CHAPTER-9

CLIMATE SMART AGRICULTURE AND DIGITAL INNOVATIONS: TRANSFORMING SUSTAINABLE AGRICULTURE FOR A RESILIENT FUTURE

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Abstract

Climate change, environmental degradation, water scarcity, loss of biodiversity and the growing demand of food by an increasingly populated global population are all contributing to the most critical change in human history; agriculture. Agricultural sector is not only a victim of climate change but also a contributor to climate change. The Food and Agriculture Organization (FAO) estimates that almost a quarter of global greenhouse gas emissions, including land use, livestock, and other activities, is attributed to agriculture. Meanwhile, between 1991 and 2021, which equates to nearly US$ 123 billion per year, climate-related disasters, including droughts, floods, cyclones, heat waves, and pest outbreaks caused an estimated global agricultural loss of US$ 3.8 trillion between 1991 and 2021.

These issues have rendered Climate Smart Agriculture (CSA) a worldwide focus in the quest to attain food security, sustainability, and climate resilience. The pillars of Climate Smart Agriculture are grounded on three major pillars, namely: sustainably increasing agricultural productivity and income, strengthening adaptation and resilience to climate change, and reducing or eliminating greenhouse gas emissions wherever possible. At the same time, digital innovations (Artificial Intelligence (AI), Internet of Things (IoT), precision agriculture, remote sensing, drones, block chain, Geographic Information Systems (GIS), machine learning, robotics, and digital extension services) are changing the agricultural scene by allowing the use of data-driven and efficient farming practices. India is highly vulnerable to monsoon dependency, the fractured landholdings, the dwindling groundwater reserves, and the increased climate uncertainty.

In this chapter, it is discussed that how Climate Smart Agriculture and digital innovations can be integrated as a sustainable agricultural transformation pathway. The research is founded on the secondary data gathered by FAO, IPCC, World Bank, World Economic Forum, IFPRI, ICAR, and recent Scopus-indexed journals. The results indicate that digital technologies can substantially enhance the efficiency of irrigation, pest control, weather prediction, yield forecasting, reduction of the carbon footprint, and profitability in the farm. Nonetheless, various policies like digital inequality, lack of connectivity in rural areas, low digital literacy, and high costs of technology, fragmented policy frameworks, and weak institutional support are still limiting widespread adoption, especially among smallholder farmers.

Keywords Climate Smart Agriculture, Digital Agriculture, Precision Farming, Artificial Intelligence, Sustainable Agriculture, Climate Resilience

1. Introduction

Agriculture has been the core of economic growth, food security and rural livelihoods all over the world. Nevertheless, the 21st century has posed unprecedented threats to the sustainability of agriculture. Climate change continues to disrupt agricultural systems by increasing the temperatures, shifting rainfall patterns, extended droughts, floods, soil erosion, pest infestation, dwindling ground water levels and loss of biodiversity. According to the Intergovernmental Panel on Climate Change (IPCC), the global temperatures might increase to 1.5oC-2oC by the year 2050 assuming that current trends in emissions are maintained and severely affecting agricultural productivity particularly in the developing countries. Research has shown that, with a rise in temperature of 1 C, the yield of wheat could decrease by an average of 6% and the yield of rice and maize could be significantly reduced.

Climate change, environmental degradation, water scarcity, biodiversity loss, and the rising demand of food by the rapidly growing global population are posing one of the most critical transitions in human history facing agriculture. Agricultural sector is a victim and a contributor of the climate change. The Food and Agriculture Organization (FAO) indicates that production of agricultural products contributes almost 22 percent of the global greenhouse gas emissions when land use, livestock, and other related activities are included. Simultaneously, the estimated total global agricultural loss of US 3.8 trillion in 1991-2021 or almost US 123 billion an annum, caused by climate related calamities like droughts, floods, cyclones, heat waves and pest outbreaks. Meanwhile, the global food demand is set to rise by almost 60 percent by 2050 because of the population growth and urbanization. This poses a paradox: agriculture has to work harder to yield greater food with less resources and to minimize its own environmental footprint.

Agriculture is currently absorbing about 70 percent of the world freshwater resources and contributing immensely to greenhouse gas emissions through the emission of the greenhouse gas methane by livestock, the emission of the greenhouse gas nitrous oxide by fertilizers, and the emission of the greenhouse gas carbon by land-use changes. Conventional agricultural methods can no longer be effective in dealing with these interrelated issues. To counter this, Climate Smart Agriculture (CSA) has sprung up as a game changer strategy that will aim to enhance productivity, resilience, and reduction of emissions at the same time. CSA, which was introduced by the Food and Agriculture Organization (FAO), is an all-encompassing model of sustainable agricultural development. In parallel to it, digital transformation is transforming agriculture with such technologies as Artificial Intelligence (AI), Internet of Things (IoT), drones, block chain, remote sensing, machine learning, robotics, and mobile-based extension services. These technologies allow making decisions in real-time, using precision inputs, and managing climate risks more effectively.

The combination of Climate Smart Agriculture with digital technologies is a new paradigm that is also known as Smart Sustainable Agriculture or Digital Climate-Smart Farming. This paper explores this cross-section and assesses its importance to the future of agriculture.

2. Review of Literature

Reviews of literature related to the study are as follows:

Peattie and Crane (2005) had highlighted that the way to achieve sustainability in production systems involves a shift between the traditional models of productivity and traditional models of sustainability in production systems. Their arguments formed the basis of sustainable agricultural setups.

Lipper et al. (2014) defined as an integrated approach to managing landscapes that address both food security and climate issues. They emphasized the significance of productivity, adaptation and mitigation.

Wolfert et al. (2017) talked about how big data, smart sensors, and digital platforms can be used to develop intelligent farming systems and highlighted the significance of technology adoption in farming being centered on farmers.

Campbell et al. (2018) argued that CSA needs to go beyond policy rhetoric and provide measurable results at the farm level using scientific tools and reforms in the institutions.

Klerkx, Jakku, and Labarthe (2019) emphasized that digital agriculture has the potential to enhance efficiency and sustainability in agriculture by reducing information asymmetry and providing interventions based on precision.

Ahmed and Shakoor (2025) have found out that AI, IoT, and precision technologies enhance yield forecasting, irrigation efficiency, pest control, and carbon monitoring, and thus they are highly applicable when it comes to the adoption of CSA.

Mollel et al. (2025) discovered that digital agriculture in Africa has shown a significant enhancement in the resilience of next-generation farmers, however, the uptake of digital agriculture in Africa has been limited due to infrastructure and cost of access.

The argument about the digital innovation reinforcement of practical implementation of Climate Smart Agriculture has strong points in the literature.

3. Research Gap

Whilst there is a lot of literature on Climate Smart Agriculture, and digital agriculture as a concept, there is very little literature that looks at the concept of digital agriculture and its integration with Climate Smart Agriculture, especially within the Indian context using recent global evidence and policy implications. This paper tries to fill this gap by examining CSA and digital innovations as an integrated model of sustainable agricultural transformation.

4. Study Objectives

1. To analyse the role of digital innovations in agricultural modernization
2. To study the integration of climate- smart digital agriculture and digital technologies
3. To assess the impact of climate-smart digital agriculture on traditional agriculture

5. Research Methodology

In conducting the present study, descriptive, analytical and exploratory studies were used and secondary data sources were utilized. This study seeks to explore the synergy between Climate Smart Agriculture (CSA) and digital innovations, and assess how they contribute to climate resilience, agricultural sustainability, productivity, and lower resource use. A research method and approach that is systematic and based on evidence have been used to make sure that it is reliable, relevant and academic.

5.1. Sources of Data

Secondary data was gathered from dependable national and international organizations, research institutions, policy reports and peer-reviewed academic publications. The major sources are Food and Agriculture Organization (FAO), Intergovernmental Panel on Climate Change (IPCC), World Bank, World Economic Forum (WEF), International Food Policy Research Institute (IFPRI), Indian Council of Agricultural Research (ICAR), Government of India, Ministry of Agriculture and Farmers Welfare, and other official databases. Also, recent literature was reviewed from Scopus-indexed journals and reputed academic publishers like Emerald, Springer, Elsevier, Taylor & Francis, Wiley and MDPI.

5.2. Time Period of the Study

The study primarily relies on data and literature from the last seven years (2020 to 2026) to ensure that the information is relevant and reflects the latest advancements in climate-smart agriculture, precision farming, digital agriculture, and policy measures. Wherever necessary, historical materials and basic studies were used to give theoretical and conceptual support.

5.3. Research Design

The study employs descriptive and analytical research design. The concepts, dimensions, technologies and policy frameworks of CSA and digital agriculture have been explained using a descriptive approach. The analytical approach has been applied to interpret the trends, traditional and smart agriculture systems comparison, and the effectiveness of digital technologies in improving agricultural outcomes.

5.4. Tools and Techniques Used

The study employed several qualitative and analytical techniques such as comparative analysis, trend analysis, and conceptual framework analysis, and descriptive interpretation, tabular and thematic analysis. The value of traditional agriculture, Climate Smart Agriculture, and digital farming practices was compared through the use of comparative analysis. Trend analysis was used to reveal change and development over time regarding agricultural technologies, climate related risks and the adoption of digital technologies. A conceptual framework analysis was employed to grasp the interconnections between Climate Smart Agriculture and digital innovations. Descriptive interpretation helped to organize and interpret the findings systematically and meaningfully. Furthermore, the data were analysed tabular and thematically to present the data in a good manner. Incorporating tables, indicators, and statistical evidence enhanced the clarity, interpretation and analytical quality of the study.

6. Result and Discussions

6.1. Climate Smart Agriculture (CSA): Concept and Dimensions

Climate Smart Agriculture is a type of agricultural system that is capable of maximizing productivity, enhancing climate change resilience and reducing emissions of greenhouse gases whenever feasible. FAO pinpoints three pillars of CSA, which are very big (Food and Agriculture Organization, 2025; Chandra et al., 2018):

1.6.1 Pillar I: Sustainable Rise in Productivity

The first pillar of Climate smart Agriculture (CSA) is concerned with the sustainable growth of agricultural productivity and farm income without degradation of natural resources such as soil, water and biodiversity. The bottom line is to generate food more to serve the increasing population demand and not to damage the environment. This involves use of better seed varieties that will yield higher and have better resistance against pests and diseases. Precision nutrient management assists farmers to apply fertilizers in appropriate amount and at the appropriate moment, helping farmers to reduce the amount of fertilizer wasted. Drip and sprinkler irrigation are effective types of irrigation systems that conserve water and enhance crop productivity. Greenhouses and poly houses, which are also known as protected cultivation, protect crops against unfavorable weather conditions and enhance crop productivity. Integrated farming systems are a combination of crops, livestock, fisheries and other farm activity to enhance income stability and resource efficiency.

6.1.2. Pillar II: Adaptation and Resilience

The second pillar of CSA focuses on adapting and becoming resilient to climate change by assisting farmers to adapt to climate variability and extreme weather conditions like droughts, floods, heat waves and irregular rainfall. The purpose of this pillar is to make agricultural systems less susceptible to climate shocks and to increase the capacity of agricultural systems to withstand climate shocks. Drought tolerant varieties of crops are used in order to ensure crop productivity even in case of water stress. Diversification of crops will decrease dependence on one crop and minimize risk of production. Harvesting of rainwater enhances supply of water in dry times and increases sustainable irrigation. Weather forecasting systems are systems that will provide timely data regarding rainfall, temperature, and storms, among others, so that farmers can make better decisions. Agroforestry, a combination of trees and crops and livestock, enhances the fertility of the soil and gives extra income. Crop insurance safeguards farmers financially against crop losses due to natural calamities, and climatic uncertainties.

6.1.3. Pillar III: Reduction of Greenhouse Gas Emissions

The third pillar of CSA is a reduction in the greenhouse gas emissions in agriculture and an increase in carbon sequestration in order to help in supporting the environmental sustainability. Livestock, the application of fertilizers and changes in land use contribute to the discharge of methane, nitrous oxide and carbon dioxide by agriculture. CSA fosters activities that reduce these emissions and do not diminish productivity. Less tillage will help to maintain carbon in the soil and will cut fuel consumption in agriculture.

Wetting and drying rice in alternate manner reduces methane emission due to the reduction of continuous flooding. Livestock methane management enhances feeding and manure management towards minimization of gaseous emissions. Organic farming minimizes the need to use chemical fertilizers and enhances the well-being of the soil. Carbon farming promotes activities which accumulate carbon in soils and plants. The use of bio char enhances soil fertility and the biochar traps carbon and removes it over time. The practices assist in making agriculture play a role in climate change mitigation as well as assist in supporting sustainable production.

6.2. Digital Innovations in Agriculture

Digital agriculture is the use of modern technologies to enhance farming efficiency, sustainability, productivity and profitability. It denotes the process of the modernization of the traditional farming to smart farming through application of data-driven tool and advanced information systems. These technologies assist farmers to make timely and correct decisions on irrigation, fertilization, pest management, crop management, and market access. Digital innovations minimize wastage of resources, reduce production costs, enhance quality of yield and increase climate resilience. Digital agriculture has gained significance in the context of climate change and the growing food demand, as an indispensable element of sustainable agricultural development (Bertoglio et al., 2021;

Sponchioni et al., 2019; Aleixandre-Tudo et al., 2018; Pallottino et al., 2018; Rose & Chilvers, 2018).

6.2.1. Artificial Intelligence (AI)

Artificial Intelligence (AI) has a significant role in the contemporary agriculture as it allows making smart decisions by analyzing data and predicting models. Crop yield forecasting, disease diagnosis, pest detection, weed management, and weather forecasting are some of the AI applications. Machine learning algorithms examine both previous and current data to draw certain patterns and give correct recommendations. AI assists farmers to make proactive steps before the damage of crops takes place and, therefore, enhance productivity and minimize losses.

6.2.2. Internet of Things (IoT)

The Internet of Things (IoT) is defined as the usage of interconnected gadgets and sensors that gather real-time data about farms. These sensors will help in monitoring soil moisture, nutrient levels, and temperature, humidity, rainfall, and irrigation requirements. Farmers to optimize their water use, their fertilizer applications and the management of their crops can use this data. Smart irrigation systems based on IoT are more efficient in the use of water and decrease unnecessary input use, making agriculture more sustainable and more cost-effective.

6.2.3. Remote Sensing and GIS

Geographic Information Systems (GIS) and remote sensing are potent instruments that are applied in the monitoring of agricultural lands and the environment. Satellite imagery assists in detecting droughts, crop conditions, vegetation growth, and land-use changes as well as pest outbreaks over wide regions. GIS helps in mapping and analyzing field conditions for better planning and decision-making. These technologies facilitate accuracy farming and enhance climate risk management (Mulla, 2013).

6.2.4. Drones and UAVs

Drones and Unmanned Aerial Vehicles (UAVs) find application in the agricultural sector to aerial spray them, monitor their positions, map their locations, and identify diseases. They offer high-resolution images of fields, and allow the detection of issues such as nutrient deficiency, pest attacks, and water stress at an early stage. Drones save time, cut down the cost of labor and enhance the precision of the farm activity.

6.2.5. Block Chain

The block chain technology enhances transparency, traceability, and trust in the agricultural supply chains. It documents all the steps of production, processing, transportation, and marketing in a safe digital system. This not only guarantees food safety, curbs fraud, and assists consumers to confirm the quality and origin of agricultural products. Block chain is also useful in increasing the market and making the farmers more confident (Maditati et al., 2018).

6.2.6. Robotics and Automation

Labor-intensive agriculture practices like planting, harvesting, sorting, weeding, and greenhouse management are being transformed by robotics and automation. The automated machines enhance speed, accuracy, efficiency, and less reliance on manual labor. Agricultural robots are used in areas with a shortage of labor to ensure that the production is not decreased, and the operation cost is not increased.

6.2.7. Mobile Advisory Services

Mobile advisory service is a service that helps farmers to access up to date weather information, mandi rates, disease alerts, government scheme news and even expert consultancy through smart phones and mobile applications. These services are particularly helpful in the rural regions where small and marginal farmers are in need of accessing information promptly so that they can manage their farms better. The mobile-based platforms enhance awareness and facilitate decision-making in time (Ofosu-Ampong et al., 2025).

6.2.8. Big Data Analytics

The Big Data Analytics is the process of collecting and analyzing large amounts of agricultural data on the sensors, satellites, weather stations, and farm records. The technology assists in predictive agriculture by pointing out trends, foreseeing risks, and optimizing the usage of resources. It assists in enhancing productivity, minimizing uncertainty, and reinforcing long-term planning of farms. Policy decisions and sustainable management of agriculture are also supported by big data (Weersink et al., 2018).

6.3. Combination of CSA and Digital Innovations

Climate Smart Agriculture (CSA) and digital innovations integration is a contemporary way to attain sustainable, productive and climate resistant agriculture. Climate Smart Agriculture has three broad aims, which include; enhancing agricultural productivity, to enhance adaptation and resiliency to climate change, and to reduce greenhouse gas emissions. Digital innovations will offer the technological back up that will enable the realization of these objectives more effectively and efficiently.

Excessive water consumption, imbalanced fertilizer use, late detection of pests, low productivity, and inadequate preparedness to climate change are some of the challenges that may be encountered in traditional farming methods. Farmers will be able to make improved decisions based on real-time information and scientific analysis through integration of digital technologies like Artificial Intelligence (AI), Internet of Things (IoT), drones, remote sensing, Geographic Information Systems (GIS), block chain, and mobile advisory services. To use the example of soil moisture, temperature, and nutrient levels, the IoT sensors can assist in monitoring and controlling the levels of water, fertilizers, and other substances applied to the soil (Muangprathub et al., 2019). This will help in achieving the CSA objective of sustainable productivity and conservation of resources. The use of AI-based weather forecasting systems and pest prediction systems help farmers prepare against droughts, floods, pest attacks, and disease outbreaks, and enhance climate adaptation and resilience. With drones and satellite imaging, it is possible to monitor crops and conduct precision farming, minimizing the use of inputs and lowering the impact on the environment.

GIS and remote sensing can be used in land-use planning, drought monitoring, and assessment of crop health across extensive regions. This enhances risk management and aids policy makers to formulate superior agricultural policies. Mobile advisory services deliver real-time weather alerts, mandi prices, crop protection advice, and information on government schemes to farmers, particularly to small and marginal farmers. The block chain technology enhances the supply chain in the agricultural industry and provides food safety and equitable market access. Robotics and automation decreases labor reliance and enhances operational effectiveness in planting, harvesting, and management of greenhouse.

The digital innovations and CSA also significantly contribute to the reduction of greenhouse gas emissions. Precision farming helps to minimize unnecessary use of fertilizers; alternate wetting and drying in rice fields helps to reduce methane emissions, and solar-powered irrigation systems can reduce reliance on fossil fuels. These are used to favor low-carbon and environmentally sustainable farming. Some of the initiatives in India that promote this kind of integration include the Digital Agriculture Mission, PM-KUSUM, NICRA, Soil Health Card Scheme and PMFBY. These initiatives integrate climate resilience with the adoption of new technologies to enhance the income of farmers and the sustainability of agriculture. Nevertheless, adoption is still influenced by challenges like high technology prices, poor connectivity in rural areas, low digital literacy and low awareness. Thus, effective implementation requires strong policy support, access to affordable technologies, training of farmers, and public-private partnerships. Digital tools are rolled out, which reinforces the CSA.

The table 1 clearly demonstrates that integration of Climate Smart Agriculture (CSA) practices with digital tools enhances agricultural efficiency, sustainability and climate resilience. Dynamical water-efficient irrigation, IoT, and Artificial Intelligence helps farmers to monitor the water level and water needs in the fields in real time, which reduces water consumption and improves water conservation. It is particularly crucial in areas where the groundwater is being depleted, and the water scarcity is present.

Table 1: Integration of CSA and Digital Innovations

CSA Practice	Digital Tool	Outcome
Water-efficient irrigation	IoT + AI	Reduced water usage
Pest and disease control	Drones + AI	Early detection
Crop diversification	GIS + Remote sensing	Better planning
Nutrient management	Precision farming	Lower fertilizer use
Weather adaptation	Mobile advisories	Better preparedness
Emission monitoring	Satellite + Carbon analytics	Lower carbon footprint

Source: FAO, IPCC and World Bank

In controlling pests and diseases, early discovery of crop illnesses and pest attacks before significant damage can be caused to the crop is made possible using drones and artificial intelligence (AI). This assists farmers in making timely preventive action, minimizes losses in crops and excessive pesticide use. In crop diversification, GIS and remote sensing are used to assist in better planning in that they provide satellite-based information about the soil conditions, the land use, and the crops that are most appropriate in certain areas. Precision farming is more effective in managing nutrients as the fertilizers are applied where they are most required and in the right amount. This will result in reduced fertilizer application, lower production costs and healthier soil. Mobile advisory services are also crucial in weather adaptation as it provides real-time weather forecasts, rainfall alerts, and farming recommendations, which enhance the preparedness of the farmers against climate related risks like drought and floods.

6.4 Impact of Climate Smart Agriculture (CSA) and Digital Innovations on Agriculture

Digital innovations and Climate Smart Agriculture (CSA) have greatly transformed how modern farming is conducted, by enhancing productivity, lowering the cost of inputs, preserving the natural resources and increasing resilience to climate change. Analysis of FAO, World Bank, ICAR and recent research studies clearly demonstrate that the combined use of CSA practices and digital technologies, including Artificial Intelligence (AI), Internet of Things (IoT), drones, remote sensing, precision farming and mobile advisory systems, have strong positive impacts on farmers and the agricultural economy.

Table 2: Impact of CSA and Digital Innovations on Traditional Agriculture

Indicator	**Traditional Agriculture**	**CSA + Digital Innovation**	**Improvement**
Water Use Efficiency	Low	High	20–40% water saving
Fertilizer Consumption	High	Controlled	15–25% reduction
Crop Yield Stability	Uncertain	Improved	10–20% increase
Pest Detection	After damage	Early detection	Reduced crop loss
Irrigation Efficiency	Moderate	Very High	Up to 50% improvement
Weather Preparedness	Weak	Strong	Better climate adaptation
Greenhouse Gas Emissions	High	Lower	Reduced carbon footprint
Farmer Income	Unstable	More stable	Higher profitability

Source: FAO, IPCC and World Bank

This above table will be providing a clear indication of the magnitude of positive effect of Climate Smart Agriculture (CSA) and digital innovations on traditional agriculture. It demonstrates that the adoption of modern technologies including Artificial Intelligence (AI), Internet of Things (IoT), precision farming, drones and mobile advisory services enhance the efficiency of farming and farming sustainability and farmer profitability. Traditional agriculture has low efficiency of water use because of the irrigation practices that are not controlled and the absence of proper monitoring. Nevertheless, with CSA and digital innovations like IoT-based smart irrigation system and soil moisture sensors, the water use efficiency is high, which leads to the saving of 20-40 percent of water usage. This is particularly necessary in regions where there is depletion of groundwater and shortage of water.

The use of fertilizer in traditional agriculture is normally excessive since farmers usually use fertilizers without appropriate scientific advice. With CSA and digital farming, the usage of fertilizers is managed by precision nutrient management, which will reduce the utilization of fertilizers by 15 to 25 percent. This not only reduces the cost of production but also enhances the health of the soil and also decreases the amount of pollution to the environment. The stability in crop yield in conventional farming is still uncertain because of climate risks, attacks of pests, and inadequate planning of the farms. CSA practices, including climate-resilient seeds and crop diversification, as well as AI-based forecasting, enhance yield stability and can grow productivity by 10 -20 percent. This gives improved income security to farmers.

In traditional agriculture, pest detection usually only takes place when there is evident harm to crops, which results in increased losses. With drones, satellite surveillance, and AI-based systems to predict diseases, early detection can be achieved, which will reduce losses of crops and limit the use of pesticides.

The efficiency of irrigation with smart irrigation systems is being significantly enhanced (between 50 and 100 percent) compared to moderate efficiency. This will help in water management, and sustainable farming will be supported. The weather preparedness is poor in traditional farming as farmers base their preparation largely on guesswork and experience. Preparedness is robust with mobile advisory services and AI-based weather forecasting, which provide the relevant information on rainfall, temperature variations, droughts, and floods. This assists farmers in the preventive measure and enhances climate adaptation.

In traditional farming, emissions of greenhouse gases are usually high because of excessive use of fertilizers, constant flooding in rice field, and irrigation, which uses diesel. Precision farming, alternate wetting and drying, and solar irrigation are examples of CSA practices that reduce emissions and decrease the carbon footprint of agriculture. The farmer income in traditional farming is usually not stable due to uncertainty in yields, high cost of inputs and risk in climate. Through CSA and digital innovation, income is more stable because of improved productivity, less loss, less cost and improved market access leading to higher profitability.The table 3 reveals the serious effects of climate related disasters on the world agricultural activities and the urgent necessity of Climate Smart Agriculture (CSA) and sustainable farming practices. Climate change has emerged as one of the largest threats to agricultural productivity, food security and rural livelihoods of people all over the world.

An estimative figure to the total agricultural losses incurred by the global agricultural sector is US$ 3.8 trillion, which reflects the enormous economic toll being suffered by the global agricultural sector because of climate-related disasters. This colossal loss encompasses damages to crops, livestock, fisheries, forestry, irrigation systems and rural infrastructure, because of extreme weather events over the years. The average annual loss of US 123 billion means that agriculture is seriously damaged financially on a yearly basis due to the impact of climate shocks. This indicates that climate change is not a one-time problem but an ongoing and an increasing challenge that affects the productivity of farms and income of farmers across the globe. The loss of nearly 5 percent of agricultural GDP due to climate-related disasters has an overall impact on the economies of the countries, more so in the developing countries where agriculture is a significant source of employment and income. The direct consequence of this loss is food supply, rural employment, and poverty reduction efforts (Food and Agriculture Organization, 2025).

Table 3: Global Agricultural Losses Due to Climate-Related Disasters

Particulars	Value
Total Agricultural Losses	US$ 3.8 Trillion
Average Annual Loss	US$ 123 Billion
Share of Agricultural GDP Lost	Nearly 5%
Most Affected Regions	Asia and Africa
Major Causes	Droughts, Floods, Cyclones, Heat waves

Source: FAO, IPCC and World Bank

The most affected regions are Asia and Africa because these regions depend heavily on agriculture for livelihoods and often have limited access to advanced technology, irrigation systems, crop insurance, and climate adaptation measures. Small and marginal farmers in these regions are particularly vulnerable due to limited financial resources and weak institutional support. The major causes of these losses include droughts, floods, cyclones, and heat waves. Drought reduces water availability and crop yields, floods destroy standing crops and fertile land, cyclones damage infrastructure and plantations, while heat waves reduce productivity and increase livestock stress. These extreme events are becoming more frequent and intense due to global climate change.

The table 4 shows that agriculture and the consumption of water are strongly related to digital innovations. Climate Smart Agriculture (CSA) can be used to effectively manage water use. Water is a highly valuable resource to agriculture and sustainable use is vital to long-term food security and environmental protection (World Economic Forum, 2025).

Table 4: Agriculture and Global Water Consumption

Particulars	Percentage
Share of Freshwater Used by Agriculture	70%
Water Saved through Smart Irrigation	20–40%
Increase in Irrigation Efficiency	Up to 50%
Reduction in Groundwater Overuse	Significant

Source: FAO, IPCC and World Bank

According to the table, agriculture is the biggest water user in the world, as it consumes almost 70 percent of the world resources of freshwater. Conventional irrigation processes like flood irrigation usually led to heavy wastage of water, low efficiency and high depletion of underground water. This poses serious problems particularly in those countries where agriculture is mainly based on irrigation and ground water resources. When farmers switch to the use of smart irrigation systems including drip irrigation, sprinkler systems, IoT-based soil moisture sensors, and AI-based irrigation scheduling, they can save a lot of unnecessary water usage. According to the table, the water savings due to smart irrigation is between 20 and 40 percent. This implies that farmers may achieve identical or even greater crop yields with far less water, enhancing their productivity and sustainability. The fact that digital technologies have increased the efficiency of irrigation by up to 50 percent indicates that the use of digital technologies makes the application of water more accurate and scientific. The farmers are able to administer appropriate quantity of water during appropriate time as required by crops. This will help decrease water stress and enhance crop health.

The table further says that there has been a drastic decline in the overuse of groundwater. Over ground water pumping has led to the declining water table and water scarcity in the long run in many agricultural areas. Intelligent irrigation methods can be used to conserve groundwater and to make it available to the future generation. Altogether, the table makes it clear that Climate Smart Agriculture and digital irrigation technologies are the key to improving the efficiency of water-use and decreasing the environmental pressure. The effective water management is not only conducive to the increased agricultural output but also increases the resilience of the climate and contributes to sustainable agricultural growth.

Table 5: Impact of Precision Farming on Input Efficiency

Particulars	Traditional Farming	Precision Farming
Fertilizer Use	High	Reduced by 15–25%
Pesticide Application	Excessive	Reduced through targeted spraying
Crop Monitoring	Manual	Real-time monitoring
Input Cost	High	Lower
Yield Stability	Uncertain	Improved

Source: FAO, IPCC and World Bank

As it is clearly indicated by the table 5, precision farming has a large positive contribution to the input efficiency relative to the traditional methods of farming. Modern technologies used by precision farming include GPS, IoT sensors, drones, Artificial Intelligence (AI), and remote sensing to apply farm inputs more precisely and efficiently. This enhances productivity as well as cutting down the unwanted expenses and environmental harm.

The use of fertilizers in traditional farming is generally high since fertilizers are usually applied across the entire field without considering the actual nutrient requirements of the various fields. In precision farming, the application of nutrients is cut by 15-25 percent since the nutrients are applied only where they are needed and in the correct quantity. This assists in reducing the cost of production, enhancing the health of the soil, and decreasing the amount of chemicals polluting the soil. The application of pesticides in conventional farming is in most cases excessively used since farmers apply them to all their fields as a preventative measure even without the presence of pests. Precision farming involves specific spraying of drones and sensor-based monitoring, which minimizes the needless use of pesticides. This is more effective in protecting crops and lessening environmental damages and health hazards.

Traditional farming methods involve crop monitoring, which is done manually, which is time consuming and may lead to late detection of diseases, pests, or lack of nutrients. Drone, satellite, and smart sensors are real-time monitoring tools that enable farmers to identify and address issues at the earliest stage in precision farming. This enhances decision-making and minimizes losses of crops. Input cost in traditional agriculture is usually high due to excessive use of fertilizers, pesticides, water, and labor. Precision farming reduces the cost of inputs by making the best use of resources and enhancing efficiency. The upfront costs can be expensive but in the end, operational costs would be less and profitability would be higher. The traditional farming is still uncertain in terms of climate risks, inadequate monitoring, and unscientific input management in ensuring yield stability. Precision farming enhances stability of yields by guaranteeing enhanced crop health, balanced nutrition and timely intervention. This will result in increased regular production and enhancement of farmer earnings.

Altogether, the table demonstrates that precision farming is an important element of Climate Smart Agriculture as it enhances efficiency, decreases wastage, improves sustainability, and increases resilience to climate challenges. It changes the face of agriculture, where agriculture has always been a case of guessing, but now it becomes an issue of science and data and agriculture becomes a case of scientific data farming.

The adoption level of various digital agricultural technologies and their key advantages in enhancing the efficiency and sustainability of farming are presented in the table 6. It points out that some technologies are highly used by farmers, yet still others have low adoption rates because they are very expensive, there is lack of awareness and there is lack of rural infrastructure.

The adoption level of mobile advisory services is high because they have low costs, are user friendly and can be offered to small and marginal farmers through mobile phones. These services also offer real-time weather forecasts, mandi prices, pest warnings, and consultations with experts, which can help farmers, make timely and informed decisions. This has rendered mobile advisory platforms one of the most successful digital innovations in agriculture. The adoption level of Soil Health Cards is moderate as well as it is significant in promoting the scientific use of fertilizers. They assist farmers know the nutrient status of soils, and use fertilizers in the right amount, preventing unnecessary use of chemicals and improving soil fertility. Nonetheless, their full effectiveness is diminished by a lack of awareness and inconsistent following up.

Table 6: Adoption Level of Digital Agricultural Technologies

Technology	Adoption Level	Major Benefit
Mobile Advisory Services	High	Weather and market information
Soil Health Cards	Moderate	Scientific fertilizer use
IoT Sensors	Low	Smart irrigation
Drones	Low	Crop monitoring and spraying
AI-based Forecasting	Moderate	Yield prediction
Block chain	Very Low	Supply chain transparency

Source: FAO, IPCC and World Bank

IoT sensors have a low adoption level mainly because of high installation costs and lack of technical knowledge among farmers. These types of sensors are very helpful in smart irrigation in that they monitor the soil moisture, temperature and humidity in real time. They enhance water-use efficiency and provide precision farming, yet affordability is a significant limitation. The level of adoption of drones is also low, owing to the high cost of purchases, deficiency of training, and regulatory issues. Their greatest advantage is crop surveillance and spraying, which enhances the early detection of diseases, as well as the wastage of pesticides. Despite its high efficiency, at present, drone technology is more widespread among large farmers and agribusiness companies. The level of adoption of AI based forecasting is moderate and it can be used in predicting yield, predicting pests and analyzing weather. It assists farmers to decrease uncertainty and enhance planning. Nevertheless, it will only be adopted more through the increased digital infrastructure and the improved extension services. The level of adoption of block chain is very low as it is a relatively new technology in the agricultural sector and hence requires sophisticated digital infrastructures. Its significant advantage is the supply chain transparency, traceability, and food safety. It assists in enhancing confidence among the producers, traders, and consumers, although, in the rural farming systems, it is still practically not used.

The table, in general, shows that simple and low-cost technologies, e.g., mobile advisory services, are faster to adopt, whereas advanced technologies, e.g., IoT, drones, and block chain technologies are more prone to adoption issues. This demonstrates that to be successful with Climate Smart Agriculture, the technology should be affordable, accessible, and accompanied by appropriate training and government policies. The increased use of these digital tools can dramatically enhance productivity, sustainability and farmer income.

Table 7: Indian Agricultural Vulnerability Indicators

Indicator	Value
Rain-fed Agriculture	52%
Small and Marginal Farmers	86%
Population Dependent on Agriculture	55%
Contribution of Agriculture to GDP	18%
Groundwater Stress States	Punjab, Haryana, Rajasthan, Gujarat

Source: FAO, IPCC and World Bank

The table 7 indicates the key vulnerability indicators of the agricultural sector in India and Climate Smart Agriculture (CSA) and digital innovations are urgently required to achieve sustainable agricultural development. The Indian agriculture is still very vulnerable to climate change due to overreliance on rainfall, small landholdings, and the growing strain on natural resources.

The table indicates that 52 percent of Indian agriculture is rain-fed implying that over half of agriculture is not assured by irrigation but by rain. This renders farmers extremely susceptible to abnormal rainfall, droughts, late monsoons, and floods. A shift in the weather patterns has a direct impact on the crop production and earnings of farmers. The other key pointer is that 86 percent of the farmers in India are small and marginal farmers. Such farmers tend to possess small land, low investment power, and inadequate access to modern technologies (smart irrigation, drones, and precision farming tools). Due to their poor financial status, they are more exposed to losses in crops due to climate changes and market volatility.

The table also shows that 55 percent of the population depends on agriculture either directly or indirectly for their livelihood. This implies that instability in agriculture not only influences the farmers but also the rural jobs, food security, and the economy. Loss of income, poverty and migration in rural settings could be caused by a poor agricultural season. It is a significant sector of the economy even with the growth in the rapid industrial and services sector since it contributes about 18 percent of the GDP of India. This contribution underscores the fact that agriculture needs to be safeguarded against climate risks and sustainable productivity ensured to stability in the national economy. The states of stress (refer to the table) in the groundwater of Punjab, Haryana, Rajasthan, and Gujarat experience severe water scarcity because of excessive pumping of the groundwater to irrigate farms. The conventional irrigation techniques like flood irrigation have exacerbated the situation. This prompts an immediate demand of intelligent irrigation systems, drip irrigation, and water management based on IoT under the CSA.

In general, the table shows clearly that Indian agriculture is very susceptible to climate change, water scarcity and structural flaws. The necessity to implement Climate Smart Agriculture and digital solutions (weather forecasting, precision irrigation, mobile advisory services, and climate-resilient farming practices) is due to high reliance on rain-fed farming, prevalence of small farmers, and depletion of groundwater. The measures will enhance resiliency, productivity, and long-term sustainability in Indian agriculture.

The table 8 identifies the key government initiatives that will facilitate Climate Smart Agriculture (CSA) and digital transformation in Indian agriculture. Such schemes will enhance agricultural productivity, enhance climate resilience, reduce environmental degradation and encourage the use of modern technologies to foster sustainable farming.

Table 8: Government Initiatives Supporting Climate Smart Digital Agriculture in India

Scheme	Focus Area	Expected Outcome
NICRA	Climate-resilient agriculture	Adaptation and resilience
PM-KUSUM	Solar irrigation	Reduced diesel dependence
Soil Health Card Scheme	Soil fertility management	Balanced fertilizer use
PMFBY	Crop insurance	Risk reduction
Digital Agriculture Mission	AI, Remote Sensing, Digital Platforms	Smart agriculture adoption

Source: FAO, IPCC and World Bank

NICRA (National Innovations on Climate Resilient Agriculture) is concerned with climate-resilient agriculture and helps farmers adapt to changing climatic conditions like droughts, floods, heat waves and irregular rainfall. Its projected resultant outcome is enhanced adaptation and resilience due to improved farming methods, climate resistant type of crops and improved management of the resources. The scheme is significant in safeguarding the farmers against climatic risks. PM-KUSUM (Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan) promotes solar irrigation by encouraging the use of solar powered pumps in agriculture. Its prime goal is to lessen the reliance of farmers on diesel and conventional electricity to irrigate their farms. This reduces the cost of production, decreases carbon emission, and promotes an environmentally friendly agricultural practice.

The Soil Health Card Scheme is aimed at management of soil fertility by giving the farmers scientific information on the status of soil nutrients. This assists in the balanced use of fertilizers by advising farmers on the appropriate type and quantity of fertilizers they should use on their farms. Consequently, it helps to enhance the health of the soil, decrease the use of chemicals in excessive amounts, and boost productivity. PMFBY (Pradhan Mantri Fasal Bima Yojana) is aimed at ensuring crops and mitigating financial risks that farmers may face because of natural calamities, crop failure, pest attacks, and uncertainties related to the climatic condition. The anticipated result is the reduction of risks and income security of farmers, including small and marginal ones as they are more susceptible to losses. Digital Agriculture Mission is among the most significant projects towards the adoption of smart agriculture. It concentrates on the application of Artificial Intelligence (AI), remote sensing, on-line platforms and data-driven farming solutions. The scheme aids precision farming, weather prediction, crop tracking and digital advisory services, to assist farmers in making better and faster decisions.

7. Conclusion and Policy implications

The paper concludes that digital innovations in combination with Climate Smart Agriculture (CSA) can be considered one of the most promising and sustainable solutions to the increasing challenges of modern agriculture. The traditional farming systems have become inadequate in the provision of a long-term agricultural sustainability due to climate change, lack of water, decreasing soil fertility, biodiversity reduction, and the growing food demand. The results indicate clearly that agriculture needs to leave behind the traditional approach and adopt more intelligent, technology-enhanced and climate-adaptive systems.

This research affirms that CSA, in terms of its three pillars sustainable productivity, adaptation and resilience, and greenhouse gas mitigation, offers a solid framework towards balancing food security with environmental sustainability. Digital technologies that can be used to enhance the practical implementation of CSA include Artificial Intelligence (AI), Internet of Things (IoT), drones, remote sensing, Geographic Information Systems (GIS), block chain, mobile advisory services, and big data analytics that significantly enhance the precision, efficiency, and decision-making. The data analysis demonstrates that smart irrigation systems can save 20-40 percent of water, irrigation efficiency can be improved by up to 50 percent, the amount of using fertilizers can be reduced by 15-25 percent, and stability in crop yields can be enhanced by 10-20 percent. The advantages of early detection of pests by the deployment of drones and AI reduce the loss of crops, whereas mobile advisory services enhance the preparedness to weather and access to markets. Accuracy farming reduces the cost of inputs and enhances profitability, making agriculture more cost effective and sustainable.

The paper also points out to the fact that agricultural losses due to climate have become alarming with global losses amounting to US$ 3.8 trillion between the year 1991 and 2021. India is highly vulnerable due to a 52 percent of agriculture is rain-fed, 86 percent of farmers are small and marginal and groundwater stress is severe in the major agricultural states like Punjab, Haryana, Rajasthan and Gujarat. These weaknesses in the structure render the implementation of CSA and digital agriculture not only beneficial but also indispensable. The policy has been provided with solid policy basis through government initiatives like NICRA, PM-KUSUM, Soil Health Card Scheme, PMFBY and the Digital Agriculture Mission. Nevertheless, several obstacles, which include high cost of high technology, poor rural internet connectivity, low digital literacy, fragmented landholdings and limited extension services, still hamper large-scale adoption, particularly by smallholder farmers (Vasavi et al., 2025; Raj & Prahadeeswaran, 2025).

Thus, technological innovation is not the only factor that would contribute to the success of Climate Smart Agriculture, as far as affordability, inclusiveness, institutional coordination, and policy design that is farmer-centered are concerned. The technology should also be accessible to the smallest of farmers and not just big commercial farms. Digital agriculture will not reduce rural inequality but can increase it without equitable access.

To sum up, Climate Smart Agriculture and digital innovations integration will become the future of sustainable agriculture. It enhances productivity, saves on water and soil resources, decreases emissions, adopts resilience to climate risks, and improves farmer income and food security. In the case of developing nations such as India, this combined method is not just an option but also a strategic need toward attaining agricultural sustainability, rural development, and long-term economic sustainability.

Changing the findings of the study, there are several important policy implications to promote Climate Smart Agriculture and digital innovations in agriculture.

First, governments are urged to make more people invest in rural digital infrastructure, such as internet connectivity, access to electricity, and digital extension services. Advanced agricultural technologies cannot be successfully applied without a good infrastructure in the rural areas.

Second, subsidies, low interest credit, equipment sharing systems and farmer cooperatives must be used to provide small and marginal farmers with affordable access to technology. Drones, IoT sensors, and specifically farming tools should not be confined to large farmers only.

Third, agricultural universities, Krishi Vigyan Kendras (KVKs), extension agencies, and mobile-based learning platforms should be strengthened to provide training to farmers and to offer them digital literacy. The success in adoption requires awareness and practical training.

Fourth, the integration of agriculture, climate change, water management, and digital development policies needs to be enhanced. Policy frameworks are usually separate, which results in gaps in implementation. There is a need to have a single climate-wise digital agricultural plan that will enhance coordination.

Fifth, more local and region-specific solutions should be given priority over the same national solutions. Agricultural challenges are also region specific and solutions to climate-smart solutions should be reflective of the local soil, climate, water availability and socio-economic conditions.

Sixth, policies of digital agriculture should focus on women farmers and other vulnerable groups in rural areas. Access to training and finance including technology will be gender inclusive and will enhance equity and boost livelihoods in rural areas.

Seventh, more robust public-private collaboration needs to be fostered to promote agri-tech startups, innovation hubs, precision farming services, and climate-smart value chains. Government, research institutions and private firms should collaborate to hasten the large-scale adoption.

Lastly, agricultural policies ought to be geared towards long term sustainability and not towards short term productivity boosts. Mainstream agricultural planning should include carbon farming, solar irrigation, water conservation, regenerative agriculture, and climate-resilient cropping systems.

Therefore, a sound policy framework can help Climate Smart Agriculture to become an effective framework of practical and inclusive model of sustainable agricultural development.

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