



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; SP-9(4): 257-261
Received: 15-02-2026
Accepted: 19-03-2026

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Climate- smart agriculture: AI strategic for climate adaptation and mitigation

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DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i4Sc.5407>

Abstract

Climate-Smart Agriculture has become one of the sustainable solutions to counter the increasing Climate Change challenges to the agricultural systems and food security. The paper is a review article that discusses how Artificial Intelligence can transform the future of climate-smart agriculture by providing effective adaptation and mitigation strategies. The paper discusses the role of AI-based technologies, such as machine learning, Internet of Things (IoT), big data analytics, and remote sensing, in transforming the agricultural practices in terms of data-based decision-making, productivity increase, and resilience to climatic variability. “The paper identifies the use of AI in major fields of crop management, weather prediction, soil and water management, and pest and disease control and shows its ability to assist in adaptive agricultural practices. Also, the contribution of AI to the reduction of climate effects is discussed based on resource optimization, minimization of greenhouse gas emissions, and enhanced sequestration of carbon. Both developing and developed countries have case studies that demonstrate the effectiveness of AI-based climate-smart solutions, and their practical application. Although promising, the review notes that there are numerous challenges such as high implementation cost, lack of infrastructure, data privacy, and the digital divide, which hinders widespread adoption. The paper also highlights the importance of enabling policy frameworks, institutional partnership and inclusive technological innovations that suit the smallholder farmers. To sum up, AI-based climate-smart agriculture presents a new promising direction in agricultural transformation in the future. Through fixing current problems and fostering innovation, AI can play an important role in securing food supply, environmental sustainability and resilience to global climate change.

Keywords: Climate-smart agriculture, artificial intelligence, climate change, precision agriculture, sustainable agriculture, adaptation, mitigation, smart farming

Introduction

Climate-Smart Agriculture (CSA) has become the new approach that should be introduced because of the growing environmental issues that threaten the sustainable development of agriculture. It is aimed at increasing productivity, resiliency, and mitigating greenhouse gas emissions at the same time. The increased interdependence between agriculture and Climate Change has raised food security concerns because of the increased temperature, unpredictable rainfall patterns and extreme weather events that are still destabilising agricultural systems across the globe (Gryshova *et al.*, 2024) ^[1]. These difficulties point to the necessity of new and dynamic solutions. In this regard, Artificial Intelligence has received a lot of notoriety due to its ability to transform contemporary agriculture. Machine learning and predictive analytics, as well as remote sensing, are AI-based technologies that allow making decisions based on data, optimizing the utilization of resources, and enhancing crop management practices (Chavula *et al.*, 2024) ^[2]. Combining AI and CSA principles, one can maximize climate resilience and reduce the environmental effects. The purpose of this review paper is to discuss the use of AI to develop climate-smart agriculture and specifically climate adaptation and mitigation strategies. It also aims to determine the major advantages, issues, and research gaps, which will give an overall idea of how AI can be used to aid sustainable agricultural transformation in a shifting climate.

2. Conceptual Framework

2.1 Climate-Smart Agriculture

Climate-Smart Agriculture is a comprehensive strategy to deal with two issues simultaneously food security and Climate Change. It is founded on three fundamental pillars: productivity, adaptation and mitigation. The productivity pillar is concerned with sustainable growth of agricultural productions and farmers. Adaptation focuses on increasing resilience of farming systems towards climate variability including droughts, floods, and temperature changes (Mandour *et al.*, 2025) ^[3]. Mitigation entails cutting down on the emission of greenhouse gases in agricultural activities, such as the effective utilization of fertilizer, sequestration of carbon and better management of livestock. Combined, the pillars will establish a balanced framework that will promote environmental sustainability and economic viability.

2.2 AI Technologies in Agriculture

Artificial Intelligence in agriculture has been used with a growing pace and has provided new solutions to the complexes in agriculture. Machine Learning (ML) can be used to predict crop yield, disease, and weather. The Internet of Things (IoT) enables real-time control of soil moisture, temperature, and plant

well-being by linking sensors. Big Data analytics involves use of large volumes of data to provide actionable information to guide decision making (Zidan & Febriyanti, 2024) ^[4]. Satellite imagery and drone-based technologies are examples of remote sensing technologies that offer valid data about land utilization, the condition of crops, and environmental transformations. All these technologies contribute to precision agriculture by increasing efficiency, minimizing resources wastage, and aiding informed decisions about managing farms.

2.3 Integration of AI with CSA

The combination of AI technologies and CSA principles will form a data-driven and adaptive system of agriculture. AI facilitates the use of climate-sensitive practices because it allows controlling the use of resources accurately, providing early alerts of extreme weather conditions, and controlling pests and diseases (Arif *et al.*, 2019) ^[5]. This synergy helps to improve the capacity of farmers to act proactively in response to the risks posed by climate and to maximize productivity and reduce environmental footprint. Moreover, AI-based insights can serve as long-term sustainability because they will match agricultural activities with ecological and climatic factors.

Table 1: Key AI Technologies and Their Agricultural Applications

AI Technology	Application Area	Function in Agriculture	Climate Benefit (Adaptation/Mitigation)
Machine Learning	Crop management	Predicts yield, detects diseases	Adaptation
IoT	Soil & water management	Monitors soil moisture and irrigation needs	Adaptation & Mitigation
Big Data	Farm decision-making	Analyzes large datasets for optimized farming	Adaptation
Remote Sensing	Crop monitoring	Tracks crop health using satellite/drone imagery	Adaptation
AI Robotics	Precision farming	Automates planting, spraying, and harvesting	Mitigation
Predictive AI	Weather forecasting	Provides early warnings for climate risks	Adaptation

3. Climate Change Impacts on Agriculture

Climate Change has become one of the greatest threats to the sustainability of agriculture, which has a direct impact on crop productivity and the food systems of the world. Among the biggest consequences is the change in the temperature, which is a factor that changes the growing seasons, shortens the time to maturity of crops, and lowers the yields, especially in crops that are sensitive to heat (Surekha *et al.*, 2026) ^[6]. More heatwaves also contribute to the stress of plants and reduce agricultural production. Another pressing issue is water scarcity which is caused by irregular patterns of rainfall and extended drought periods. The water scarcity has impacts on the irrigation systems and a decrease in soil moisture which lowers crop production

and heightens reliance on unpredictable climatic conditions. Secondly, soil degradation due to erosion and other factors such as nutrient depletion and salinization decreases the fertility of the land and the agricultural productivity in the long term. Climate change also helps in the proliferation and severity of pests and diseases (Uddin *et al.*, 2024) ^[7]. The increase in temperatures and variation in humidity produces good conditions in the growth of destructive insects, pathogens, and weeds, resulting in massive losses of crops. Such interdepending issues eventually jeopardize the food security of the world, by interfering with the stability and dependability of the food production systems.

Table 2: Impact Pathways of Climate Change on Agriculture

Climate Change Factor	Direct Impact on Agriculture	Secondary Effects	Overall Consequences
Rising Temperature	Shortened crop growth cycle, heat stress	Increased evapotranspiration	Reduced crop yield
Irregular Rainfall	Droughts and floods	Water scarcity, soil erosion	Crop failure, unstable production
Extreme Weather Events	Storms, cyclones, heatwaves	Damage to crops and infrastructure	Economic losses
Soil Degradation	Loss of soil fertility	Nutrient depletion, salinization	Long-term productivity decline
Pest & Disease Proliferation	Increased infestations	Spread of invasive species	Higher crop losses
Water Scarcity	Reduced irrigation availability	Overdependence on rainfall	Decline in agricultural output
CO ₂ Concentration Changes	Altered plant growth patterns	Nutritional quality reduction	Food quality issues

4. AI for Climate Change Adaptation

Artificial Intelligence in agriculture is an important way to improve adaptive capacity to Climate Change. The AI-based solutions can help farmers become more proactive to climate variability, to make improved decisions, to use the available resources more efficiently, to reduce the risks of environmental uncertainties. Crop management is one of the major fields where

AI can be of great assistance (Mehta *et al.*, 2023) ^[8]. Using machine learning algorithms, state-of-the-art yield prediction systems use historical and real-time data, including weather, soil, and crop health, to predict the results of production. Besides, AI enables smarter crop decisions by suggesting crop strains resistant to adverse climatic conditions depending on the local conditions, thus minimizing the possibility of crop failure.

In weather prediction, predictive analytics using AI results in more accurate and timely weather forecasting. AI systems can also give early warnings of extreme weather events like drought, floods, and storms by processing large volumes of meteorological data. This allows the farmers to make proactive actions, like setting the planting seasons back or putting up some form of protection measures to minimize possible losses (Devi, 2023) ^[9]. It is also important that AI is used on soil and water management by using precision irrigation methods. Sensors with IoT and artificial intelligence (AI) track soil moisture, weather, and water needs of crops in real-time. This will enable the effective utilization of water thereby minimizing wastage and maximizing the growth of crops despite the water shortage. Also, AI assists in controlling pests and diseases by means of image-detection systems. These systems can detect early infestations or infections using computer vision and deep learning and image data taken by smartphones or drones (Begna & Wakweya, 2025) ^[10]. The early detection allows intervention in time, minimizes damage to crops and limits the distribution of pests and diseases. All in all, adaptive strategies powered by AI can greatly enhance agricultural resilience to a shifting climate.

5. AI for Climate Change Mitigation

The introduction of Artificial Intelligence into agricultural systems has a huge impact on reducing the impact of Climate Change by decreasing greenhouse gas emissions and encouraging the use of resources in a sustainable manner. The reduction of emission by means of input management is one of the major mitigation strategies. The AI-based technologies allow applying fertilizers accurately by examining the nutrient content of the soil, the needs of the crop, and the environmental factors (Kabato *et al.*, 2025) ^[11]. This will reduce excessive use of chemical fertilizers, a significant contributor to the emission of nitrous oxide, and reduce the carbon footprint of farming practices. Also, livestock monitoring systems based on AI monitor the health of animals, their feeding behavior, and productivity, which ensures a reduction of methane emissions due to the enhanced feed efficiency and herd control. Other notable sectors are carbon sequestration, where AI can aid in monitoring and optimizing carbon storage in soil. State-of-the-art algorithms, along with remote sensing and data analytics, are useful in estimating the level of organic carbon in soil and determining appropriate practices like conservation tillage and

cover cropping. Through proper monitoring and control, AI can help to implement carbon-smart farming methods that can be used in mitigating climate in the long term. Moreover, AI maximizes resource use with intelligent energy usage and accuracy agriculture methods (Olatunbosun *et al.*, 2026) ^[12]. Robotic systems maximize the utilization of machinery, irrigation, and energy supplies and minimize fuel use and operational emissions. AI also assists in reducing agricultural waste by enhancing supply chain management and post-harvest management. On the whole, the use of AI in mitigation measures does not only decrease the environmental impact but also helps to promote sustainable agricultural productivity, which implies the balance between economic gains and environmental protection.

6. Case Studies and Applications

The real-life application of Artificial Intelligence to agriculture proves that it holds a great potential in the development of Climate-Smart Agriculture in various geographical settings. The adoption of AI-based solutions to assist smallholder farmers is on the increase in India. Machine learning-driven mobile-based advisory systems are used to give real-time advice on crop choices, irrigation timetable, and pest control (Raza *et al.*, 2023) ^[13]. These tools improve decision-making in unpredictable climatic conditions and increase the productivity of farms and minimize the cost of inputs. Smart farming practices in developed nations like United States and Netherlands are developed and more technologically based. Precision agriculture is applied by farmers on AI-integrated applications, such as autonomous irrigation systems, climate-controllable greenhouses, and yield optimization predictive analytics. These systems are based on the use of big data and remote sensing in order to guarantee efficient use of resources and environmental sustainability (Vishnoi & Goel, 2024) ^[14]. Drones and robotics also contribute to an increase in agricultural productivity and climate resiliency. Application AI-based drones are very popular in monitoring crops, spraying fertilizers and pesticides, and taking high-resolution images of the fields. Likewise, farming robots are used to automate planting, harvesting and weeding, making it less reliant on labor and enhancing precision in operations. These technologies are not only more productive, but also less harmful to the environment because they guarantee targeted use of inputs and minimize wastage (Raihan, 2024) ^[15].

Table 3: Case Studies of AI in Climate-Smart Agriculture

Country	AI Tool/Technology	Application Area	Outcomes/Benefits	Climate Impact
India	AI Advisory Apps	Crop & farm management	Improved farmer decision-making, reduced input costs	Adaptation
United States	Precision Agriculture AI	Irrigation & yield analysis	Increased efficiency, higher productivity	Adaptation & Mitigation
Netherlands	Smart Greenhouse Systems	Controlled environment	Optimized resource use, year-round production	Mitigation
China	AI-powered Drones	Crop monitoring & spraying	Reduced pesticide use, enhanced crop health	Adaptation & Mitigation
Australia	Livestock Monitoring AI	Animal health tracking	Improved productivity, reduced methane emissions	Mitigation
Brazil	Remote Sensing + AI	Land and crop analysis	Better land use planning, reduced deforestation	Mitigation

7. Benefits of AI-driven CSA

Combining Artificial Intelligence with Climate-Smart Agriculture has several advantages that can increase agricultural output and sustainability of the environment. Among the main benefits, there is a higher productivity rate because AI-driven technologies allow strictly monitoring and controlling crops, which results in a higher yield and a better efficiency of farms. With predictive analytics and real-time data insights, farmers are

able to make informed decisions about planting, irrigation, and harvesting (Jimaima *et al.*, 2026) ^[16]. The other major advantage is a more resilient climate. AI technologies enable farmers to embrace the dynamics of the changing climatic conditions by ensuring they have the right weather forecasts, early warnings and suggestions on the type of crops that are resistant to the changing climate. This makes one less susceptible to extreme weather and stability in food production systems is guaranteed.

Moreover, precision agriculture methods are used to optimize the use of resources including water, fertilizers, and pesticides (Wakweya, 2023) ^[17]. Through the efficient use of inputs, AI can lower the cost of operation in addition to alleviating the degradation of the environment, which is conducive to sustainable agriculture.

8. Challenges and Limitations

Although there is a lot of potential, there are a number of challenges to the adoption of AI in agriculture. The lack of infrastructure, especially in rural regions, constrains the access to reliable internet connectivity, electricity, and digital tools required to implement AI. Initial expenses of AI devices, such as sensors, drones, and data platforms, may be out of reach to small and marginal farmers (Ariom *et al.*, 2022) ^[18]. The question of data and privacy are also quite problematic since large amounts of agricultural data are gathered, stored, and processed, which begs the question of who owns them and what their security is. Moreover, the digital divide that exists between developed areas and those that are not developed makes access to solutions that are based on AI uneven. Farmers have limited technical knowledge and are not trained to use these technologies more, which limits their potential to fully utilize them to achieve sustainable agriculture (Barooah *et al.*, 2023) ^[19].

9. Policy and Institutional Framework

The adoption of AI-driven climate-smart agriculture needs to be encouraged with effective policy and institutional support. Governments have a significant role in formulating policies that promote technological innovation, give subsidies and promote the development of digital infrastructure in rural regions (Ishtiaque *et al.*, 2024) ^[20]. The integration of AI into the

agricultural systems can be done with the help of strategic initiatives and public-private partnerships. The contributions of international agencies like the Food and Agriculture Organization play a significant role in terms of offering guidelines, technical support and financial aid towards sustainable agricultural practices. The need to have detailed regulatory frameworks has also been increasing to combat the problems of data governance, ethical use of AI and environmental sustainability. Subsidies, grants, and research and development funding should be used to guarantee inclusive access to AI technologies, especially to smallholder farmers in the developing world (Sarker *et al.*, 2019) ^[21].

10. Future Directions

The next stage of the Climate-Smart Agriculture is the adoption of new high-tech digital solutions, especially Artificial Intelligence, blockchain, and remote sensing. These technologies coming together can produce an efficient, transparent, and data-driven agricultural ecosystem. AI and blockchain can increase traceability, enhance supply chain transparency, and can ensure fair prices to farmers, whereas remote sensing technology can give real-time data on crop health, soil, and climatic changes. The other way forward is inclusive technology development, which is specific to the small and marginal farmers. Bridging the digital divide may be achieved through the affordable, user-friendly AI tools, mobile-based advisory systems, and localized solutions that will facilitate the mass adoption. Moreover, the agricultural models of future should focus on sustainability by intertwining ecology with technology advancement. This involves encouraging agriculture with low carbon use, effective use of resources, and food systems that are resilient and able to endure climate uncertainties.

Table 4: AI-Driven Climate-Smart Agriculture Framework

Component	AI Technology Used	Application Area	Function	Climate Role
Data Collection	IoT Sensors, Remote Sensing	Soil, weather, crops	Real-time data monitoring	Adaptation
Data Processing	Big Data Analytics	Farm decision systems	Data interpretation & insights	Adaptation
Predictive Modeling	Machine Learning	Weather forecasting, yield prediction	Risk forecasting & planning	Adaptation
Precision Farming	AI Robotics, Automation	Planting, irrigation, fertilization	Resource optimization	Mitigation
Decision Support Systems	AI-based Advisory Tools	Farmer guidance	Smart recommendations	Adaptation
Carbon Management	AI + Remote Sensing	Soil carbon tracking	Enhancing carbon sequestration	Mitigation
Supply Chain Optimization	AI + Blockchain	Post-harvest management	Reduce waste & improve efficiency	Mitigation
Monitoring & Feedback	AI Dashboards	Farm performance tracking	Continuous improvement	Adaptation & Mitigation

11. Research Gaps

Although there is a great deal of progress, there are still a number of gaps in the area of AI application in agriculture. The availability of region-specific AI models that take into account local climatic, soil, and socio-economic factors is also limited, which restricts their use in various agricultural environments. Also, there is a lack of long-term research that would enable evaluation of the long-term effectiveness of AI-based interventions to determine their effect on productivity, environmental sustainability, and livelihoods of farmers. Interdisciplinary research which incorporates agriculture, computer science, environmental science and socio-economic studies is also urgently needed to come up with holistic and practical solutions.

12. Conclusion

To sum up, the combination of Artificial Intelligence and Climate-Smart Agriculture is a revolutionary direction of creating sustainable, resilient, and efficient agricultural systems. With the effects of Climate Change becoming more pronounced than ever, solutions to the problem that are innovative and rely on data have now become more important than ever in the agricultural sector. Machine learning, remote sensing, and predictive analytics are examples of AI-powered technologies that have proven to be effective in increasing crop yields, improving resource use, and enhancing the resilience of farmers to climatic uncertainties. In addition to enhancing productivity, AI also plays an important role in ensuring climate resilience through early warning initiatives, precision agriculture, and

informed decisions. It also facilitates mitigation process by cutting the emission of greenhouse gases by efficient use of fertilizers, and energy and sustainable livestock practices. These advantages (cumulatively) underscore the key role of AI in the realization of the main goals of climate-smart agriculture, namely, productivity, adaptation, and mitigation. Nevertheless, the vast potential has to be challenged by a number of issues to be resolved to facilitate its widespread adoption. The constraints in infrastructure, high implementation, lack of technical skills, and issues to do with data privacy and ownership remain a hindrance to the development, especially in developing countries. Inclusive agricultural transformation requires bridging the digital divide and making it accessible to small and marginal farmers. To proceed, there is a need to have a robust policy framework, more investment in research and development, and joint government, business, and international organizations. Further effectiveness will be increased by promoting the implementation of capacity-building initiatives and creating region-specific AI solutions. In general, AI-based climate-sensitive agriculture has enormous potential in guaranteeing the global food security as well as promoting environmental sustainability in the face of a fast climatic change.

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