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Climate-Smart Agriculture: Bridging Productivity, Adaptation and Mitigation

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Abstract

Climate change is altering temperature, rainfall and extreme-weather patterns, creating a dual challenge for agriculture: producing enough food for a growing population while conserving soil and water and remaining resilient to climate shocks. Climate-Smart Agriculture (CSA), originally formulated by the Food and Agriculture Organisation of the United Nations, offers an integrated framework built on three pillars: sustainably increasing productivity and farm income, strengthening adaptation and resilience, and reducing greenhouse gas emissions where feasible. This article explains the three pillars and describes practical CSA interventions suited to Indian conditions, including zero tillage and crop residue retention, laser land levelling, alternate wetting and drying, drip and micro-irrigation, rainwater harvesting, climate-resilient varieties, millets, intercropping and agroforestry, and soil-test-based and precision nutrient management. It also discusses the main barriers to adoption, such as high initial costs, fear of financial loss and limited technical knowledge, and the role of Custom Hiring Centres, Krishi Vigyan Kendras and crop insurance in addressing them. Matching practices to local climate, soil and farmer resources, rather than adopting every available technology, is the key to building resilient, productive and profitable farming systems.

Keywords: Climate-Smart Agriculture; Climate Change; Adaptation; Mitigation; Resilience; Zero Tillage; Water Management; Nutrient Management.

Introduction

Our planet's climate is shifting faster than at any point in modern history, and the numbers tell a stark story. Rising temperatures, shifting rainfall patterns and the growing frequency of extreme weather events are transforming the conditions under which crops are grown, and food is produced. According to global climate monitors like the World Meteorological Organisation (WMO), recent years have shattered temperature records, with human-induced global warming hovering around 1.35°C to 1.4°C above pre-industrial levels. Overall, global surface temperatures have risen by approximately 1.2°C over the past two centuries (IPCC, 2021). Moreover, every year from 2015 to 2025 ranked among the eleven warmest years on record, highlighting the persistent upward trend in global temperatures (WMO, 2026).

For India, long-term data from the India Meteorological Department (IMD) show that the country's mean annual temperature has warmed by approximately 0.89°C over the past century, with the last two decades recording more unprecedented hot years than any previous period. Even more alarming than the rising heat alone is the breakdown of predictable weather systems. Increasing heat stress, prolonged dry spells, intense rainfall, floods and changing monsoon patterns can disrupt sowing schedules, damage standing crops, reduce water availability and affect the quality of agricultural produce. In northern India, terminal heat stress during grain development damages wheat yields, while in southern regions, unseasonal cyclonic storms frequently lodge standing paddy crops (Dhara *et al.*, 2025). These risks are compounded when a prolonged dry spell is followed by intense rainfall, leaving farmers with little time to adjust their management decisions. Consequently, the traditional cropping calendars that guided farm management for generations have become erratic and difficult to anticipate (Niwas & Khichar, 2016).

This situation presents a critical dilemma. On

one hand, global population growth demands expanded agricultural output to safeguard food security (FAO, 2017; Godfray *et al*., 2010). On the other hand, producers must achieve higher yields amid severe climatic volatility while conserving finite natural capital, particularly soil health and freshwater reserves (IPCC, 2019). Feeding a growing population while mitigating the impacts of climate change and managing natural resources sustainably is therefore a central challenge for Indian agriculture (Nautiyal *et al*., 2024; Joshi *et al.,* 2019). The key question is not merely how to increase gross tonnage, but how to do so through practices that remain economically viable, ecologically sustainable, and resilient to climate shocks.

Addressing this challenge calls for a shift from conventional, input-intensive approaches towards farming systems that are productive, resource-efficient and resilient to climatic uncertainty. This imperative underpins Climate-Smart Agriculture (CSA), an approach originally formulated by the Food and Agriculture Organisation of the United Nations (FAO, 2010; Lipper *et al*., 2014). CSA provides an integrated framework targeting three core objectives: sustainably enhancing agricultural productivity, strengthening adaptive capacity against climate variability, and reducing greenhouse gas emissions where feasible. Rather than relying solely on conventional agronomic packages, CSA advances the adoption of stress-tolerant crop cultivars, site-specific nutrient management, precision water application, conservation agriculture, and agro-meteorological advisory services (Kishore *et al*., 2018). CSA as a strategy for adapting to a changing climate has also been discussed by Nautiyal *et al*. (2025).

As climate uncertainty becomes an increasingly important factor in farm management, the question is no longer whether agriculture needs to adapt, but how quickly and effectively that adaptation can take place. Climate-Smart Agriculture offers an approach for bringing productivity, resilience and environmental sustainability into the same conversation. Understanding its principles, practical interventions, and limitations is an essential step towards building farming systems that can withstand climate shocks while continuing to support food security and rural livelihoods.

Understanding the Three Pillars of CSA

Climate-smart agriculture is built on a simple premise. A farm cannot focus solely on harvesting more crop today if the method destroys tomorrow's harvest. To create a farming system that can survive erratic weather while feeding a growing world, the UN Food and Agriculture Organisation (FAO) framed CSA around three interconnected pillars (Figure 1).

Productivity: Growing more food and securing farmers' income

The first and most immediate priority of climate-smart agriculture is food security and farmer livelihood. Farmers cannot protect the environment if they cannot feed their families or earn a living. This pillar aims to increase crop production and farm income without harming natural resources such as soil and water. As the world's population continues to grow, the demand for food is also increasing. However, increasing production by clearing forests, overusing fertilisers, or extracting excessive groundwater is not a sustainable solution. To achieve higher productivity, farmers are encouraged to adopt efficient farming practices such as balanced use of fertiliser, soil test-based nutrient management, improved crop varieties, and integrated pest management. These practices help increase yields while reducing unnecessary input costs. The objective is to produce more food using available resources efficiently, ensuring that farming remains productive, profitable, and sustainable in the long term.

Adaptation and Resilience: Preparing for weather shocks

The second pillar of climate-smart agriculture focuses on helping farmers adapt to changing climate conditions and building resilience against extreme weather events. Even if greenhouse gas emissions are reduced today, the effects of climate change are already being experienced across the world. Farmers are increasingly facing challenges such as unseasonal rainfall, prolonged dry spells, floods and heat waves. This pillar aims to strengthen the ability of crops, livestock, soil, and farming communities to withstand and recover from climate-related shocks. This is important because a single drought, flood, or storm can destroy an entire season's harvest and severely affect farmers' incomes and livelihoods. To reduce these risks, farmers can adopt several climate-resilient practices. These include switching to short-duration, drought-tolerant, or flood-tolerant crop varieties (such as submergence-tolerant rice that survives two weeks under standing water), conserving soil moisture through mulching and zero-tillage so that crops survive unpredictable dry spells, and diversifying farms by combining crops with livestock, pulses, or agroforestry, so that if one crop fails due to weather, the farmer still has an alternative source of income.

Mitigation: Reducing the footprint of farming

The third pillar of climate-smart agriculture focuses on reducing greenhouse gas emissions from agricultural activities and promoting environmentally sustainable farming practices. Agriculture contributes to climate change through emissions from paddy fields, livestock and excessive use of chemical fertilisers. This pillar encourages farmers to adopt practices that reduce emissions while maintaining productivity. Techniques such as efficient water management in rice cultivation, balanced fertiliser application, minimum tillage, green manuring and agroforestry can help lower agriculture's environmental impact. These practices also improve soil health and increase carbon storage in the soil. By reducing emissions and conserving natural resources, climate-smart agriculture helps create a more sustainable and climate-friendly farming system for future generations.

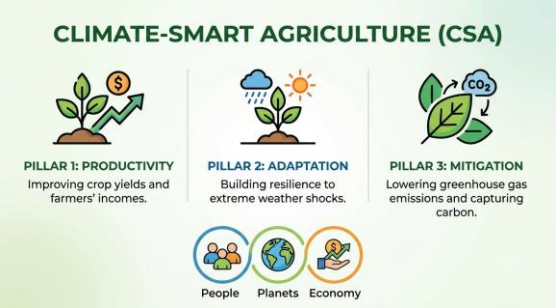


Fig. 1. Pillars of Climate-smart Agriculture

Climate-Smart Practices on the Ground: Turning Ideas into Action

Climate-Smart Agriculture is not just a scientific concept; it includes practical methods that farmers can use in their fields. From protecting the soil and using irrigation water more efficiently to selecting resilient crop varieties, farmers can adopt a range of practices to manage climate-related risks. These approaches can help conserve natural resources, improve input-use efficiency, stabilise crop production and, in some cases, reduce greenhouse gas emissions. The most effective strategy is not to adopt every available technology, but to combine practices that suit local climatic conditions, soil characteristics, cropping systems and farmers' resources.

1. Soil and Tillage Management: Protecting Soil Health

Healthy soil is the foundation of resilient agriculture. It stores water, supplies nutrients, supports beneficial organisms and provides the physical environment needed for root growth. However, repeated intensive tillage can disturb soil structure, accelerate the decomposition of organic matter and leave the soil vulnerable to erosion. Protecting soil through reduced disturbance and maintaining adequate soil cover can therefore help farming systems withstand periods of drought and intense rainfall.

Zero tillage: Under zero tillage, seeds are sown directly into the soil without conventional ploughing, using specialised seed drills. In India's rice–wheat systems, the Happy Seeder enables wheat sowing into fields where rice residues remain on the surface, helping farmers manage crop residues without burning them (Figure 2). Zero-till seed drills can reduce the number of field operations, saving time, fuel and labour. By limiting soil disturbance, these methods can also help conserve soil moisture and reduce erosion. Their success, however, depends on appropriate machinery, effective weed management and suitable crop and residue management practices.



Fig. 2. Happy Seeder for zero-tillage sowing

Crop residue retention (mulching): After harvesting, leftover straw and other crop residues can be retained on the soil surface rather than burned or removed indiscriminately. This protective cover reduces direct exposure of the soil to sunlight and raindrops, moderates soil temperature, slows moisture loss and helps control erosion. As residues gradually decompose, they contribute organic matter and recycle nutrients. In the rice–wheat belt, retaining rice straw and using suitable sowing machinery can provide a practical alternative to residue burning, which contributes to air pollution and greenhouse gas emissions.

Why it is climate-smart: Zero tillage and residue retention can improve soil-water conservation, reduce fuel consumption and help protect soil structure. Over time, well-managed conservation agriculture can support soil health and more stable crop production. However, changes in soil carbon depend on soil type, climate, the depth of measurement and the overall management system. These practices are most effective when integrated with crop diversification, appropriate nutrient management and effective weed control

(Govaerts *et al*., 2007; Aryal *et al*., 2015b).

2. Water-Smart Management: Making Every Drop Count

Agriculture is highly sensitive to water availability, yet both water scarcity and excessive rainfall can damage crops. Declining groundwater levels, irregular monsoons and increasing competition for freshwater make efficient water management essential. Climate-smart water management aims not only to reduce water use, but also to ensure that crops receive water at the right time and in the right quantity.

Laser land levelling: Uneven fields often result in the accumulation of water in low-lying areas while elevated patches remain inadequately irrigated. A level field allows water to spread evenly, reducing water wastage and improving the efficiency of irrigation and fertiliser use. Laser land levelling uses laser-guided equipment to create a more uniform field surface, allowing irrigation water to spread more evenly (Jat *et al*., 2006). This can reduce irrigation time, improve crop establishment and enhance the efficiency of water and fertiliser use. Studies have reported irrigation water savings of around 20–25% under suitable conditions (Aryal *et al*., 2015a).

Alternate Wetting and Drying (AWD): Rice is often grown under flooded conditions, but continuous flooding is not always necessary throughout the crop's growth. AWD is a water-management technique in which farmers allow the field water level to fall to a prescribed threshold before irrigating again. A perforated field tube can help monitor the water level and guide irrigation decisions. When properly managed, AWD can reduce irrigation water use and methane emissions without necessarily reducing yields (Setyanto *et al*., 2018).

Drip and micro-irrigation: These systems deliver water in controlled quantities, either near the plant's root zone or through small emitters along crop rows. They are particularly useful for many horticultural crops, vegetables, orchards and other crops where precise irrigation is feasible. By reducing unnecessary wetting and improving control over water application, micro-irrigation can improve water-use efficiency and reduce pumping requirements. Its effectiveness depends on system design, maintenance, filtration and appropriate scheduling.

Rainwater harvesting and moisture conservation: Climate-smart water management also includes collecting rainwater in farm ponds, storage structures and suitable recharge systems. Practices such as mulching, contour farming and maintaining soil organic matter can help conserve moisture and reduce runoff. In rainfed regions, combining these measures with appropriate cropping patterns can help farmers make better use of limited and increasingly variable rainfall (Heryani *et al*., 2023).

Why it is climate-smart: Efficient irrigation, better field preparation, and rainwater conservation can reduce water and energy waste, improve crop performance, and strengthen resilience to dry spells. Where practices such as AWD also reduce methane emissions, they contribute to climate-change mitigation. The aim is to increase the productivity of every unit of water while protecting local water resources for future use.

3. Crop Diversification and Climate-Resilient Varieties

Growing the same crop repeatedly can increase the risk of pest attacks and crop losses during extreme weather. Climate uncertainty makes dependence on a single crop or a narrow range of varieties particularly risky. A crop that performs well under normal conditions may suffer substantial losses when exposed to prolonged drought, extreme heat, flooding or an unexpected shift in rainfall. Diversifying crops and choosing varieties suited to local climate risks can help farmers spread production risks and make agricultural systems more adaptable.

Climate-resilient varieties: Scientists have developed crop varieties that can tolerate drought, flooding, and high temperatures. For example, Swarna-Sub1 is a well-known flood-tolerant rice variety developed for areas vulnerable to temporary submergence. It carries the SUB1 gene, which enables rice plants to survive complete submergence for approximately two weeks under suitable conditions. This characteristic can help protect crops from short-duration flash floods, although prolonged submergence or other adverse conditions may still cause damage (Bailey-Serres *et al*., 2010). In salt-affected regions, the ICAR–Central Soil Salinity Research Institute (ICAR-CSSRI) has developed several crop varieties suited to saline and sodic soil conditions. These include KRL 19, KRL 210 and KRL 283 in wheat; CSR 46, CSR 56, CSR 76, CSR 101, CSR 104 and CSR 105 in rice; and CS 58, CS 60 and CS 62 in mustard. By enabling cultivation in soils affected by salinity or sodicity, these varieties can help farmers utilise otherwise challenging agricultural land, sustain crop productivity and improve the livelihoods of farming communities in salt-affected areas.

Similarly, heat-tolerant wheat varieties can help reduce yield losses when temperatures rise during critical stages of crop development. Selecting suitable varieties according to local climate risks, soil conditions, and recommended cultivation practices is essential for strengthening agricultural resilience.

Climate-resilient varieties in rainfed hill agriculture: Hill agriculture depends largely on rainfall and is therefore highly vulnerable to erratic rainfall patterns. In rainfed villages of Uttarkashi district, Uttarakhand, the short-duration, wilt-resistant pigeon pea variety VL Arhar-1 was introduced under the National Innovations in Climate Resilient Agriculture (NICRA) project to cope with uneven rainfall and limited irrigation. Demonstrations showed that it performed better in terms of yield and economic returns than the local Tur (Nautiyal *et al*., 2021).

Promoting millets: Crops such as pearl millet (bajra), finger millet (ragi), and sorghum (jowar) are well suited to many dry and hot regions. They generally require less water than water-intensive crops and can grow under relatively harsh conditions (Kumar *et al*., 2024) (Figure 3). Their inclusion in crop rotations or diversified cropping systems can reduce dependence on water-intensive crops and broaden the range of food and fodder available to farming households. However, their performance still depends on the suitability of the variety, soil conditions, rainfall distribution and crop management.



Fig. 3. Hardy millets resilient to heat and drought

Intercropping and agroforestry: Growing two or more crops together, such as cereals and pulses, can improve land use and diversify farm income. Trees planted along field boundaries can provide shade, reduce wind damage, and offer additional products and income.

Controlled-environment production: Indoor vertical farming is frequently regarded as a climate-resilient production strategy, because crops grown in such systems do not depend on regional weather conditions. Its energy requirements, however, are high, and they need to be managed for the system to remain sustainable (Rathor *et al*., 2024). Deep learning-based image analysis can also support early and accurate detection of crop diseases, including under extreme environmental conditions (Rathor *et al*., 2025a; Rathor *et al*., 2025b).

Why it is climate-smart: Crop diversification and climate-resilient varieties can reduce vulnerability to specific weather-related stresses, improve the stability of production and support more efficient use of land and water. They can also strengthen household food and nutritional security by broadening the range of crops produced. The key is to match crops and varieties to local agroclimatic conditions rather than assuming that a single crop or variety will perform equally well in every region.

4. Smart Nutrient Management: Applying the Right Nutrient at the Right Time

Fertilisers play an important role in maintaining crop productivity, but applying more than a crop requires does not necessarily produce higher yields. Excessive or poorly timed fertiliser application can increase production costs and lead to nutrient losses through runoff, leaching and gaseous emissions. Climate-smart nutrient management focuses on supplying crops with the nutrients they need, in the right quantities and at the right time.

Soil-test-based fertiliser application: Soil testing helps farmers understand the nutrient status of their fields and make fertiliser decisions according to crop requirements. Combining soil-test results with recommended fertiliser doses, organic manures and suitable crop residues can improve nutrient availability while avoiding unnecessary applications (Murthy *et al*., 2024).

Precision nutrient management: Tools such as leaf colour charts, SPAD meters and optical sensors like GreenSeeker can help assess crop nitrogen status and guide in-season fertiliser application (Ali and Salem, 2024). These approaches allow farmers to adjust nutrient applications according to crop needs rather than relying entirely on fixed schedules. Agriculture informatics and digital tools can further support such site-specific decision-making (Singh *et al*., 2023). Recent advances in artificial intelligence and data science are further widening the scope of such applications (Kotyal *et al*., 2024; Yusuf *et al*., 2024). Their usefulness depends on suitable calibration, crop-specific recommendations and farmers' access to the required tools and advisory services.

Natural and low-cost approaches: Natural farming, which relies on locally available farm resources and bio-inputs, is also being promoted

as a low-cost alternative that can reduce dependence on purchased chemical fertilisers (Nautiyal and Singh, 2024).

Why it is climate-smart: Efficient nutrient management can reduce avoidable input costs, improve nutrient-use efficiency and limit nutrient losses to the environment. It can also reduce greenhouse gas emissions associated with excessive nitrogen application, particularly nitrous oxide emissions from agricultural soils. The objective is to maintain or improve crop productivity while using nutrients more efficiently and protecting soil, water and air quality.

The Reality Check: Barriers to Adoption and the Role of Policy

Despite its many benefits, climate-smart agriculture is not yet widely adopted because farmers face several challenges.

Challenges in adopting climate-smart agriculture

- **High initial costs:** Equipment such as a happy seeder, laser land leveller and drip irrigation system can be expensive, especially for small and marginal farmers.
- **Fear of financial losses:** Changing farming practices may involve an adjustment period, and farmers often hesitate to take risks that could affect their income and food security.
- **Lack of technical knowledge:** Many farmers need proper training and guidance to use modern machinery and climate-smart techniques effectively.

Role of Government and Agricultural Institutions

Government support and agricultural institutions can make climate-smart practices more affordable and accessible.

- **Custom Hiring Centres (CHCs):** These centres enable farmers, particularly small and marginal farmers, to rent agricultural machinery and equipment at affordable rates. Access to technologies such as zero-till seed drills, Happy Seeders and laser land levellers can reduce initial investment costs and facilitate the adoption of resource-efficient farming practices.
- **KVK training and demonstrations:** KVKs help bridge the gap between agricultural research and field-level implementation through farmer training programmes, frontline demonstrations, on-farm trials and technical advisory services. By demonstrating climate-smart technologies under local conditions, KVKs help farmers understand their benefits, learn appropriate management practices and make informed decisions. Climate-resilient technologies demonstrated through KVKs under the NICRA project are one example (Nautiyal *et al.*, 2021).
- **Crop insurance:** The Pradhan Mantri Fasal Bima Yojana (PMFBY) helps protect farmers against eligible crop losses. By offering financial protection against eligible risks, including certain weather-related crop losses, crop insurance can help farmers manage climate-related uncertainties and recover from adverse agricultural seasons.

Conclusion

Climate-Smart Agriculture is no longer a distant vision or merely an environmental initiative; it is an urgent necessity for securing the future of farming. As extreme weather events and unpredictable seasons increasingly challenge traditional agricultural practices, farmers need practical, affordable and locally suitable solutions to protect their livelihoods and sustain crop production. From conserving soil moisture and using water efficiently to cultivating climate-resilient varieties and adopting improved nutrient management, every step towards climate-smart farming can contribute to a more resilient agricultural system. It ensures that the soil stays fertile, farm incomes remain secure, and humanity continues to have food on the table no matter how unpredictable the skies become.

Conflict of Interest: The authors declare that they have no competing interests or conflicts of interest.

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