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Innovations in climate-smart agriculture: Tools, technologies, and transformation pathways

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Abstract

The agrifood sector possesses major challenges due to a growing world population and the depletion of natural resources caused by climate change, which impacts food security and producer income. In order to feed around 9 billion people by 2050, nations worldwide will need to produce almost 70% more food, thereby rendering the problem of food security even more challenging. Agriculture must, therefore, adapt to the current environment in order to meet the demand for food security and to withstand the effects of a changing climate. A key strategy for climate change adaptation is sustainable intensification, which additionally reduces emissions per unit of output. AI-based climate-smart agriculture technologies enable to maximize the utilization of resources, minimize environmental impact, and enhance crop resilience. This analysis examines current climate-smart innovations in the agrifood sector that support sustainable solutions and increase profitability for farmers. Smallholder farmer communities in India can benefit from increased agricultural output, food security, and the sustainability of their livelihoods through the use of digital technologies for scaling Climate-Smart Agriculture practices. As climate smart agriculture is based on three components boosting productivity, reducing greenhouse gas emissions, and building resilience and adapting key concepts like carbon sequestration, resilience, vulnerability, and productivity serve as indicators for future empirical measurements of the concept. By using adaptation and mitigation approaches, it supports the agricultural system in resisting from losses and fast recoveries.

Keywords: Climate Smart Agriculture, food security, Sustainable, climate change, artificial intelligence, sustainability

1. Introduction

Agriculture is one of the sectors most vulnerable to climate change; productivity and livelihoods are threatened by rising temperatures, changed rainfall patterns, harsh weather, and depleted natural resource bases. However, according to Zhao *et al.* (2023) [40], agriculture is a significant source of greenhouse gas (GHG) emissions. These two issues are addressed by the idea of Climate Smart Agriculture (CSA): (i) raising incomes and productivity; (ii) strengthening resilience to climate risks; and (iii) lowering or eliminating greenhouse gas emissions from farming systems. According to Raj and Prahadeeswaran (2025) [30], "smart farming" is a dynamic convergence of agricultural science and technology that is changing how we interact with the soil. The goal of Climate Smart Agriculture (CSA) is to improve sustainable food production by addressing both climate change and food security. By increasing resource efficiency, cutting postharvest losses, and eliminating waste, it seeks to raise agricultural output and incomes. Additionally, by guaranteeing food security and reducing losses, CSA assists farmers in adapting to climate change. Additionally, it lowers greenhouse gas emissions by using fertilizer and managing manure better (Begna and Wakweya, 2025) [41]. Farmers now have more control over producing livestock and growing crops thanks to the use of intelligent agricultural technologies, which has increased their efficiency and predictability. As a result, smart farming technologies have become more widely used worldwide, and consumer demand for agricultural products has increased (Bollini et al., 2019; Latino et al., 2021) [9, 19].

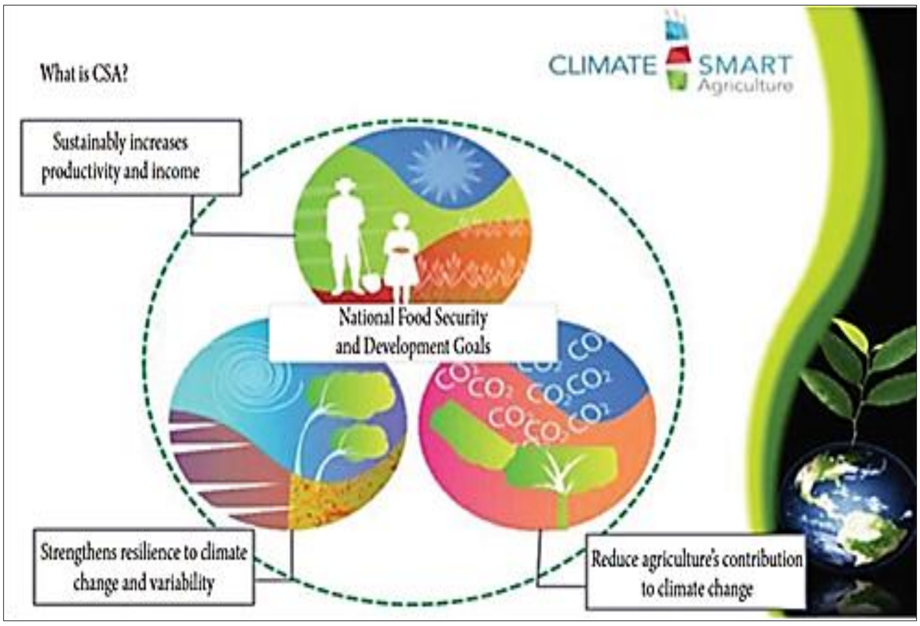

Fig 1: Major Components of Climate Smart Agriculture (FAO, 2016) [13]

The demand for food will probably increase by almost 60% as the world's population is predicted to surpass 9.7 billion by 2050, placing tremendous pressure on agricultural systems to produce more with fewer resources (United Nations, 2017; Roy and Madhekar, 2025) [38, 31]. Experts have pushed for CSA as a result of this worry (Elferink and Schierhorn, 2016) [20]. Crop production needs to rise by 60-100% by 2050 in order to fulfill future food demands. In order to address these global issues and guarantee that agriculture can feed future generations, the shift to more sustainable farming methods is essential (Medhekar, 2024) [21]. Robotics, sensors, and drones are examples of smart agricultural technology that make it possible to optimize resources and control crops precisely. By combining the scientific and agricultural communities, a geospatial cloud framework can support big data analysis for sustainable agriculture (Ayed and Hanana, 2021; Balyan et al., 2024) [6, 7]. These technologies use data analytics, artificial intelligence (AI), and the Internet of Things (IoT) to boost crop yields, optimize agricultural practices, and increase resource efficiency (Hashir et al., 2024) [16]. Enhancing agricultural data systems is essential for managing this time of change, necessitating both institutional and technological innovation. In the changing agricultural landscape, these developments are crucial for addressing food security, environmental effects, and societal transformation. As per Kife et al. (2022) [35], these strategies also seek to improve animal health, lower GHG emissions, increase soil fertility, decrease crop failure, and conserve water. Moreover, CSA incorporates ecological and socioeconomic factors to guarantee that present food production practices do not jeopardize future food production (Antwi-Agyei and Amanor, 2023) [5]. The main technologies and techniques supporting CSA are reviewed in this article, along with the transformation routes needed to scale and integrate them into agricultural systems. With an emphasis on tools like IoT, AI, machine learning, and other cutting-edge breakthroughs and their role in boosting productivity, sustainability, and resilience in farming systems, it also examines how current technology developments are changing agriculture.

2. Tools & Technologies Driving Climate-Smart Agriculture

2.1 Digital & Precision Agriculture Tools

In order to make data-driven decisions, optimize input utilization, improve monitoring, and ultimately increase resilience, digital technologies are being used in agriculture more and more. Agriculture is one of the areas undergoing digital change due to the Internet of Things (IoT). Farmers' opinion of the advantages and readiness to use IoT technology for crop monitoring are positively influenced by their awareness of these technologies. IoT-driven business model innovation for small and medium-sized businesses is a gradual process that includes phases of conception, experimentation, and replication (Paiola et al., 2022) [25]. IoT in agriculture offers insightful data for identifying diseases, crop management, and better decision-making. The transition to more intelligent, productive, and sustainable farming is being driven by sensors. In agriculture, sensors have taken center stage, opening the door for data-driven, eco-friendly methods (Saad et al., 2021) [32].

Use of Internet-of-things (IoT) sensors (for temperature, nutrient status, and soil moisture) and connected systems that provide real-time guidance for fertilizer or irrigation. For instance, IoT/AI frameworks for local weather forecasting and decision support are starting to appear (Das and Nayak, 2024) [11]. IoT-enabled smart irrigation systems can solve agricultural water scarcity and boost crop yields by 25% (Gupta et al., 2020) [15]. Irrigation processes can be remotely monitored and controlled by the system. Optimized irrigation techniques, lower costs, and increased agricultural productivity can result from the use of automated and sensory-based irrigation systems (Obaideen et al., 2022) [24].

In many industries, such as electronics, robotics, automotive, healthcare, environmental monitoring, and more, sensors are essential for collecting data for monitoring, control, automation, and analysis (Alves et al., 2023) [2]. Continuous real-time monitoring of biodiversity and environmental conditions is made possible by integrated platforms that combine sensors, mobile apps, and cloud-based analytics. These systems can offer ecologists and decision-makers new insights while lowering the needs of data processing (Gallacher et al., 2021) [14]. satellite imaging and remote sensing to track soil moisture, crop health, and yield projections. In addition to CSA, assessments of digital agriculture include "remote sensing" and "IoT/AI" as key research areas (Bertoglio et al., 2021) [8].

AI is revolutionizing a number of industries, including healthcare and agriculture. AI-powered solutions for automated cow lameness detection are being developed in dairy farming to improve farm productivity and animal welfare (Siachos et al., 2024) [33]. The development of AI and associated technologies has led to the creation of smart farms, or farming models with high cognitive ability. When compared to conventional techniques, AI-driven agricultural interventions produce measurable improvements in crop management and resource efficiency (Ali et al., 2023) [1]. While no conventional standards were provided, other AI applications reached up to 90% precision in disease diagnosis and 98.4% accuracy in predicting irrigation demands (Tace et al., 2023) [36]. According to Pierre et al. (2023) [27], using AI techniques instead of manual ones in crop management led to a 20% increase in yield and a 0.40% improvement in yield prediction accuracy.

AI and machine learning algorithms provide farmers with information about irrigation systems, fertilizers, herbicides, and seed selections (Nguyen et al., 2021) [22]. AI enables precise decision-making by offering real-time information into crop health, weather patterns, and soil characteristics (Su et al., 2021) [34]. Although AI-based solutions are reasonably priced, businesses must take into account expenses beyond technology, such as business consultation, feasibility studies, data scientists, minimum viable products, deployment, maintenance, and ongoing learning (Tishtykbayeva et al., 2023) [37]. Using automation and sensors, precision irrigation and variable-rate fertilizer application increase productivity and cut waste. For example, the potential and difficulties of such water-smart technology are identified in a comprehensive study of climate-smart irrigation (CSI) in South Asia (Prutzer et al., 2023) [29]. These technologies lower input costs, increase yields and resilience, and utilize fewer resources (water, fertilizer). By lowering emission intensities (per unit output), they also make mitigation possible. Adoption of CSA techniques, for instance, increased household food-security results, according to a micro-study conducted in Kenya (Wekesa et al., 2018) [39].

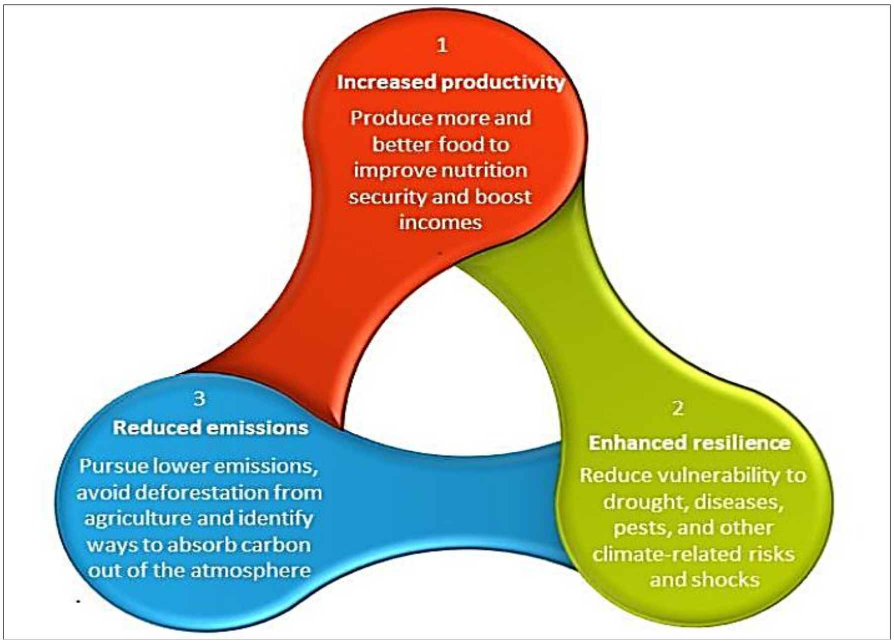

Fig 2: Tripple Win in Climate Smart Agriculture (Nimanka *et al.*, 2022) [23]

2.2 Climate-Resilient Crops & Resource efficient Livestock systems

Breeding, genetics, and resource-efficient livestock systems are examples of biological innovation that are crucial for climate change adaptation. Crop varieties that can tolerate heat, salinity, drought, and floods are crucial. Resilient crop breeding is highlighted as a significant development in CSA in the review by Zhao et al. (2023) [40].

Improved feed and manure management (to lower methane and N2O emissions) and livestock systems tailored to heat stress are becoming more prevalent in CSA. Resilient nutrient management is further aided by advancements in fertilizer technology, such as slow-release, bio-based, and nanofertilizers. The importance of "climate-smart fertilizers" in CSA is highlighted in a recent paper (Nimanka *et al*., 2023) [23]. Improved nutrition systems and resilient genetics stabilize yields under climatic stress, lessen susceptibility, and aid in mitigation through lower emissions per unit output.

2.3 Smart Water & Energy-Efficient Technologies

Energy access and scarcity of water are two of the biggest challenges to agricultural climate change adaptation. Water utilization is optimized when drip and micro-sprinkler irrigation systems are paired with intelligent controls and sensors. Cost-savings, conservation, and obstacles such high upfront costs are included in the review of CSI in South Asia (Prutzer et al., 2022) [29]. In agriculture, machine learning (ML) is being used more and more to improve resource efficiency and decision-making. ML-driven irrigation systems have shown significant productivity increases and water reductions in agricultural agriculture. For example, the AIRA system used k-nearest neighbors (KNN) and neural networks with IoT-enabled soil moisture sensors to optimize irrigation scheduling, leading to significant water reduction and improved plant hydration (Patil et al., 2024) [26]. Water-use reductions of up to 46% have been demonstrated by the use of LoRa-enabled machine learning (ML) systems in various cropping scenarios, according to recent research (Lakshmi et al., 2023) [18]. Concurrently, frameworks powered by support vector machines (SVM) have been created to optimize irrigation pump scheduling, utilizing wireless sensor networks to save labor costs and improve system responsiveness (Priya, 2024) [28]. Furthermore, by predicting irrigation requirements based on soil moisture and meteorological inputs, a cloud-integrated machine learning platform has claimed water savings of more than 50% (Kota et al., 2024) [17].

Infrastructure for harvesting rainwater, solar-powered pumping units, and on-farm renewable energy production are examples of complementary sustainable energy initiatives that increase energy resilience and reduce reliance on fossil fuels. Greenhouse gas (GHG) emissions and operating expenses are decreased by the use of biogas digesters that use agricultural leftovers and energy-efficient equipment. When taken as a whole, these technical advancements improve farm flexibility to energy and climate variability, maintain productivity under environmental stress, and promote the decarbonization of agricultural operations.

2.4 Regenerative Agriculture

Sustainable agricultural advancement requires transformative, system-level strategies that go beyond discrete technological advancements. By combining trees, crops, and animals, integrated land-use models like agroforestry and silvopastoral systems improve biodiversity, stabilize microclimates, and increase carbon sequestration. In addition to increasing production, regenerative agriculture improves soil structure, water retention, and biodiversity, all of which contribute to the restoration of ecosystem integrity. According to recent research, climate-smart agriculture (CSA) needs to go beyond small adjustments in order to accomplish true systemic change (Zhao et al., 2023) [40]. Artificial intelligence (AI) and machine learning (ML) applications are being used more frequently in the livestock industry for computer vision-based animal body weight estimation, early health condition diagnosis in dairy herds, and unmanned aerial vehicle (UAV)-assisted pasture condition monitoring. When combined, these ecological and digital advances promote increased sustainability, resilience, and efficiency in a variety of agricultural systems (Dorea & Menezes, 2024) [12].

3. Transformation Pathways for Scaling CSA

While tools and technologies matter, their large-scale adoption and integration require systemic transformation policy, finance, institutions, capacity and collaboration.

3.1 Enabling Policy and Institutional Frameworks

In order to scale climate-smart agriculture (CSA), strong institutional support systems and policy frameworks are needed. It is essential to have national CSA strategies that clearly link agricultural development with the goals of mitigation and adaptation to climate change. According to Zhao et al. (2023) [40], attaining revolutionary results requires matching agricultural growth pathways with national and international climate goals. Policy tools that promote resource-efficient, low-emission behaviors, such as subsidies, incentives, and regulatory frameworks, are also necessary for effective implementation. Extension and advisory services that spread climate-smart practices via professional training, farmer field schools, and digital extension platforms are equally crucial. However, widespread adoption is still hampered by large knowledge and capability gaps (Anand & Singh, 2023) [3]. The uptake of innovative technologies is highly contingent upon capacity development, digital inclusion, and the contextual adaptation of tools to local needs. As highlighted by Khatun et al. (2025) [4], digital solutions alone are insufficient without parallel investments in farmer training and institutional support.

3.2 Multi-Stakeholder Collaboration and Innovation Ecosystems

To achieve systemic transformation in CSA, dynamic innovation ecosystems must be established rather than relying on discrete technology initiatives. To promote knowledge sharing and coordinated action, cooperation between government agencies, agribusinesses, extension organizations, farmer associations, and research institutions is crucial. According to bibliometric assessments, fragmented initiatives and insufficient inter-organizational links are the major reasons why CSA adoption is still low in many locations (Khatun et al., 2025) [4]. Therefore, strengthening multi-stakeholder collaborations can increase the overall resilience of agricultural systems, improve scalability, and speed up the diffusion of innovation.

Table 1: Adaptation measures for CSA in different Countries (Zhao *et al.*, 2023) [40]

Country	Representative Countries	Major Difficulties	Adaptation Measures for CSA
Developing countries	Maharashtra of India in Asia	• Significant climate risks; • Lack of irrigation water; • GHG emissions.	• Irrigation water management technologies, such as well digging, pipe well, rainwater collection, drip irrigation, and other groundwater extraction methods; • Combined with nutrient management methods, such as farmyard manure, earthworm compost, and straw residue incorporation.
	Mekong Delta of Vietnam in Asia	• Significant climate risks; • Low yield; • GHG emissions.	• Using excellent rice varieties; • Optimizing sowing and harvest dates; • Reducing chemical fertilizers; • Modifying irrigation plans.
	Nepal in Asia	• Significant climate risks; • Low yield; • GHG emissions.	• Adopting management measures, such as no tillage, crop rotation, and straw returning to the field; • Improving soil biological activity, water use efficiency, and soil physical properties.

	Pakistan in Asia	• Significant climate risks; • Low yield; • GHG emissions.	• Use bed seeders and lasers to level the land; • Through using the measures of indirect water use and drainage management, less tillage and fallow, and improved varieties resistant to drought and waterlogging.
	Zambia in Africa	• Significant climate risks; • Low yield; • GHG emissions.	• Protective agricultural measures, such as organic mulching of surface crops in farmlands, rotation of legumes and cereals, and improved crop varieties.
	Malawi in Africa	• Significant climate risks; • Low yield; • GHG emissions.	• Adopting the continuous agroforestry intercropping of two main fertilizer species; • Agroforestry complex system.
	Namibia in Africa	• Significant climate risks; • Low yield; • GHG emissions.	• Collecting nutrient rich earthworm compost hectare; • Carrying out hydroponic cultivation; • Planting mushrooms along the coast of the Namib Desert; • Gathering wood water.
Developed countries	California in the United States	• Flexibility of agricultural system; • GHG emissions; • Production efficiency.	• Upgrading underground water pumps; • Installing drip irrigation or micro sprinkler irrigation systems; • Formulation and implementation of policies.
	France in Europe	• Impacts of climate change on agricultural development; • GHG emissions.	• Paying attention to the service functions of agricultural ecosystems; • Developing precision agriculture.
	Switzerland in Europe	• Impacts of climate change on agricultural development; • GHG emissions.	• Recycling the waste generated by the farm itself to the biogas plant for free; • Production of renewable energy.
	Netherlands in Europe	• Impacts of climate change on agricultural development; • GHG emissions.	• Adopting the LED horticultural technology; • Increase the viability of horticulture.
	Cyprus in Asia	• Impacts of climate change on agricultural development; • GHG emissions.	• Using agricultural robots to spray pesticides on crops; • Strengthening crop protection and production; • Reducing the use of pesticides; • Improving the sustainability of the agricultural environment.

3.3 Emerging Frontiers & Research Directions
The integration of biotechnology and digital breakthroughs is becoming more and more important in climate-smart agriculture (CSA). Hyper-local weather forecasting, real-time farm-level decision support, and predictive analytics through IoT- and AI-based forecasting frameworks are made possible by the confluence of artificial intelligence (AI), machine learning (ML), and Internet of Things (IoT) technologies. Crop types that are both nutrient-efficient and climate-resilient are being developed thanks to parallel advancements in synthetic biology and sophisticated breeding methods. Furthermore, urban and vertical farming types of controlled-environment agriculture are emerging as key components of circular economy strategies, supporting low-footprint and resource-efficient food production systems (Das & Nayak, 2024) [11]. Long-term socioeconomic studies that examine the paths for CSA acceptance, behavioral change, and fair scaling in climate-vulnerable areas are equally important.

4. Conclusion
The development of climate-smart agriculture involves a wide range of innovations in the fields of biology, technology, systems, data, and finance. But these developments by themselves cannot guarantee a low-carbon, resilient, and productive agricultural revolution. Enabling policies, institutional frameworks, capacity building, and cooperative partnerships must all advance concurrently in order to bring about such change. Despite the widespread use of CSA technology, there is still little widespread acceptance, as the literature repeatedly emphasizes, especially among smallholder and drought-affected communities. Incorporating complementing technology and practices into logical, context-specific bundles that are co-designed with farmers and other stakeholders will also be the most successful strategy. These should be supported by trustworthy data and digital infrastructure and integrated into favorable financial and regulatory ecosystems. Through such an integrated approach, CSA can move beyond adaptation to serve as a transformative framework reshaping agriculture into a sustainable, resilient, and low-emission system.

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