soils, manure, and compost. Economic and population growth are identified as primary drivers for the escalating GHG emissions, a trend expected to persist into the future. Consequently, mitigating GHG emissions while ensuring food security is deemed one of the paramount challenges of this era (Amundson *et al.*, 2018).The intertwining of agriculture and climate change presents a critical dilemma. Land use changes, such as deforestation, contribute to nearly 30% of global GHG emissions, while the repercussions of climate change exacerbate land degradation, diminish agricultural yields, and intensify food insecurity, particularly affecting smallholder farmers (Onyeneke*et al.*, 2018). To address these challenges, resilient agricultural production systems are imperative, necessitating effective natural resource management (Turyasingura *et al.*, 2022). Transitioning towards such systems not only mitigates emissions but also enhances agricultural productivity, underscoring the substantial benefits of mitigation efforts (Mwungu*et al.*, 2018).

Climate-Smart Agriculture (CSA) is a multifaceted approach aimed at bolstering scientific governance and investment frameworks to achieve Sustainable Agricultural Development (SAD), particularly in the face of Climate Change (CC) challenges (FAO, 2012). It represents a sustainable strategy capable of enhancing agricultural productivity and income by implementing adaptation measures while fostering resilience to climate change and minimizing greenhouse gas (GHG) emissions (Engel *et al.*, 2016).CSA entails methodologies that revolutionize agricultural systems to bolster food production and security amidst shifting climatic conditions (Campbell *et al.*, 2014). It stands as a transformative and sustainable agricultural paradigm, seeking to bolster productivity and food security systems by integrating key climate change pillars such as adaptation, resilience, and mitigation, alongside innovative technological insights. This integration aims not only to increase profits but also to diminish vulnerability by curtailing GHG emissions (Adesipo*et al.*, 2020).Moreover, CSA emphasizes the utilization of low-impact agricultural systems including conservation agriculture, agroecology, ecosystem services, small-scale irrigation, aquaculture, agroforestry systems, soil and water conservation, nutrient management, integrated crop and livestock management, landscape approaches, grassland and forestry management, and implementing best practices for minimizing tillage and selecting breeds. These practices collectively enhance food productivity and fortify adaptation and mitigation measures (Chandra, 2018).

The essence of CSA lies in the transformation and realignment of agricultural development strategies to effectively address the challenges posed by climate change (IPCC, 2014). It serves as a strategic framework encompassing policy, capital, and technology to realize Sustainable Agricultural Development (SAD) and ensure Food and Nutritional Security (FNS) amidst evolving climatic scenarios.CSA endeavors to enhance livelihoods and food safety, particularly for small and marginal farmers, through improved management and utilization of natural resources, coupled with appropriate production, development, storage, processing, and marketing strategies for agricultural commodities. It is designed to consider the socioeconomic and environmental contexts to maximize potential gains while minimizing trade-offs, with assessments made on regional resource availability and energy impact (FAO, 2016).Climate-Smart Agriculture (CSA) adopts an integrated approach with its three pillars: increasing agricultural productivity and improving livelihoods, fostering resilient agricultural systems, and mitigating GHG emissions. CSA strategies are tailored to local contexts and involve capacity-building for stakeholders to offset higher implementation costs (FAO, 2016). It's noted that practices promoting adaptation and food security often coincide with reduced GHG emissions or increased carbon sequestration. While the efficacy of field-level adaptation practices may be debated, agronomic adaptations can potentially enhance yields by an estimated 15%–18%.In recent years, Climate-Smart Agriculture (CSA) has emerged as a cornerstone concept for numerous global entities operating within the intersection of climate change, agriculture, and development (World Bank, 2015). Furthermore, CSA has been acknowledged as a vital mechanism for advancing the Sustainable Development Goals (SDGs) (World Bank, 2015). Many developing nations are actively exploring cost-effective and dependable weather monitoring and forecasting systems. They aim to integrate these systems with cutting-edge technologies such as agricultural drones, bio-sensors, IoT-based sensors, remote sensing, and husbandry techniques, among others, to elevate crop and livestock management while bolstering food security (Adoghe, 2017).CSA integrates various methods, strategies, and institutions that may not be entirely novel but are unfamiliar to individuals involved in agriculture, such as peasants, shepherds, farmers, growers, or fishermen, particularly in light of shifting climate patterns. What distinguishes CSA is its innovative approach to addressing multiple challenges concurrently and internationally experienced in agriculture and food production. This approach aims to prevent the adoption of ineffective strategies, regulations, funding, and investments. CSA primarily targets three key objectives:

- Achieving a sustainable increase in income and productivity.
- Strengthening adaptability to Climate Change (CC) and Climate Variability (CV).
- Contributing to the mitigation of Climate Change (CC).

The first pillar emphasizes increasing agricultural productivity and livelihoods sustainably. Climate-smart agriculture (CSA) emerges as a strategy that aligns with sustainable development and green economy goals, aiming to improve food and nutrition security while conserving natural resources (Amin *et al.*, 2015). CSA seeks to boost agricultural productivity and income from various sources like crops, livestock, and fisheries while minimizing environmental harm. This approach, therefore, significantly contributes to enhancing food and nutritional security. A key concept within this strategy is sustainable intensification.

The second pillar focuses on enhancing resilience to climate change (CC) impacts by developing and implementing adaptive strategies. Adaptation aims to reduce the vulnerability of human and natural systems to CC and associated risks by enhancing adaptive capacity and resilience. CSA plays a crucial role in reducing farmers' exposure to immediate risks and enhancing their resilience to withstand shocks and long-term stresses. This approach emphasizes the protection of ecosystem services provided by natural environments, which are essential for maintaining productivity and facilitating adaptation to climate variability (OECD-DAC, 2011).

Mitigation efforts focus on reducing atmospheric greenhouse gas (GHG) concentrations by addressing their emission sources. Strategies to combat climate change include adopting technologies that reduce GHG emissions and inputs per unit of output. Given that approximately 30% of global GHG emissions are attributed to agricultural and deforestation activities, there is considerable potential for mitigation. There are three main approaches to mitigating climate change in agriculture:

- Emission reduction: Efficient management of carbon and nitrogen flows within agricultural ecosystems can reduce the release of CO_2, CH_4, and N_2O.
- Emission avoidance or displacement: There are opportunities to improve energy efficiency in the agricultural sector. For example, using biofuels instead of fossil fuels in agricultural operations can significantly prevent or replace GHG emissions.

- Emission removal: CSA practices can capture and sequester GHGs or their precursors from the atmosphere.

4.2 Impact of Climate Change on Agriculture:

The agricultural sector faces significant challenges due to climate fluctuations, including variations in global rainfall patterns, rising levels of carbon dioxide, and increasing average temperatures. These changes have led to a higher frequency of extreme weather events, such as floods and droughts, posing serious threats to crop productivity worldwide (Hussain *et al*., 2019). The variability in temperature and precipitation directly impacts the growth and maturation of crops, making them more vulnerable to various biotic and abiotic stresses (Chaudhry *et al*., 2022). Recent research indicates that these stresses account for substantial losses, ranging from 30% to 50%, in global agricultural productivity (Rajput *et al*., 2021). Such detrimental effects on crop yields have the potential to compromise global food security (Abbass *et al*., 2022), making food insecurity and climate change two of the most pressing challenges of the 21st century (Neupane *et al*., 2022). India, with its historical dependence on the monsoon, is particularly susceptible to changes in rainfall patterns. Even slight alterations in the monsoon trend can have drastic effects on agriculture. Additionally, the rising temperatures are adversely impacting Indian agriculture, with the Indo-Gangetic Plain being particularly vulnerable. Studies suggest that pre-monsoon variations will disproportionately affect wheat crops in this region, especially with a projected temperature increase of over 0.5°C during the time slice of 2010-2039.

Climate change is anticipated to have significant repercussions on rain-fed or un-irrigated crops, which constitute approximately 60% of cropland. For instance, a 0.5°C increase in winter temperatures is predicted to lead to a reduction of 0.45 tonnes per hectare in rain-fed wheat yield in India (Mahato, 2014). Recent research conducted at the Indian Agricultural Research Institute suggests that for every 1°C increase in temperature over the growing season, there could be a potential loss of 4-5 million tons in wheat production in the future. Additionally, rice production may decrease by nearly a tonne per hectare with a 2°C temperature rise. In Rajasthan, a 2°C temperature increase is estimated to result in a 10-15% reduction in Pearl Millet production. Furthermore, if maximum and minimum temperatures rise by 3°C and 3.5°C respectively, Soyabean yields in Madhya Pradesh are expected to decline by 5% compared to 1998. Agriculture in the coastal regions of Gujarat and Maharashtra faces severe vulnerability due to inundation and salinization, exacerbating the impact of climate change on fertile areas.

4.3Strategies for Implementing Climate-Smart Agriculture

To achieve the pillars of Climate-Smart Agriculture (CSA), it is essential to adopt a variety of CSA interventions. This requires integrated, scientific, multidisciplinary, and diversified strategies focused on natural resource management. Such an approach represents a significant paradigm shift, transforming traditional agriculture into a modernized system under the principles of CSA. Consequently, interventions across areas such as land, water, soil, Agroforestry, Conservation Practices (ACP), energy, and livestock are crucial for making agriculture climate-smart. The comprehensive and integrated implementation of these methods, tailored to site-specific resources, is urgently needed.

4.3.1Land Use Management

Land use management encompasses a variety of agricultural practices and techniques aimed at enhancing soil nutrients and water retention capacity, such as the restoration of degraded lands and wastelands. Effective land use management necessitates the creation of comprehensive land cover (LC) databases and expert systems, which serve as essential tools for natural resource management and land use planning. Techniques like minimum or zero tillage, efficient irrigation and nutrient management, and residue incorporation can improve crop productivity, water use efficiency (WUE), and nutrient use efficiency (NUE) while reducing greenhouse gas (GHG) emissions from agricultural activities (Branca *et al.* 2011).

Land use management strategies, including afforestation, agroforestry, reforestation, soil organic carbon (SOC) management, and biochar application, contribute to carbon sequestration in soil or vegetation and mitigate climate change effects. Conserving and restoring natural ecosystems such as wetlands, coastal areas, peatlands, and forests, along with biodiversity conservation and disaster risk management, also play a significant role in reducing GHG emissions and promoting sustainable development within climate-smart agriculture (CSA).

Sustainable land use management can address soil degradation caused by agricultural activities through practices like green manuring, cover crop production, crop residue retention, minimum or zero tillage, and improved grazing management. These practices offer co-benefits for climate change adaptation and mitigation. The mass production of forage legumes, such as lablab, cowpea, pigeon pea, lucerne, and sesbania, enhances feed conversion efficiency and reduces methane emissions by approximately 25-33%.

Diversifying forests and crops, implementing varied crop rotations, and managing rangelands and pastures can maintain or enhance forest carbon stocks, reduce GHG emissions, and support climate change adaptation. This diversification also improves the nutritional quality of food. Such interventions increase overall herd productivity and adaptability to climate change through diverse land resource utilization. Common farm practices like adding soil organic matter (SOM), controlling soil erosion, improving fertilizer use, managing crops (e.g., fallow rice), and cultivating drought- and flood-tolerant varieties significantly contribute to climate change adaptation and mitigation.

Additionally, integrating trees in fields as windbreaks, live fences, fodder banks, alley cropping, or improved fallows can sequester atmospheric carbon in both biomass and soil. This integration provides fuelwood and other forest-based commodities, helps prevent the destruction of natural forests, and supports climate change adaptation and mitigation (Awazi *et al.*, 2019). In areas prone to drought and heat due to climate change, agroforestry systems are vital for carbon sequestration and effective carbon sink creation.

4.3.2 Crop Production Management

Appropriate management practices in ACP are crucial for achieving sustainability in the face of climate change (CC) scenarios. Sustainable crop production intensification (SCPI) plays a vital role in this context. SCPI is an approach within ACP that enhances and preserves natural resources while minimizing adverse environmental impacts through the use of natural biological inputs and processes. This method aids in developing agricultural systems that are resilient to climate change (CC). SCPI relies on management practices that uphold soil health, avoid monocropping, and promote the cultivation of well-adapted, high-yielding varieties using high-quality seeds or planting materials. It also involves the integrated management of nutrients, pests, weeds, and diseases, along with efficient water management. Consequently, climate-smart ACP entails sustainable crop production under CC conditions, ensuring that the crops grown are less susceptible to climatic variability (CV). Examples of approaches for CC adaptation and mitigation can be seen in Fig. 1 (FAO, 2011).

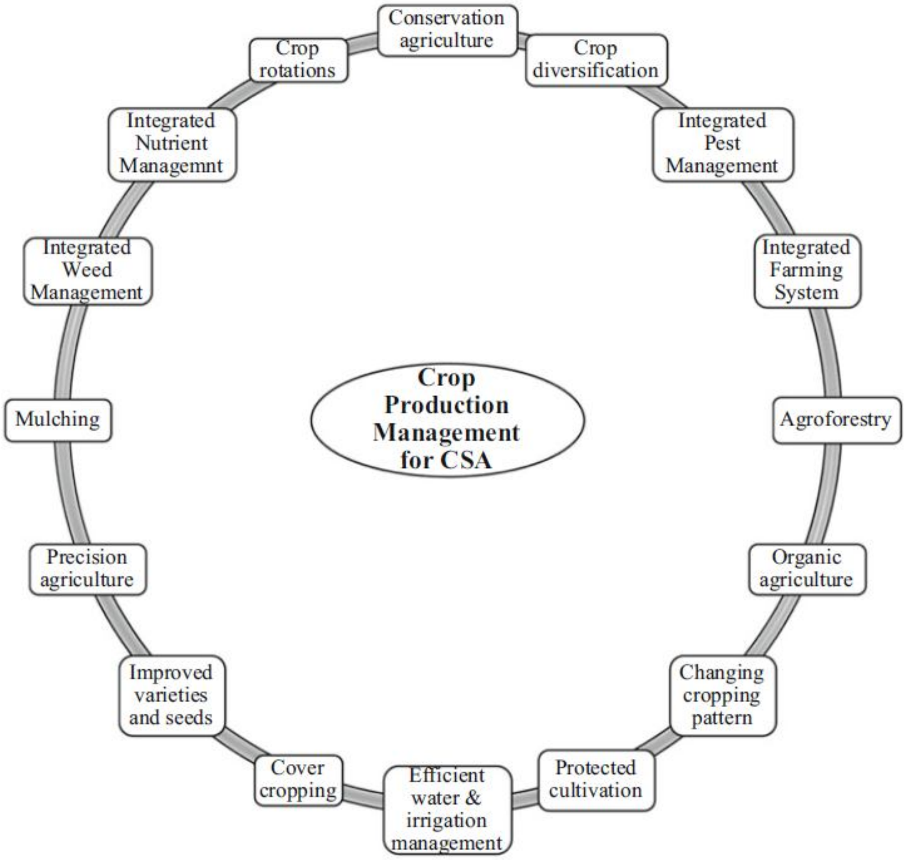

Figure 1 Crop production management strategies for CSA (Abhilash, 2021)

These approaches are discussed below:

Conservation Agriculture (CA): This approach involves minimal or no tillage, direct seeding, residue management, and crop diversification. CA can enhance productivity and soil quality, particularly through the accumulation of soil organic matter (SOM). It represents a viable option for achieving safe and intensive agricultural production (ACP) across diverse agro-ecological settings by efficiently utilizing available resources and maintaining soil fertility (Amin *et al.,* 2015).

Integrated Nutrient Management: This method supplies nutrients from multiple sources, including inorganic fertilizers, green manure, biofertilizers, and organic manure, significantly reducing the reliance on chemical fertilizers and thus lowering greenhouse gas (GHG) emissions. It requires site-specific, demand-driven, and balanced fertilizer and nutrient application. Utilizing microbes as biofertilizers can also improve soil fertility and crop productivity.

Mulch Cropping and Cover Cropping: These practices help maintain soil health and provide favorable conditions for crop growth, protecting soil from erosion and suppressing weed emergence, which reduces the need for herbicides.

Changing Cropping Patterns and Crop Rotations: Integrating legume crops and millets into rotations can prevent the build-up of specific pests, diseases, and weeds, while also maintaining soil nutrient balance. Millets are adaptable to various agro-ecological conditions, require fewer external inputs, and are more stress-resistant, contributing to climate change (CC) adaptability and nutritional security (Bandyopadhyay *et al.*, 2017).

Crop Diversification: Diversifying crops and livestock can enhance resilience by controlling pest outbreaks, reducing pathogen spread, and mitigating the impacts of climate variability and extreme weather events. Switching from rice-wheat systems to high-value cash crops can increase farmers' income, reduce water and fertilizer use, and improve food nutrient value (Sapkota *et al.*, 2015).

Integrated Pest Management (IPM): IPM combines various methods, including biocontrol agents, traps, mulches, soil sterilization, pesticides, and resistant varieties, to manage pests effectively.

Integrated Weed Management: This approach uses cultural, mechanical, biological, and chemical methods to control weeds, minimizing the environmental impact of herbicides.

Efficient Water and Irrigation Management: Practices such as sprinkler or drip irrigation, minimizing water conveyance losses, and reducing evaporation and runoff can optimize water use in agriculture.

Organic Agriculture: Supplying nutrients through organic sources and avoiding chemical inputs can be an effective alternative for sustainable farming.

Nutrient-Use Efficient Crop Varieties: Cultivating crops that require fewer external fertilizers can reduce GHG emissions.

Integrated Farming Systems: Combining crops, poultry, dairy, and fishery supports sustainable agriculture and livelihood, particularly for small and marginal farmers, while enhancing nutritional security.

Energy Crops for Biofuels: Cultivating crops for biofuel production can reduce the dependency on fossil fuels.

Reduced Fuel Consumption: Lowering fuel use in mechanical farming operations can significantly cut GHG emissions.

Improved Rice Cultivation Techniques: Techniques like the System of Rice Intensification (SRI) and aerobic irrigated rice can reduce methane emissions from flooded rice paddies (Friedrich and Kassam, 2009).

Agroforestry: This method can sequester significantly more carbon compared to traditional row crops, contributing to carbon sequestration (Verchot*et al.*, 2007).

Use of Fermented Organic Waste: Applying compost made from biogas slurry instead of unfermented waste can reduce methane emissions from rice cultivation (Pathak and Wassmann,2007).

Adaptation to Agroclimatic Regions: Identifying and repositioning crops sensitive to climate change in suitable areas, and adjusting cropping sequences and practices can optimize yields under changing conditions (Amin *et al.,* 2015).

Precision Agriculture: Utilizing remote sensing (RS), geographic information systems (GIS), sensors, and variable rate applicators to apply inputs precisely can enhance productivity and input use efficiency while protecting the environment.

Protected Cultivation: Using technologies like polyhouses, greenhouses, and shade houses to control environmental conditions can support crop growth by managing temperature, moisture, and pest pressures.

By adopting these practices, farmers can achieve sustainable agriculture, mitigate climate change impacts, and ensure food and nutritional security in the long run.

4.3.3 Soil Management

Soil is a crucial natural resource for achieving sustainability through CSA. Soil acts as a medium for cultivating plants and providing various nutrients and water for their growth. It supports soil biodiversity and regulates carbon, oxygen, and many other nutrient cycles. So, proper soil management is a crucial practice in the CSA.CCimpacts soil in many ways like Erratic rainfall patterns and frequent drought deplete the water and nutrientssupplying capacity of soil to the plants, Increased risk of soil erosion by higher rainfall intensity, Increased rate of mineralization of SOM due to rise in temperature.SOC sequestration has the tendency to decrease the CO_2 content in the atmosphereand, thus, contributes to CC mitigation.The management of the soil for CSA can be done in thefollowing ways:

- Before adopting any CSA practice for soil management, various physical, chemical, and biological characteristics of the soil influencing soil health and SOC sequestration should be assessed by in situ inspection through soil testing kits or by taking soil samples and analyzing it in the laboratory. The CSA practice should be adopted by these analysed properties (Faures*et al*., 2013).
- The practice of minimum or no-tillage substantially decreases the runoff rate, increases the soil water infiltration, and avoids the formation of plough pan in the subsoil. CA also augments the SOM and decreases SOC mineralization rate, which further facilitates the process of SOC sequestration. In this way, CA contributes to the reduction of GHG emission (Faures*et al*., 2013).Crop rotation in CA, especially with leguminous, will reduce the infestation of pests and diseases along with boosting the soil nutrients.It wasreported a 90% decrease in soil erosion in no-till plots in comparison to conventionally tilled plots in a study conducted in Parana, Brazil (Altieri *etal.*,2011).CA based on rice-wheat systems emits 10–15% less GHG as compared to conventional systems by creating more aerobic soil environments (Sapkota *et al*., 2015)
- In areas having steeper slopes, the soil erosion can be prevented in many ways, like by plantation of the vegetation across the slope or by the construction of soil and water conservation structures like tied ridges, bunds, terraces, trenches, etc. The

excess runoff water can be safely disposed of the slopes by using grassed waterways, chute spillway, drop inlet spillway, etc. (Faures*et al.*, 2013).

- Many agronomic practices like agroforestry, mixed cropping, cover cropping, contouring, strip cropping, etc. also help in decreasing soil erosion and increasing SOC sequestration.
- In arid and semiarid regions, there is a problem of wind erosion, which may either take away the fertile topsoil or deposit the blown away sand dunes on the productive soils. This can be prevented by planting drought-resistant species, rotational grazing, and planting windbreaks in the direction perpendicular to the prevailing wind.
- Mulching by crop residues is also an essential practice for buffering soil temperature, decreasing soil water evaporation and nutrient loss, and increasing SOM, which further enhances the soil moisture content, soil biodiversity, soil structure, and soil water infiltration. This practice also reduces soil erosion by avoiding the dispersion of soil particles by raindrops or runoff. The risk of development of salinity or waterlogged condition in the soil can also be reduced by it (Faures*et al.*, 2013).
- Integrated soil fertility management should be performed in CSA as it provides nutrients to the plants through various sources like compost, organic manure, green manure, crop rotations, intercropping, and inorganic fertilizers in thedesired amount along with conservation of soil and water in order to achievedecreased nutrient losses, increased soil CS, enhanced water storage, reduced soilerosion, increased NUE, and reduced GHG emissions.
- Precision nutrient management can improve fertilizer use efficiency by application of nutrients in the appropriate form, in the optimum amount, at the appropriate time synchronizing with crop demand, and at the correct place. The tools for precision nutrient management of nitrogenous fertilizers are Leaf Colour Chart, chlorophyll meter, and optical sensors like Green Seeker.Decision support systems, which are computer or android mobile-based, suchas Nutrient Expert and Crop Manager, can also facilitate the farmers for precisemanagement of nutrients (Pampolino*et al.*, 2012).

4.3.4 Water Management

Water is a finite natural resource that is diminishing rapidly due to indiscriminate and excessive exploitation. The growing population places tremendous pressure on water resources, underscoring the need for sustainable water resource management. Climate change impacts agricultural water through increased rainfall variability, higher temperatures, and extreme weather events such as floods and droughts. Sustainable water management is thus crucial for climate change mitigation. Practices like irrigation scheduling, precision irrigation, efficient drainage systems, in situ moisture conservation, and rainwater harvesting structures play significant roles in contributing to the three pillars of Climate-Smart Agriculture (CSA).Adaptation strategies for smart water management in the context of climate change include:Micro-irrigation systems: Methods like micro-sprayers, trickle, or drip irrigation apply water directly to the plant root system. These systems save 20–48% of irrigation water, 10–17% energy, 30–40% labor costs, and 11–19% fertilizer, while enhancing agricultural crop productivity (ACP) by 20 to 38% (PMKSY, 2019). These localized irrigation methods are not only critical for conserving water but also reduce energy usage (Shah, 2009) and carbon emissions.Pressurized micro-irrigation with sensor-based scheduling: Utilizing soil moisture sensors like tensiometers, gypsum or resistance blocks, frequency domain reflectometry (FDR), and time domain reflectometry (TDR) for irrigation scheduling can maintain soil moisture at field capacity in the root zone, addressing manual irrigation issues (Cardenas and Dukes,2012). Wireless sensor arrays and plant-based sensors like sap flow, infrared thermometers, trunk diameter variation, and leaf turgor pressure sensors are also used to monitor plant water stress, making them effective adaptation strategies.

Information and communication technology (ICT): Advances in ICT have led to the development of irrigation scheduling and soil water balance software like BEWARE (Chartzoulakis*et al.*, 2008) and IrriSatSMS (John *et al.*, 2009). These tools help in scheduling irrigation for different crops. In water-scarce regions, regulated deficit irrigation (RDI) or subsurface irrigation (SSI) can be adopted as a climate change adaptation measure.

Minimizing water losses: Advanced technologies such as telemetry systems, remote sensing (RS), and geographic information systems (GIS) help minimize water losses during conveyance, distribution, and application networks under climate change conditions.

Solar pumps: These pumps are ideal for using available groundwater with minimal emissions in areas where groundwater is shallow.

RS and GIS applications: These technologies are beneficial for various aspects of water management, including command area development, cropping pattern mapping, crop yield projection, flood monitoring, hazard mapping, and environmental impact assessment of river interlinking projects. Remote sensing also aids in identifying groundwater occurrences, development, storage, and flow direction, as well as aquifer mapping and potential groundwater recharge areas.

ICT-based systems: Automated irrigation systems, crop and agro-meteorology advisories, and insurance for crops and livestock can help farmers mitigate the adverse effects of climate change and variability (Altieri and Nicholls,2013).

Efficient on-farm infrastructure: Land leveling, minimum or no-tillage, the System of Rice Intensification (SRI), direct-seeded rice, crop diversification, appropriate irrigation scheduling, rainwater harvesting, site-specific soil and water conservation structures, and improved agronomic practices enhance on-farm irrigation efficiency and help arrest the declining water table, ultimately aiding climate change mitigation and adaptation.

Rainwater harvesting: This practice in rainfed areas acts as a drought-proofing strategy. Integrated watershed management and constructing artificial recharge structures are also effective adaptation approaches.

Balancing water and energy efficiency: High-pressure drip irrigation systems may have lower energy efficiency compared to gravity-based systems. Achieving sustainability requires balancing increased energy efficiency with water efficiency.

Sustainable water management addresses issues such as erosion, drainage, irrigation, flood, and drought. Recognizing the urgency of conserving and managing water resources, the Government of India has launched initiatives like PMKSY (2019) to achieve "more crop per drop" and "Har Khet Ko Pani" (PMKSY, 2019).

4.3.5Livestock Management:

The livestock sector contributes to the CC as well as it is influenced by its effects(FAO, 2006). Eighteen percent of GHG emissions are from livestock (Steinfeld *et al.*,2006). Livestock mainly emits methane gas through an enteric fermentation process,which has 25 times more heat-trapping capacity than CO_2. This methane emissionfrom livestock can be decreased by improving their diet.The diet can be improvedby feeding them with good quality feed additives as well as by replacing feedshaving low digestibility with that of high digestibility. Inclusion of higher fats andprotein and providing antioxidants, vitamins, and mineral supplementations in thelivestock diet are beneficial in CC adaptation and mitigation.Grazing management through rotational grazing helps in therestoration of degraded grasslands, improves soil health, and enhances climateresilience. Improved varieties of pastures should be cultivated in grasslands for cattlegrazing. Research developments are in progress for developing vaccines againstmethanogens present in the rumen of livestock, which would eventually minimizethe release of methane gas (Wright and Klieve,2011).Manure also releases GHGs inthe atmosphere. Therefore, better manure management techniques like compostingshould be adopted. Livestock diversification is an approach in CSA for increasing resistance againstCC-related pests and diseases (Batima *et al.*, 2005). The breeds having a highertolerance to temperature and humidity, resistance toward diseases, and the ability tosurvive under low input conditions should be reared (Pankaj *et al.*, 2013). A regular supply of clean and cool water to animals is one such strategy.Splashing cool water on animals during a hot period at regular intervals can reduceheat stress. The stocking density of animals should be reduced during the hot period.Animals should be kept under proper shade as well-designed shades can reduce theheat load of about 30-40% on animals. Roofs of cattle sheds composed of hay orcorrugated steel sheets are good for shading purposes. Ventilation and air circulationshould be increased in animal sheds by the use of fans and open housing system orby increasing the height of buildings. Plantation of trees around cattle sheds canprovide long-term cooling effect (Das,2017).

4.3.6 Energy Management

Energy is crucial for the agriculture sector, and the use of non-renewable energy sources like fossil fuels (FF) is a significant contributor to greenhouse gas (GHG) emissions, which are closely linked to climate change (CC). Therefore, addressing these challenges by incorporating renewable energy sources is essential. The substantial demand and extensive use of energy in agriculture necessitate prudent management of both renewable and non-renewable energy sources. Effective energy management focuses on optimizing energy use in the context of sustainability, primarily through energy conservation and efficiency.Globally, agriculture's energy dependence has shifted significantly from human and animal power to tractors, electricity, and diesel power, leading to a reliance on FF. Agricultural activities are responsible for approximately 35% of global emissions, predominantly from developing countries. In recent years, the agriculture sector has seen a 10.4% growth rate in energy use, compared to 3.6% in industry and 3.2% in the transport sector (Jha *et al.*, 2012). Energy consumption in agriculture can be categorized into direct and indirect use. Direct energy use includes activities such as pumping and mechanization (tractors, power tillers), while indirect use involves fertilizers and pesticides.

In India, a significant portion of energy used in agriculture, particularly electricity, is dedicated to pumping water for irrigation. Therefore, enhancing the efficiency of pump sets is crucial for energy conservation. Several activities can help manage energy efficiently and sustainably in the context of CC (Fig. 2):

- Increasing the inventory of bio-based products to replace petroleum-based products can reduce GHG emissions. Biomass such as wood, animal dung, and agricultural waste can be decomposed anaerobically to produce biogas, which can be used for heating and lighting purposes.

- Laser-aided land leveling has proven to be a promising technology for mitigating CC. This technique can save up to 40% of water, improve fertilizer use efficiency, and enhance crop yields. It reduces GHG emissions by minimizing irrigation water demand, thereby decreasing energy needs for pumping water.
- Promoting conservation agriculture (CA) machinery like zero till, Happy Seeder, seed-cum-fertilizer drills, raised bed planters, and laser-guided land levelers can save energy during various farm operations.
- Choosing the appropriate capacity of pumps to meet irrigation requirements and matching pump sets with water sources (canals or wells) is essential for saving energy in a CC scenario.
- Installing variable speed drives (VSDs) on pumps is an important energy-saving measure, as they allow pumps to operate at optimal speeds. Reducing the speed of a motor by 20% can result in energy savings of up to 50%.
- Implementing IoT-based smart irrigation systems can optimize irrigation timing and conditions, which is beneficial for CC adaptation.
- Replacing synthetic fertilizers with manure and farm residues can reduce the need for external inputs, improve crop yields, enhance energy efficiency, and sustain productivity, farm income, and profits.
- Generating biogas in situ allows the use of its by-products as liquid organic fertilizer, which can increase crop yields and reduce environmental pollution.

In light of CC, it is imperative to promote energy-smart technologies that can reduce energy consumption in farming operations and lower crop water requirements.

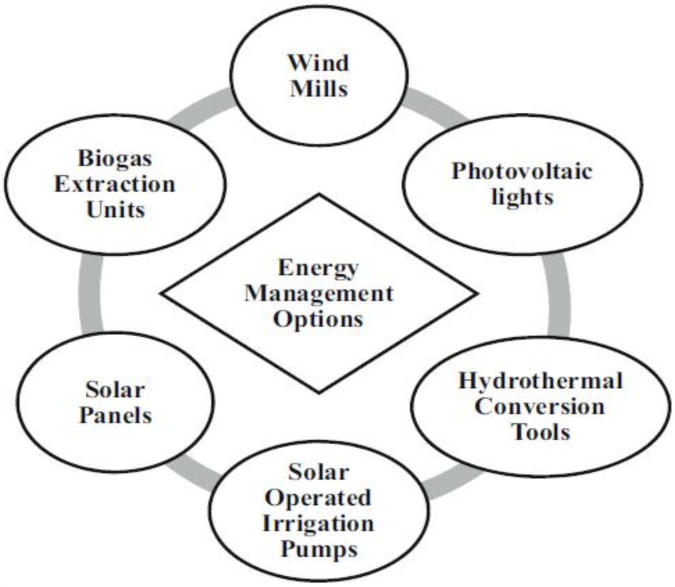

Figure 2 Energy management options for climate-resilient agriculture (Abhilash, 2021).

4.4 Challenges in CSA

Shortage of Agricultural Water Resources

Water security is fundamental to ensuring food security. Currently, the scarcity of water resources for agriculture has become a significant constraint on global food security and the sustainable development of Climate-Smart Agriculture (CSA). It is projected that global water demand will increase by 55% (Schlamovitz andBecker,2021). This growing water scarcity is increasingly affecting agricultural water users worldwide (Salehi *et al.,* 2022). Long-term planning and management necessitate a thorough assessment of agricultural water resources. For instance, in South Korea, agriculture in irrigated regions is highly susceptible to water shortages due to seasonal variations in rainfall and water quality (Nam *et al.,* 2017). Recently, climate variability, including droughts and heatwaves, has exacerbated the uneven spatial and temporal distribution of water resources, leading to a decline in available agricultural water (Kim *et al.,* 2018). Therefore, accurately estimating the supply and demand of agricultural water resources in the context of climate change is becoming increasingly crucial for the advancement of CSA.

Climate Variability and Climate Change

Human-induced climate change presents significant challenges to global food production and the sustainable development of climate-smart agriculture (CSA). Addressing climate change, enhancing agricultural productivity, and reducing greenhouse gas (GHG) emissions sustainably are shared concerns for the global community (FAO, 2013). Climate variability and change have altered the distribution of agricultural climate resources such as light, heat, and water. These changes particularly harm smallholder agriculture by decreasing crop yields and income, thereby exacerbating food insecurity (McKinley *et al.,* 2021).A survey conducted in Ghana revealed that climate variability significantly impacts subsistence agriculture, causing 58% of families to experience food anxiety and preventing 62% from obtaining their preferred quantity and quality of food (Asare-Nuamah, 2021). Climate change directly affects agriculture by increasing average temperatures, extending growing seasons, raising the frequency of hot days and nights, creating more unpredictable precipitation patterns, and elevating CO_2 levels (Janowiak *et al.*, 2016). In the Indo-Gangetic Plain, higher average and maximum temperatures, along with increased precipitation during the growing season, have directly contributed to a 1-8% reduction in wheat yields.The growing unpredictability of climate and environmental factors continues to threaten food security in many regions (IPCC, 2018). If GHG emissions persist at their current levels, many countries are likely to face extreme climatic conditions such as prolonged droughts, severe droughts, and intense rainfall, further endangering food security (Van andKim,2020).

Agricultural GHG Emissions

Agricultural greenhouse gas (GHG) emissions pose increasing challenges to the sustainable development of climate-smart agriculture (CSA). The use of fossil fuels, changes in land use, and deforestation have significantly contributed to the rise in anthropogenic GHG emissions. The Intergovernmental Panel on Climate Change (IPCC) highlighted the impact of these emissions on climate change (IPCC, 2014). Such emissions have led to an imbalance in ecosystems (Aneja *et al.,* 2009). Agriculture is the second-largest source of global anthropogenic GHG emissions, accounting for 56% of total non-CO_2 emissions (USEPA, 2015). It is estimated that seven countries—Argentina, Australia, Brazil, Canada, Chile, China, India, and the United States—are responsible for more than half of the world's total soil emissions and 49% of global agricultural emissions (Maraseniand Qu,2016).While agriculture is a major source of GHG emissions, it also holds significant potential for emission reduction. This necessitates enhancing agricultural production efficiency, ensuring food security, and simultaneously cutting down agricultural GHG emissions. Various technologies can effectively curb these emissions by controlling GHG output (such as through clean energy alternatives, renewable energy technologies, and new energy technologies), increasing GHG absorption (such as with carbon fixation technologies), and adapting to climate change (such as by developing new crop varieties and adjusting agricultural production structures).

Information Resource Integration

In the realms of production, management, transportation, and sales within CSA, product information and data support are critical. Ensuring the security of this information and data is essential for the successful progression of CSA. Nevertheless, the development of CSA faces several challenges regarding information and security, such as low standardization, fragmented data collection and organization, and a lack of precision and efficacy in agricultural data gathering. Real-time sharing of technological resources remains challenging, exacerbating the acute issue of CSA information security. Ensuring the basic security of agricultural information has thus become a significant concern for the sustainable development of CSA. Additionally, CSA contends with the problem of information overload in agriculture. If false information cannot be effectively identified, it will adversely impact the long-term development of CSA.

4.5 Government Schemes on CSA:

The various schemes of government on Climate smart Agriculture are given in Table 1.

Table 1 Description of various government schemes on CSA

S.No.	**Name of Scheme**	**Key Points**
01	National Innovation on Climate Resilient Agriculture (NICRA)	Launched in February, 2011 by ICAR with an outlay of Rs.350 crores. Aims to enhance the resilience of Indian agriculture, covering crops, livestock and fisheries to climatic variability and climate change through development and application of improved production and risk management technologies.
02	National Mission on Sustainable Agriculture (NMSA)	Mission under NAPCC(National Action Plan on Climate Change), includes programmatic interventions like Soil Health Card, Paramparagat Krishi Vikas Yojana, Mission Organic Value Chain Development for Northeastern Region, Rainfed Area Development, National Bamboo Mission and Sub-mission on Agro-Forestry. Works through adoption of sustainable development pathway by progressively shifting to environment friendly technologies, adoption of energy efficient equipment’s, conservation of natural resources, integrated farming, etc. Promotes location specific improved agronomic practices through soil health management, enhanced water use efficiency, judicious use of

		chemicals, crop diversification.
03	The National Adaptation Fund for Climate Change (NAFCC)	Implemented during 2015-16. Established to meet the cost of adaptation to climate change for the State and Union Territories of India that are particularly vulnerable to the adverse effects of climate change. Under the NAFCC, various projects have been sanctioned in different states i.e., Punjab, Himachal Pradesh, Odisha, Manipur, Tamil Nadu, Kerala, Mizoram, Chhattisgarh, J&K, Meghalaya, Telangana, Andhra Pradesh etc.
04	Climate Smart Village	An institutional approach to test, implement, modify and promote CSA at the local level and to enhance farmers‟ abilities to adapt to climate change. Adopts Portfolio of interventions to tackle the climate challenges of the agriculture sector that cover the full spectrum of farm activities. CSVs were piloted in two states of India: Karnal district of Haryana state and Vaishali district of Bihar state which later spread into districts of Punjab, Andhra Pradesh and Karnataka.
05	Pradhan Mantri Krishi Sinchayee Yojna (PMSKY)	Implemented from 1 July 2015. Aims to give more priority on water conservation & the vision to extend the area under irrigation. 'Har Khet Ko Paani' –main motto for increasing the water efficiency
06	Pradhan Mantri Fasal Bima Yojna (PMFBY)	Introduced in 2016 (kharif season). Voluntary for States/UTs as well as for farmers keeping in view their risk perception and financial considerations etc. Till 2020-21 cumulatively 2,938.7 lakh farmer applications for a sum insured of Rs. 10,49,342 crore have been enrolled under the scheme.
07	Soil Health Card Scheme	Launched in February, 2015. Providing detailed information on test-based soil nutrient status of their own land along with recommended dose of fertilizers The Government of India targeted to issue 10.48 crores of SHCs since inception of the Scheme.
08	National Water Mission (NWM)	A Mission for conserving the water sources and minimizing its wastage, and also to optimize Water Use Efficiency (WUE) by 20 per cent including agriculture sector.
09	Paramparagat Krishi Vikas Yojna (PKVY)	Launched in 2015 under NMSA. Objective of supporting and promoting organic farming which in turn result in improvement of soil health.
10	Biotech-KISAN	Launched in 2017. Scientist-farmer partnership Scheme for agriculture innovation. Objective to connect science laboratories with the farmers to find out

		innovative solutions and technologies to be applied at farm level. So far 146 Biotech-KISAN Hubs have been established covering all 15 agro-climatic zones and 110 aspirational districts in the country. Over two lakhs farmers benefitted so far by increasing their agriculture output and income. Over 200 entrepreneurships developed in rural areas.
11	Sub-mission on Agro-forestry	Launched during 2016-17 with the objective of planting trees on farm bunds. Potential to bring sustainability in agriculture by mitigating the impact of climate change.
12	National Livestock Mission	Initiated by the Ministry of Agriculture and Farmers Welfare. Got commenced from 2014-15. Focusing mainly on livestock development through sustainable approach ultimately protecting the natural environment, ensuring bio-security, conserving animal bio-diversity and farmers' livelihood.

4.5 Future Directions of CSA

4.6.1 Using Advanced Internet Technology to Ensure Agricultural Information Security

4.6.1.1 Application of Remote Sensing Techniques

Remote sensing technology is extensively employed across various domains due to its ability to provide rapid, large-scale, real-time, and dynamic observations that are also economically viable. This technology enables the detection and monitoring of the physical characteristics of the Earth's surface through data collection from satellites or unmanned aerial vehicles. The three primary attributes of remote sensing data are spatial resolution, spectral resolution, and temporal resolution (Meier *et al.,* 2020). Spatial resolution refers to the pixel size of an image, influencing the capacity to discern objects within the imagery. Spectral resolution pertains to the interval, size, and quantity of spectral sampling, affecting the sensor's ability to detect targets within the electromagnetic spectrum. Temporal resolution denotes the frequency at which data is acquired. With ongoing advancements in these resolutions and improvements in remote sensing algorithms and products, remote sensing has become a crucial tool with significant potential applications in regional-scale CSA (Padua *et al.,* 2019).For many years, image-based remote sensing has been integral to precise crop management. The advent of hyperspectral imaging has significantly enhanced the ability to identify and differentiate crop nutrients, diseases, and canopy structures (Mulla, 2012). Furthermore, the combination of images, general reflectometry, and three-dimensional (3D) mapping of crop spectral dynamics has offered valuable insights into agricultural productivity (Dandoisand Ellis,2013). The integration of a wireless sensor network on the ground with remotely operated aerial vehicles can further optimize fertilizer and pesticide management in the field (Costa *et al.,* 2012).

Currently, there are challenges related to the spatiotemporal resolution of remote sensing data. High spatial resolution data typically have low temporal resolution, complicating the monitoring of dynamic crop changes during peak growth periods. Conversely, high temporal resolution data often have low spatial resolution, resulting in mixed pixels in data fusion. Enhancing the accuracy of remote sensing inversion remains a challenge. The future direction for sustainable CSA development lies in the fusion of multi-source remote sensing data. By integrating data with different spatial and temporal resolutions, it is possible to achieve more accurate and precise monitoring of dynamic changes in crop growth, given the increasing availability of remote sensing data.

4.6.1.2 Application of Internet of Things

The Internet of Things (IoT) is a vast network of interconnected computing devices, sensors, and machines that communicate over the internet. Each device possesses a unique identifier and is capable of remote sensing and monitoring (Pylianidis*et al*., 2021). In agriculture, IoT is primarily utilized to gather data via various sensors that measure environmental and crop parameters such as temperature, humidity, pH levels, and leaf color. Research has explored numerous aspects of IoT application in agriculture, including the evaluation of IoT applications (Jusoh *et al*., 2021), the development of IoT architectures for food safety control (Dias *et al*., 2021), and the integration of IoT with agricultural UAVs for smart farming (Boursianis*et al*., 2020).To advance IoT in climate-smart agriculture (CSA), several areas require enhancement: First, IoT systems need high adaptability and customizability to accommodate the diverse needs of farmers. Second, efficient deployment and configuration of IoT systems are crucial, necessitating reliable network connections and farm infrastructure, along with sufficient human and economic resources. Finally, ensuring the security of IoT systems in CSA is essential, as the data collected is valuable and often considered a trade secret by farmers.

4.6.1.3 Application of Artificial Intelligence

Artificial intelligence (AI) represents a promising avenue for the future of Climate-Smart Agriculture (CSA). AI leverages digital computers or other controlled machines to emulate, enhance, and augment human intelligence, allowing for the perception of the surrounding environment and the acquisition of relevant knowledge. Currently, AI is being applied across numerous agricultural domains. It can analyze and synthesize data from various agricultural sectors to facilitate plant identification, predict weed presence, forecast crop yields, estimate greenhouse gas (GHG) emissions, predict climate patterns, control pests, and assess risks associated with crop planting (Hamrani*et al*., 2020). Specifically, AI can enhance crop yields by accurately predicting optimal sowing and harvesting times and monitoring crop health, while also reducing agricultural input costs related to fertilizers, chemicals, and irrigation. This technology can help minimize agricultural risks by addressing issues such as insufficient rainfall, weed proliferation, and disaster-induced losses. Moving forward, the use of AI technologies should be intensified to collect and analyze data from diverse sources, including soil, climate, diseases, and pests. The application of deep learning techniques can further refine the accuracy of plant identification, fruit counting, and crop yield forecasting.

4.6.2 Improvement of Cropping Patterns and Management Techniques

The use of multiple cropping patterns such as rice-wheat rotation and rice-potato-sesame cropping exemplifies crop diversification and no-till agriculture, which can enhance agricultural productivity and lower greenhouse gas emissions (Datta *et al*., 2011). Integrating inorganic fertilizers with organic amendments is a prevalent practice for improving soil quality and crop yields, especially in soils with low fertility (Mi *et al.*, 2018). To reduce CO$_2$ emissions, soil protection practices such as utilizing crop residues, enhancing nitrogen use efficiency, and minimizing planting are recommended (Hobbs *et al.*, 2008). The application of crop residues can boost soil organic carbon levels, thereby increasing crop yields (Arunrat*et al.*, 2020). These measures also contribute to water conservation, improved soil structure, better nutrient cycling, and overall agricultural productivity, while reducing greenhouse gas emissions. It is crucial to recognize that carbon sequestration and loss in soils can vary significantly across different agricultural systems. Furthermore, conservation agriculture techniques, known for their ecological benefits, have been widely adopted in agricultural production and are considered vital for sustainable farming. Advancements in cropping patterns and management practices are essential for achieving climate-smart agriculture in the future.

4.6.3 Carrying out "Internet + Weather" Service and Improving the Quality of Agricultural Service

Agriculture has progressed towards increased mechanization and industrialization. As it continues to evolve, there will be greater demands on meteorological services. Leveraging Internet technology to integrate these services with farmers' needs is essential. By utilizing technology platforms, a vertical meteorological service system for agriculture can be established, connecting growers, transporters, service providers, and consumers.In the future, integrating "internet and weather" services will enhance the quality of agricultural support. Combining human-computer interaction, comprehensive meteorological observation, and automated weather stations will better serve rural and agricultural development. This approach will improve weather forecasting, monitoring, and early warning capabilities, helping to achieve the objectives of Climate-Smart Agriculture (CSA).

4.6.4 Agricultural Weather Index-Based Insurance

Agricultural weather index-based insurance employs agrometeorological indicators as triggers for compensation mechanisms, mitigating the impact of natural risks on agricultural production. When these indicators surpass a specified threshold, insurers are obligated to compensate the insured. This type of insurance integrates financial instruments into the risk management of natural disasters, drawing in social funds to help disperse agricultural risks. This approach offers agricultural producers a novel method for transferring risk. One of its significant advantages is the ease of claim settlement and promotion, which helps overcome issues like adverse selection and moral hazard associated with traditional insurance, while also reducing operational costs (Abdi *et al.*, 2022).As weather index-based insurance products continue to develop for various weather conditions, many developing countries are beginning to integrate these products into their agricultural insurance markets. Currently, there are numerous pilot programs for weather index-based insurance in these nations. Looking ahead, agricultural weather index-based insurance is seen as a key area for the advancement of Climate-Smart Agriculture (CSA). To support stable agricultural production, ensure food security, and achieve CSA objectives, it is crucial to conduct further research on evaluation methods and indicator systems for this type of insurance. Additionally, a deeper understanding of the causes, processes, and mechanisms of related disasters is necessary.

4.7Conclusions

Climate change poses significant threats to both the environment and human well-being, particularly in the realm of food security. Agriculture, vital for many in developing countries, faces unprecedented challenges due to climate change's impact on crop production. Initially seen as a victim, agriculture is increasingly recognized as both a contributor to and a potential solution for climate change. Climate-Smart Agriculture (CSA) offers strategies to address these challenges, focusing on sustainable food production, reduced greenhouse gas emissions, and enhanced resilience. Various CSA practices, tailored to farmers' circumstances, include crop diversification, efficient water and energy management, integrated pest and nutrient management, and the promotion of climate-smart technologies. However, widespread adoption of CSA faces obstacles such as lack of funding, farmer education, enabling legislation, and clear understanding of CSA concepts. Overcoming these barriers requires effective education programs, policy integration, and financial support at all levels of governance. Despite challenges, CSA holds immense potential for sustainable agriculture, livelihood improvement, and environmental stewardship.

Ethics approval/approval of an ethics committee Every piece of information in this review complies with moral norms.

Consent for participation The corresponding author certifies that all authors of this paper took part in the research and provided the above-mentioned contributions.

References

Abbass, K., Qasim, M. Z., Song, H., Murshed, M., Mahmood, H. and Younis, I. 2022. A review of the global climate change impacts, adaptation, and sustainable mitigation measures. *Environ. Sci. Pollut. Res.,***29**: 42539–42559.

Abdi, M. J., Raffar, N., Zulkafli, Z., Nurulhuda, K., Rehan, B. M., Muharam, F. M., Khosim, N. A. and Tangang, F. 2022. Index-based insurance and hydroclimatic risk management in agriculture: A systematic review of index selection and yield-index modelling methods. *Int. J. Disaster Risk Reduct.,* **67**: 102653.

Abhilash, S. 2021. Science of climate change. **In** Climate change: Science and politics. Ravindran, P. K. (Eds). *Kerala Shastra Sahitya Parishad.*

Adesipo, A., Oluwaseun, F., Kamil, K., Ondrej, K., Petra, M., Ali, S. and Mayowa, A. 2020. Smart and climate-smart agricultural trends as core aspects of smart village functions. *Sensors,* **20**: 5977.

Adoghe, A. U., Popoola, S. I., Chukwuedo, O. M., Airoboman, A. E. and Atayero, A. A. 2017. Smart weather station for rural agriculture using meteorological sensors and solar energy. **In** Proceedings of the World Congress on Engineering, London, UK, 5–7, pp. 1–4.

Altieri, M. A. and Nicholls, C. I. 2013. The adaptation and mitigation potential of traditional agriculture in a changing climate. *Clim Change*. https://doi.org/10.1007/s10584-013-0909-y

Altieri, M. A., Marcos, L. A., Bittencourt, H. V., Kieling, A. S., Comin, J. J. and Lobsyo, P. E. 2011. Enhancing crop productivity via weed suppression in organic no-till cropping systems in Santa Catarina, Brazil. *J Sustainable Agri*, **35**(8): 1–15. https://doi.org/10.1080/10440046.2011.588998

Amin, A., Mubeen, M., Hammad, H. M. and Nasim, W. 2015. Climate smart agriculture: an approach for sustainable food security. *Agri Res Communication***3**:13–21.

Amundson, R. and Beaudeu, L. 2018. Soil carbon sequestration is an elusive climate mitigation tool. *Proc. Natl. Acad. Sci. USA*,**115**: 11652–11656.

Aneja, V. P., Schlesinger, W. H. and Erisman, J. W. 2009. Effects of agriculture upon the air quality and climate: Research, policy, and regulations. *Environ. Sci. Technol.*, **43**: 4234–4240.

Arshad, M., Kächele, H., Krupnik, T. J., Amjath-Babu, T. S., Aravindakshan, S., Abbas, A., Mehmood, Y. and Müller, K.2016.Climate variability, farmland value, and farmers' perceptions of climate change: Implications for adaptation in rural Pakistan. *Int. J. Sustain. Dev. World Ecol.*, **11**: 532–544.

Arunrat, N., Sereenonchai, S., Chaowiwat, W., Wang, C. and Hatano, R. 2020. Soil organic carbon in sandy paddy fields of Northeast Thailand: A review. *Agronomy*, **10**: 1061.

Asare-Nuamah, P. 2021. Climate variability, subsistence agriculture and household food security in rural Ghana. *Heliyon*, **7**: e06928.

Awazi, N. P. and Tchamba, M. N. 2019. Enhancing agricultural sustainability and productivity under changing climate conditions through improved agroforestry practices in smallholder farming systems in Sub-Saharan Africa. *Afr J Agric Res*, **14**(7): 379–388.

Bandyopadhyay, T., Muthamilarasan, M. and Prasad, M. 2017. Millets for next generation climate-smart agriculture. *Frontiers in Plant Science***, 8**: 1266.

Batima, P., Bat, B., Tserendash, L., Bayarbaatar, S., Shiirev-Adya, S., Tuvaansuren, G., Natsagdorj, L. and Chuluun, T. 2005. Adaptation to climate change, vol 90. ADMON Publishing, Ulaanbaatar.

Boursianis, A. D., Papadopoulou, M. S., Diamantoulakis, P., Liopa-Tsakalidi, A., Barouchas, P., Salahas, G., Karagiannidis, G., Wan, S. H. and Sotirios, K.G. 2020. Internet of things (IoT) and agricultural unmanned aerial vehicles (UAVs) in smart farming: A comprehensive review. *Internet Things*, **18**: 100187.

Branca, G., Lipper, L., Neves, N., Lopa, D. and Mwanjioka, I. 2011. Payments for watershed services supporting sustainable agriculture development in Tanzania. *J Environ Dev***20**(3): 278–302.

Campbell, B. M., Thornton, P., Zougmore, R., van Asten, P. and Lipper, L. 2014. Sustainable intensification: What is its role in climate smart agriculture?.*Curr. Opin. Environ. Sustain*., **8**: 39–43.

Cardenas, L. B. and Dukes, M. D. 2012. Soil moisture sensor landscape irrigation controllers: a review of multi-study results and future implications. *American Society of Agricultural and Biological Engineers***55**(2): 581–590.

Chandra, A., McNamara, K. E. and Dargusch, P. 2018. Climate-smart agriculture: Perspectives and framings. Clim. Policy, **18**: 526–541.

Chartzoulakis, K., Kasapakis, I. and Tzobanoglou. 2008. Improving water efficiency: the irrigation advisory service of Crete, Greece. **In**: The 3rd international conference on water resources and arid environments and the 1st Arab Water Forum.

Chaudhry, S. and Sidhu, G. P. S. 2022. Climate change regulated abiotic stress mechanisms in plants: A comprehensive review. *Plant Cell Rep*., **41**: 1–31.

Costa, F. G., Ueyama, J., Braun, T., Pessin, G., Osório, F. S. and Vargas, P. A. 2012. The use of unmanned aerial vehicles and wireless sensor network in agricultural applications. **In** Proceedings of the 2012 IEEE International Geoscience and Remote Sensing Symposium; IEEE: New York, NY, USA, pp. 5045–5048.

Dandois, J. P. and Ellis, E. C. 2013. High spatial resolution three-dimensional mapping of vegetation spectral dynamics using computer vision. *Remote Sens. Environ*., **136**: 259–276.

Das, S. 2017. Impact of climate change on livestock, various adaptive and mitigative measures for sustainable livestock production. *Appro Poult Dairy Vet Sci***1**(4): 517. https://doi.org/10.31031/APDV.2017.01.000517

Datta, A., Rao, K. S., Santra, S. C., Mandal, T. K. and Adhya, T. K. 2011. Greenhouse gas emissions from rice-based cropping: Economic and technologic challenges and opportunities. *Mitig. Adapt. Strateg. Glob. Chang*., **16**: 597–615.

Dias, R. M., Marques, G. and Bhoi, A. K. 2021. Internet of things for enhanced food safety and quality assurance: A literature review. *Adv. Electron. Commun. Comput*., **709**: 653–663.

Engel, S. and Muller, A. 2016. Payments for environmental services to promote ‘climate-smart agriculture’ Potential and challenges. *Agric. Econ*., **47**: 173–184.

FAO. 2006. Livestock’s long shadow: environmental issues and options. FAO, Rome.

FAO. 2011. Save and grow: a policymaker’s guide to the sustainable intensification of smallholder crop production. FAO, Rome.

FAO. 2012. Towards the future we want: end hunger and make the transition to sustainable agricultural and food systems. FAO, Rome.

FAO. 2013. Climate-Smart Agriculture: Sourcebook. FAO: Rome, Italy.

FAO. 2016. Climate Change, Agriculture and Food Security. The State of Food and Agriculture: Vol. 2016. Rome: FAO.

Faures, J. M., Bartley, D., Bazza, M., Burke, J., Hoogeveen, J., Soto, D. and Steduto, P. 2013. Climate smart agriculture sourcebook. FAO, Rome, p. 557.

Friedrich, T. and Kassam, A. 2009. Adoption of conservation agriculture technologies: constraints and opportunities. Invited paper at the IV World Congress on Conservation Agriculture. New Delhi, India.

Hamrani, A., Akbarzadeh, A. and Madramootoo, C. A. 2020. Machine learning for predicting greenhouse gas emissions from agricultural soils. *Sci. Total Environ*., **741**: 140338.

Hobbs, P. R., Sayre, K. and Gupta, R. 2008. The role of conservation agriculture in sustainable agriculture. *Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci.*, **363**: 543–555.

Hossain, M. S., Lu, Q., Arshad, M., Shahid, S., Fahad, S. and Akhter, J. 2019. Climate change and crop farming in Bangladesh: An analysis of economic impacts. *Int. J. Clim. Chang. Strateg. Manag*., **7**: 424–440.

Hussain, M., Butt, A. R., Uzma, F., Ahmed, R., Irshad, S., Rehman, A. and Yousaf, B. 2019. A comprehensive review of climate change impacts, adaptation, and mitigation on environmental and natural calamities in Pakistan. *Environ. Monit. Assess*., 192: 48.

INCCA (Indian Network for Climate Change Assessment). 2010. Assessment of the greenhouse.

IPCC (Intergovernmental Panel on Climate Change). 2018. Annex I: glossary. Masson-Delmotte, V., Zhai, P., Portner, H. O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Pean, C., Pidcock, R., Connors, S., Matthews, J. B., Chen, Y., Zhou, X., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M. and Waterfield, T. (eds.). Global Warming of 1.5_C. An IPCC Special Report on the impacts of global warming of 1.5_C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. IPCC, Geneva.

IPCC. 2014. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Climate Change: Synthesis Report; IPCC: Geneva, Switzerland.

Janowiak, M. K., Dostie, D. N., Wilson, M. A., Kucera, M. J., Skinner, R. H., Hatfield, J. L., Hollinger, D. and Swanston, C. W. 2016. Adaptation resources for agriculture: Responding to climate variability and change in the Midwest and Northeast. *Tech. Bull*., **72**: 320856.

Jha, G. K., Pal, S. and Singh, A. 2012. Changing energy-use pattern and the demand projection for Indian agriculture. *Agricultural Economics Research Review***25**(1): 61–68.

John, W. H., Nicholas, J. C., Evan, W. C., Thomas, M.S. and Bill, W. 2009. IrriSatSMS irrigation water management by satellite and SMS - a utilization framework, CSIRO Land and Water Science.

Jusoh, M., Muttalib, M. F. A., Krishnan, K. T. and Katimon, A. 2021. An overview of the internet of things (IoT) and irrigation approach through bibliometric analysis. *Earth Environ. Sci.*, **756**: 012041.

Kim, S. M., Kang, M. S. and Jang, M. W. 2018. Assessment of agricultural drought vulnerability to climate change at a municipal level in South Korea. *Paddy Water Environ.*, **16**: 699–714.

Leisner, C. P. 2020. Review: Climate change impacts on food security-focus on perennial cropping systems and nutritional value. *Plant Sci.*, **7**: 110412.

Mahato, A. 2014. Climate change and its impact on agriculture. *International Journal of Scientific and Research Publications*, **4(**4).

Maraseni, T. N. and Qu, J. 2016. An international comparison of agricultural nitrous oxide emissions. J. *Clean*. *Prod*., **135**: 1256–1266.

McKinley, J. D., LaFrance, J. T. and Pede, V. O. 2021. Climate change adaptation strategies vary with climatic stress: Evidence from three regions of Vietnam. *Front. Sustain. Food Syst*., **10**: 26.

Meier, J., Mauser, W., Hank, T. and Bach, H. 2020. Assessments on the impact of high-resolution-sensor pixel sizes for common agricultural policy and smart farming services in European regions. *Comput. Electron. Agric*., **169**: 105205.

Mi, W., Sun, Y., Xia, S., Zhao, H., Mi, W., Brookes, P. C., Liu, Y. and Wu, L. 2018. Effect of inorganic fertilizers with organic amendments on soil chemical properties and rice yield in a low-productivity paddy soil. *Geoderma*, **320**: 23–29.

Mulla, D. J. 2012. Twenty-five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. *Biosyst. Eng*., **114**: 358–371.

Mwungu, C. M., Mwongera, C., Shikuku, K. M., Acosta, M. and Laderach, P. 2018. Determinants of adoption of climate-smart agriculture technologies at farm plot level: an assessment from southern Tanzania.

Nam, W., Kim, T., Hong, E. and Choi, J. 2017. Regional climate change impacts on irrigation vulnerable season shifts in agricultural water availability for South Korea. *Water*, **9**: 735.

Neupane, D., Adhikari, P., Bhattarai, D., Rana, B., Ahmed, Z., Sharma, U. and Adhikari, D. 2022. Does Climate Change Affect the Yield of the Top Three Cereals and Food Security in the World? *Earth*, **3**: 45–71.

OECD-DAC. 2011. Available at Tracking aid in support of climate change mitigation and adaptation in developing countries. Available at: https://www.oecd.org/dac/stats/47477193.pdf. Accessed 27 October 2019

Onyeneke, R. U., Igberi, C. O., Uwadoka, C. O. and Aligbe, J. O. 2018. Status of climate-smart agriculture in southeast Nigeria. *GeoJournal*, **83**: 333-346.

Pádua, L.; Marques, P.; Adão, T.; Guimarães, N.; Sousa, A.; Peres, E.; Sousa, J.J. Vineyard variability analysis through UAV-based vigour maps to assess climate change impacts. *Agronomy***2019**, 9, 581.

Pampolino, M. F., Witt, C., Pasuquin, J. M., Johnston, A. and Fisher, M. J. 2012. Development approach and evaluation of the nutrient expert software for nutrient management in cereal crops. *Comput Electron Agric***88**: 103–110.

Pankaj, P. K., Ramana, D. B. V., Pourouchottamane, R. and Naskar, S. 2013. Livestock management under changing climate scenario in India. *World Journal of Veterinary Science***1**(1): 25–32.

Pathak, H. and Wassmann, R. 2007. Introducing greenhouse gas mitigation as a development objective in rice-based agriculture: II. Cost-benefit assessment for different technologies, regions and scales. *Agric Syst***94**: 826–840.

PMKSY (Pradhan Mantri Krishi Sinchayee Yojana). 2019. Available at: https://pmksy.gov.in/. Accessed 31 Oct 2019

Pylianidis, C., Osinga, S. and Athanasiadis, I. N. 2021. Introducing digital twins to agriculture. *Comput. Electron. Agric.*, **184**: 105942.

Rajput, V. D., Minkina, T., Kumari, A., Harish, Singh, V. K., Verma, K. K., Mandzhieva, S., Sushkova, S., Srivastava, S. and Keswani, C. 2021. Coping with the challenges of abiotic stress in plants: new dimensions in the field application of nanoparticles. *Plants*, **10**: 1221.

Salehi, M. 2022. Global water shortage and potable water safety; Today's concern and tomorrow's crisis. *Environ. Int.*, **158**: 106936.

Sapkota, T. B., Jat, M. L., Aryal, J. P., Jat, R. K. and Chhetri, A. K. 2015. Climate change adaptation, green-house gas mitigation and economic profitability of conservation agriculture: some examples from cereal system of Indo-Gangetic Plains. *J Integrative Agri*,**14**(8):1524–1533.

Schlamovitz, J. L. and Becker, P. 2021. Differentiated vulnerabilities and capacities for adaptation to water shortage in Gaborone, Botswana. *Int. J. Water Resour. Dev.*, **37**: 278–299.

Shah, T. 2009. Climate change and groundwater: India's opportunities for mitigation and adaptation. *Environment Research Letters Journal*,**4**(03): 1–13.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M. and de Haan, C. 2006. Livestock's long shadow: environmental issues and options. Food and Agriculture Organization of the United Nations, Rome.

Turyasingura, B. and Chavula, P. 2022. Climate-Smart agricultural extension service innovation approaches in Uganda. *International Journal of Food Science and Agriculture.*

USEPA (United States Environmental Production Agency). 2015. National Greenhouse Gas Emissions Data: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2013. Wind Energy Essentials; John Wiley & Sons, Inc.: Hoboken, NJ, USA, pp. 298–314.

Van, D. M. and Kim, J. 2020. Projections on climate internal variability and climatological mean at fine scales over South Korea. *Stoch. Environ. Res. Risk Assess.*, **34**: 1037–1058.

Verchot, L., Van Noordwijk, M., Kandji, S., Tomich, T., Ong, C., Albrecht, A., Mackensen, J., Bantilan, C., Anupama, K. and Palm, C. 2007. Climate change: linking adaptation and mitigation through agroforestry. *Mitig Adapt Strat Glob Chang*,**12**: 901–918. https://doi.org/10.1007/s11027-007-9105-6

World Bank. 2015. Accelerating climate-resilient and low-carbon development: The Africa climate business plan; World Bank: Washington, DC, USA.

Wright, A. G. and Klieve, A. V. 2011. Does the complexity of the rumen microbial ecology preclude methane mitigation?.*Animal Feed Science Technology*, 166–167:248–253. https://doi.org/10.1016/j.anifeedsci.2011.04.015