Review Article

Climate Smart Agriculture: Innovating Sustainable Practices for a Changing Climate

Abstract

Climate Smart Agriculture (CSA) is a strategy aimed at lowering greenhouse gas emissions, strengthen climate change resilience, raising crop production and incomes significantly. In a variety of agro-ecological zones, the implementation of climate smart agriculture methods has significantly improved the availability of food, adaptability to fluctuations in the climate, and emissions reduction. One of the key benefits of CSA is its ability to improve agricultural productivity and stabilize food security, particularly for small-scale farmers in developing nations who are most vulnerable to climate change. By integrating sustainable techniques such as conservation agriculture, crop diversification, and agroforestry, CSA helps ensure stable yields, even amid erratic weather patterns. Enhanced soil fertility, enhanced irrigation practices and the use of varieties of crops that are climate resilient all contribute to sustained productivity, mitigating the risks of crop failure and food shortages. CSA also strengthens agricultural systems' resilience to climate impacts by promoting practices like zero tillage, residue management, and efficient irrigation, which improve soil health and water retention, making crops more resistant to droughts and floods. In addition to boosting resilience, CSA contributes to climate change mitigation by reducing agriculture's carbon footprint. Precision farming, organic agriculture, and other low-emission practices help curb greenhouse gas emissions from farming activities. Mobile technology is also emerging as a key driver of CSA by providing real-time information, decision-making support, and access to essential resources, further enhancing the adaptability and sustainability of farming systems. The significance of CSA as a strategic solution to the threats that climate change poses to food security and agricultural sustainability is being more widely acknowledged by governments. As a result, numerous initiatives have been launched at national, regional, and international levels to encourage the widespread adoption of CSA practices. In order to achieve sustainable agricultural development and ensure food security in the face of climate change, CSA must be scaled up around the world.

Introduction

Agriculture will confront some significant obstacles in the years to come. It needs to confront the fact that there are around one billion people who go hungry every day and that there will be more than two billion people on the globe by 2050. As the ordinary individual around the world becomes wealthier and eats more food and meat, food consumption patterns are also shifting. There is more competition for resources used in food production, such as energy, water, and land. Especially in nations with limited resources, climate change brings new difficulties for agriculture. At the same time, a large portion of greenhouse gas (GHG) emissions caused by humans (19–29%) come from numerous modern farming methods that harm the ecosystem. In 2011, farms accounted for 6 billion tons, or more than 13 percent, of global greenhouse gas emissions. Through emissions from transportation and electricity generation included, the energy sector is the largest emitter in the world, with agriculture coming in second. The majority of emissions associated with farms are methane (CH4) and nitrous oxide (N_2O). The two largest sources, contributing to 65 percent of global agricultural emissions, are the addition of natural or synthetic fertilizers and wastes to soils (N2O) and cattle belching (CH4). Farm fuel use, field burning of crop leftovers, rice farming, and manure management are smaller contributors. Smaller sources include farm fuel consumption, rice cultivation, field burning of agricultural leftovers, and manure management. In 2011, the top 10 nations with the highest agricultural emissions were China, Brazil, the United States, India, Indonesia, the Russian Federation, the Democratic Republic of the Congo, Argentina, Myanmar, and Pakistan, in decreasing order. A concept of climate-smart agriculture was first proposed in 2010 (Food and Agriculture Organization of the United Nations, 2013). The general idea of modifying all aspects of agriculture (crops, animals, aquaculture, and capture fisheries) to adapt more effectively to a changing climate has so far proven a hit. Since agriculture is a major source of greenhouse gas emissions, climate-smart approaches that reduce or eliminate greenhouse gas emissions from the atmosphere while simultaneously increasing productivity and resilience to climatic changes are essential. Climate Resilient Agriculture (CRA) is another name for it. CRA refers to the integration of adaptation, mitigation, and other agricultural techniques that improve the system's ability to cope with damage and bounce back quickly from a variety of climate-related disruptions. Events like drought, flooding, heat or cold waves, irregular rainfall patterns, extended dry spells, explosions in insect or pest populations, and other perceived threats brought on by climate change are examples of such disturbances. CSA is characterized by three goals. First and foremost, increasing crop production to promote greater incomes, food security, and development; second, increasing adaptive capacity at all scales (from farms to nations); and third, lowering greenhouse gas emissions and increasing carbon sinks. It is, in essence, the system's capacity to recover. Climate resilient agriculture has a feature that allows the system to identify threats that require action and assess the success of those actions. The main goal of CRA is to use best practices to manage natural resources—such as land, water, soil, and genetic resources—judiciously and better. Climate-smart agriculture contributes in a sustainable way by lowering greenhouse gas emissions, boosting agricultural productivity, and strengthening food production systems' resilience (Kumar *et al*., 2012).

Climate change and Indian agriculture

1. **Shift in monsoon pattern**: Climate change is causing India's monsoon patterns to change, which has serious implications for livelihoods, agriculture, and water supplies. From 1901 to 2018, the temperature in India rose by 0.6 to 25.1 degrees Celsius. A few of the climatic changes that may arise from this temperature increase include changed rainfall patterns and the disruption of conventional monsoon cycles, which can lead to an uneven distribution of rainfall. There may be more rainfall in certain areas and drought in others. Crop sowing dates may be impacted by a delayed monsoon commencement. Furthermore, the early monsoon departure may impact crop maturation and harvest. Longer dry spells and more intense and frequent extreme weather events, such heavy rainfall that causes erosion and flooding, can result from rising temperatures.
2. **Loss in cropped area**: Approximately 33.9 million hectares of agriculture were devastated by hydro-meteorological disasters such floods and high rainfall between 2015–16 and 2021–22, causing India to suffer large losses in cropped area. The productivity of agriculture and food security are significantly impacted by this loss. Extreme weather conditions have become more frequent and intense due to climate change. Flash floods caused by heavy rainfall can erode land, wash away topsoil, and interfere with planting schedules. The abrupt flooding of fields in many areas prevents farmers from recovering their crops, sometimes resulting in complete

losses. Improving irrigation infrastructure, encouraging climate-resilient farming methods, and putting into practice efficient disaster management plans are all crucial to overcoming these obstacles. By taking such steps, the effects of harsh weather can be lessened and future losses to the sector of agriculture can be avoided.

3. **Hunger Prevalence**: The Global Food Policy 2022 research from the International Food Policy Research Institute (IFPRI) emphasizes the concerning possibility that by 2030, climate change might cause about 90 million Indians to go hungry. Rising temperatures, changing rainfall patterns, and an increase in unfavorable weather conditions are expected to significantly reduce agricultural productivity.
4. **Impact on productivity of crops**: Crop productivity is expected to be greatly impacted by climate change, with possible declines of 10% to 40% by 2100. Rising temperatures, more variable rainfall, and a shortage of irrigation water are the main causes of this reduction. Depending on how sensitive they are to regional conditions and climatic influences, different crops will suffer different amounts of loss. For example, yields of wheat and rice could decrease by about 20% and 35%, respectively. Barley may see declines of roughly 13%, whereas sorghum may be the most severely affected, with losses of up to 50% possible. The most significant effects are anticipated to be seen by maize, a staple crop in many areas, with loss of production estimated at over 60%. Location and particular climatic conditions affect these variations, thus some places may see more significant changes than others. Especially at risk are areas that depend significantly on rain-fed agriculture or are already vulnerable (World Bank, 2022).

Importance of Climate smart agriculture

Climate-smart agriculture (CSA) is essential especially when climate change disrupts the distribution of rainfall and makes droughts worse. For the following main reasons, CSA is significant in this situation:

1. Crop resilience to climate variability- Weather in dry farming areas can be unpredictable. CSA strategies, including selecting varieties of crops resistant to drought and conserving water, assist farmers in adjusting to these changes and ensure higher yields even under adverse conditions.

2. Enhanced Soil Health: Sustainable agriculture, particularly in arid areas, depends on healthy soil. CSA encourages methods that enhance soil structure, fertility, and moisture retention, including as cover crops, decreased tillage, and organic amendments. This reduces soil erosion while simultaneously promoting crop growth.
3. Efficient Water Use: The shortage of water is a serious concern in dry farming. CSA promotes techniques such as rainwater obtaining, mulching, and drip irrigation, which maximize water utilization and minimize waste. These techniques preserve precious water resources while ensuring that crops receive enough moisture.
4. Pest and Disease Management: The shortage of water is a serious concern in dry farming. CSA promotes techniques such as rainwater obtaining, mulching, and drip irrigation, which maximize water utilization and minimize waste. These techniques preserve important water resources while ensuring that crops receive enough moisture. By incorporating pest management techniques like crop rotation, biological control, and the use of resistant cultivars, farming systems become more resilient and less dependent on chemical pesticides, which promotes environmental sustainability and safeguards beneficial organisms that support ecosystem health.
5. Economic Viability for Farmers: Climate-smart agriculture (CSA), which encourages sustainable methods that increase production, reduce costs, and strengthen resilience to climate change, is essential to enhancing farmers' financial sustainability. By implementing CSA practices, farmers can increase crop yields through improved soil health, better water management, and the use of climate-resilient varieties. This increased productivity directly translates into higher incomes, allowing farmers to invest in their operations and improve their standard of living (U.S. Department of Agriculture, 2015).

Best practices for climate smart agriculture

Water smart practices

Direct seeded rice: Direct seeded rice is an innovative practice in climate-smart agriculture that offers several advantages in terms of resource efficiency, resilience, and sustainability. This method involves sowing rice seeds directly into the soil rather than transplanting seedlings, which can significantly enhance agricultural productivity while reducing water and labor inputs. One of the primary benefits of direct seeded rice is its water efficiency. Traditional rice cultivation typically requires flooded fields, which can lead to high water consumption. In contrast, direct seeding can be done under aerobic or semi-aerobic conditions, reducing water usage by up to 30-50%. This is particularly important in regions facing water scarcity or where irrigation resources are limited, allowing farmers to maintain productivity despite changing climate conditions. Direct seeded rice also enhances resilience to climate variability. It allows for greater flexibility in planting schedules, enabling farmers to adapt to changing weather patterns and optimize sowing times based on rainfall forecasts. This adaptability can help maintain crop yields even in unpredictable climates (Jnanesha and Kumar 2017).

Furrow irrigated raised bed system: The furrow irrigated raised bed system is an effective climate-smart agriculture practice that optimizes water use, enhances soil health, and improves crop productivity. This method involves creating raised beds with furrows for irrigation, allowing for better management of water and nutrients while reducing soil erosion. One of the key advantages of this system is its water efficiency. The raised beds facilitate controlled irrigation, where water is applied directly to the furrows, minimizing evaporation and runoff. This targeted approach allows for effective moisture management, particularly in areas prone to drought or water scarcity. By using less water compared to traditional flat-field irrigation, farmers can maintain productivity even in challenging climatic conditions. Additionally, the raised beds improve drainage, reducing the risk of waterlogging, which can be detrimental to many crops. This is especially beneficial in regions that experience heavy rainfall, as it helps to maintain optimal soil conditions for root growth and development (Singh *et al*., 2017).

Drip irrigation: Drip irrigation is a highly efficient climate-smart agriculture practice through a system of tubes, pipes, and emitters that supplies water straight to plant roots. Water scarcity and climate fluctuation are major factors, and this technique greatly improves water use efficiency. The reduction of water waste is one of drip irrigation's main advantages. By targeting the root zone, this system reduces evaporation and runoff compared to traditional irrigation methods. With this accuracy, farmers may maintain or even increase crop yields while using 30–70% less water. This effectiveness is particularly crucial in areas with limited water supplies that are arid or semi-arid. Additionally, drip irrigation enhances resilience to climate change. It allows farmers to adapt their watering schedules based on real-time conditions, optimizing water use during dry spells or fluctuating rainfall patterns. This adaptability can help maintain consistent crop production despite climate variability (chouhan *et al*., 2016).

Carbon smart practices

Residue management: Residue management plays a vital role in climate-smart agriculture by enhancing soil health and promoting sustainability. When crop residues are properly managed, they help improve soil structure and foster microbial activity, which boosts nutrient cycling and supports crop growth. It enhances carbon sequestration by returning crop residues to the soil, which contributes organic matter that improves soil structure and increases its capacity to store carbon. By minimizing tillage and keeping residues on the surface, farmers can protect the soil from erosion and degradation, thereby preserving existing carbon stocks. Moreover, residues provide food for soil microorganisms, fostering a healthy microbial community that aids in breaking down organic matter and stabilizing soil carbon. This process contributes to overall soil health, which enhances its resilience and ability to store more carbon over time (Singh *et al*., 2023).

Soil amendments: Soil amendments are a highly effective carbon-smart practice for several reasons. They enhance soil quality by increasing organic matter content, which improves the soil's ability to sequester carbon. When organic amendments like compost, manure, or biochar are added, they decompose over time, enriching the soil and stabilizing carbon.

These amendments also improve soil structure, promoting better water retention and aeration, which fosters healthy root development and enhances microbial activity. A thriving microbial community is essential for effective nutrient cycling and further carbon stabilization. Furthermore, the use of synthetic fertilizers, which contribute to greenhouse gas emissions, can be minimized with the utilization of soil amendments. By improving nutrient availability naturally, they contribute to more sustainable farming practices. Using amendments can also enhance soil resilience to climate change impacts, such as drought or heavy rainfall, thereby supporting long-term agricultural productivity. Overall, incorporating soil amendments not only boosts soil health but also plays a significant role in carbon sequestration and reducing emissions, making them an essential component of climate-smart agriculture (Bamdad *et al*., 2021) .

Nutrient smart practices

Integrated nutrient management: A climate-smart technique that is essential to improving agricultural resilience and sustainability is integrated nutrient management. By combining organic and inorganic nutrient sources, this approach optimizes nutrient use, improving crop productivity while minimizing environmental impacts. One key benefit is its ability to enhance soil health. By incorporating organic matter through compost, manure, or cover crops, integrated nutrient management increases soil carbon content, which aids in carbon sequestration and improves soil structure. Healthier soils can better retain moisture and nutrients, making crops more resilient to climate extremes like drought or heavy rainfall. Integrated nutrient management promotes biodiversity and encourages practices that support ecosystem functions, enhancing overall farm resilience. By aligning nutrient management with the specific needs of crops and local conditions, In addition to increasing yields, this strategy supports long-term sustainability in the face of climate change (Shahi *et al*., 2020).

Leaf color chart: Using a leaf color chart is a climate-smart practice that helps farmers assess the nutrient status of their crops efficiently. By observing leaf color, farmers can determine whether their plants are receiving adequate nutrients, particularly nitrogen. This visual tool allows for timely and precise adjustments to fertilization strategies. One significant advantage of using a leaf color chart is that it promotes more efficient nutrient use. By applying fertilizers based on actual plant needs rather than blanket applications, farmers can reduce excess fertilizer use. This minimizes the risk of nutrient runoff into water bodies, which significantly increases greenhouse gas emissions and pollutants. Moreover, the practice enhances crop health and productivity. When plants receive the right nutrients at the right time, they are more resilient to climate-related stresses such as drought or disease, leading to more stable yields. This resilience is crucial as climate variability increases (Ali *et al*., 2017).

Environmental smart practices

Climate-smart technologies play a crucial role in reducing greenhouse gas emissions across various sectors by enhancing efficiency, promoting sustainable practices, and facilitating adaptation to climate change. For example, precision agriculture utilizes GPS and sensor technology to optimize the application of fertilizers and water, reducing excess inputs that can lead to nitrous oxide emissions. Renewable energy technologies, such as solar, wind, and bioenergy systems, replace fossil fuels, significantly cutting carbon emissions in electricity generation and heating. Improved livestock management practices, including the use of feed additives, can reduce methane emissions from ruminants, while better breeding practices enhance overall livestock efficiency. Soil carbon sequestration techniques, such as cover cropping and conservation tillage, increase soil organic matter and capture carbon in the soil, supported by monitoring technologies. Waste management innovations like anaerobic digestion convert organic waste into biogas, reducing methane emissions from landfills while providing a renewable energy source. Upgrading machinery and implementing energy-efficient practices in manufacturing and transportation also minimize fossil fuel consumption and associated emissions. Additionally, carbon capture and storage technologies capture carbon dioxide from industrial processes and store it underground, helping mitigate emissions from high-emission industries. By adopting these climate-smart technologies, we can significantly lower greenhouse gas emissions, support sustainable development, and enhance resilience to climate change (Pathak and Aggarwal, 2012).

Knowledge smart practices

Certain recently developed mobile applications is used for smart farming such as Apple doc, Meghdoot app, plantix, Kisan suvidha app etc.

Apple doc: This mobile application for precision farming was created by SKUAST-K and is based on artificial intelligence. APPLE DOC fixes the issues that orchardists are facing. Through this smartphone application, the area's apple growers may access real-time information and prompt professional advice regarding weather advisories, chemical usage, soil samples, and other pertinent information (Greaterkashmir.com).

Meghdoot app: The Meghdoot app is a mobile application developed by the Indian Meteorological Department (IMD) to provide essential weather-related information and services, particularly aimed at farmers. It offers daily and weekly weather forecasts, including details on temperature, humidity, and precipitation. This information helps users make informed decisions regarding their agricultural practices. One of the key features is the agro-advisory service, which provides tailored recommendations based on current and predicted weather conditions, helping farmers optimize their activities and improve yields. The app also includes rainfall alerts, notifying users about impending rainfall, which is crucial for planning tasks like planting and harvesting (Dhulipala *et al.*, 2021).

Plantix app: Plantix is a mobile application designed to assist farmers and gardeners in diagnosing plant diseases, pests, and nutrient deficiencies. By utilizing image recognition technology, users can take photos of affected plants, and the app analyzes these images to provide insights and recommendations. One of the key features is disease diagnosis, where users can identify various plant diseases by uploading images and receiving instant feedback on possible issues. The app also helps recognize common pests that may be affecting crops, offering suggestions for management. Additionally, Plantix detects signs of nutrient deficiencies, guiding users on how to correct them. It provides tailored agricultural advice based on the specific crops and issues identified, helping users implement effective solutions. The app fosters community support by allowing users to connect with other farmers and experts to share experiences and solutions.

Kisan Suvidha app: The Indian government launched the kisan suvidha app as a way to give farmers access to vital data and services. It serves as a one-stop platform to access various agricultural resources and tools that can enhance farming practices. One of the key features of the app is the availability of weather forecasts, which help farmers plan their activities based on expected conditions. The app also offers market prices for different crops, enabling farmers to make informed decisions about when and where to sell their produce. Additionally, Kisan Suvidha provides information on agricultural schemes, subsidies, and government policies, helping farmers understand their entitlements and benefits. The app includes a section for expert advice, allowing users to seek guidance on best practices, pest management, and crop cultivation techniques (Ministry of Agriculture and farmers).

Government initiatives on climate smart agriculture

Pradhan mantra krishi sinchayee yojana: The Pradhan Mantri Krishi Sinchai Yojana (PMKSY) is an initiative by the Government of India aimed at enhancing irrigation and water conservation in agriculture. The program focuses on improving the efficiency of water use, ensuring access to irrigation for all farmers, and promoting sustainable agricultural practices. Key objectives include the expansion of irrigation coverage, promoting rainfed agriculture, and implementing efficient water management techniques. The scheme encourages the use of modern irrigation methods like drip and sprinkler systems, aiming to increase crop productivity and reduce dependence on monsoon rains. Additionally, PMKSY supports the development of infrastructure, such as irrigation canals and water storage facilities, to ensure a reliable water supply for agricultural needs. Overall, the program seeks to boost agricultural productivity, improve farmers' livelihoods, and promote sustainable water management practices in the agricultural sector (National portal of India, 2023).

Climate smart villages: Climate-smart villages are innovative initiatives designed to enhance the resilience of rural communities to climate change while promoting sustainable agricultural practices. These villages focus on integrating climate-smart agriculture, improving food security, and enhancing the livelihoods of farmers. Key components include the adoption of sustainable farming techniques, such as crop diversification, soil health improvement, and efficient water management. The initiative also emphasizes the importance of local knowledge and community involvement in decision-making processes. By fostering collaboration among farmers, researchers, and policymakers, climate-smart villages aim to implement adaptive measures that address the specific challenges posed by climate change. Ultimately, the goal is to create resilient communities that can thrive in changing environmental conditions while contributing to overall sustainability (Singh *et al*., 2022).

National Innovation on Climate Resilient Agriculture (NICRA): The Government of India's National Innovation on Climate Resilient Agriculture (NICRA) program aims to make Indian agriculture more climate change resilient. The program focuses on developing and promoting climate-resilient technologies and practices to improve productivity and sustainability. NICRA encompasses various components, including research on climate-smart agricultural practices, strengthening local institutions, and providing farmers with training and resources to adapt to changing climate conditions. It emphasizes the use of weather forecasting and agro-advisories to help farmers make informed decisions. The initiative also supports the development of resilient crop varieties and efficient water management practices. By promoting adaptive strategies, NICRA aims to secure food production and improve the livelihoods of farmers in the face of climate challenges (Ministry of Agriculture and farmers, 2023).

Conclusion

Climate Smart Agriculture (CSA) is a vital approach to achieve sustainability. It involves adopting practices that improve productivity, enhancing resilience and reduce greenhouse gas emission. Indian agriculture is highly vulnerable to variations in temperature and rainfall, which have negative impact on crop yield and food security. Many farmers do not have knowledge regarding climate change due to this they rely on traditional methods. Small-scale farmers may struggle to implement CSA practices due to limited resources. So, there is a need to increase awareness of current technologies and practices such as water saving irrigation, residue management etc. that can aid in climate adaptation. To overcome this issue government of India has launched climate smart agriculture approaches, various new technologies and schemes to combat the climate change issue faced by the farmers.

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