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Climate resilience technologies in agriculture: A review towards sustainable food systems

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Abstract

Climate change is a big problem for farming around the world. It causes temperatures to change more often, rainfall to be less predictable, and more frequent extreme weather events like droughts and floods. These changes hurt how much food is produced, affect the income of farmers, and make it harder to have enough food for everyone. At the same time, farming itself is a major source of greenhouse gas emissions. Because of this, there has been a growing focus on Climate-Smart Agriculture (CSA), which is a complete approach that helps make farming systems more sustainable, able to handle climate changes, and lower in emissions. Climate-Smart Agriculture tries to increase farming output and farmer income in a lasting way, help farming systems better deal with climate challenges, and reduce or cut down on greenhouse gas emissions as much as possible.

This chapter gives a full picture of what Climate-Smart Agriculture is, the key ideas behind it, and how it is used. It looks at the main principles of CSA, such as improving productivity, building resilience, and cutting emissions. It also highlights the important role of new digital tools like artificial intelligence, sensors, drones, digital twins, and blockchain in making farming more efficient, helping farmers make smart decisions based on data, and better managing risks from climate change.

Keywords: Climate change, climate-smart agriculture, climate resilience technologies, precision farming

Introduction

Agriculture is becoming more affected by the negative effects of climate change, making it one of the most at-risk sectors around the world. Higher temperatures, changing rainfall patterns, and more frequent extreme weather events like droughts, floods, cyclones and heatwaves are directly affecting how crops grow, how livestock do and the overall stability of farms. These changes are causing serious problems for global food supplies, the incomes of farmers and the balance of ecosystems in farming areas (FAO 2018). Lower yields in important food crops could make food shortages and price changes worse, especially in areas that are very sensitive to weather changes. These trends show the need to change traditional farming into systems that are better able to adapt and survive (UNDP 2018).

At the same time, agriculture is a big part of causing climate change. The sector is responsible for about a quarter of all human-made greenhouse gas emissions, mostly from methane in livestock and rice farming, nitrous oxide from fertilizers, and carbon loss from cutting down forests and changing land use. So, agriculture must be part of the answer to fighting climate change, not just a victim of its effects. Dealing with these two problems making sure there is enough food for a growing population while adapting to and reducing climate change has led to the idea of Climate-Smart Agriculture (CSA). CSA is a complete and integrated way of changing farming systems to be more sustainable. It focuses on achieving productivity, resilience, and reduction of greenhouse gases all at the same time, within the broader goal of sustainable development (Khatari *et al.*, 2017) ^[4].

The three main parts of Climate-Smart Agriculture are: increasing agricultural productivity and farmers' incomes in a sustainable way, improving the ability to deal with climate changes and extreme weather events, and cutting back or removing greenhouse gas emissions where possible. Climate Resilience Technologies are important tools within the CSA framework. These include

crop varieties that can withstand stress, tools for managing water and nutrients more precisely, conservation farming methods, advice services that use climate information, and early warning systems. These technologies help farmers predict climate risks, use resources more efficiently, and keep productivity high even when the weather changes.

This chapter gives a full look at Climate-Smart Agriculture and Climate Resilience Technologies, covering their basic ideas, guiding principles, useful tools, and ways to put them into practice. It also discusses the increasing role of digital technologies like artificial intelligence, sensors, drones, remote sensing, and systems that help with decisions based on data in making farming more resilient, more efficient, and helping move toward sustainable, low-emission agricultural systems.

Concept of Climate-Smart Agriculture (CSA)

Climate-Smart Agriculture (CSA) is an overall farming approach that aims to increase the productivity of farms and farmers' incomes in a sustainable way. It also helps farmers become more resilient to changes in climate and reduces greenhouse gas emissions where possible. This approach looks at three main goals together: making sure people have enough food, adapting to climate changes and reducing the impact of climate change. These goals are not considered as separate issues but are looked at as connected challenges. The idea of Climate-Smart Agriculture was introduced by the Food and Agriculture Organization (FAO) of the United Nations in 2010^[5].

It came about because there were growing worries about how climate change is affecting farming systems. Since then, CSA has become a widely accepted guide for creating agricultural policies, development programs and investment plans that respond to climate change across different types of farming areas. Unlike traditional farming methods that often focus only on getting the highest possible crop yields, CSA takes a longer-term and more sustainable view. It focuses on using resources more efficiently, improving the natural environment, and lowering the negative effects on the planet, while making sure farming remains profitable and stable. This broad approach is especially important in areas where farming is under stress from climate changes, land loss and shortage of water.

Importantly, Climate-Smart Agriculture is not a single technique or a set of fixed rules. It is more about a flexible, system-based approach that works with many different practices, technologies and ways of organizing things, depending on the local situation. CSA is adapted to fit the local climate, what crops are grown, the economic and social conditions, and the skills of the farmers, making it useful and relevant in many farming environments. CSA encourages combining traditional and local knowledge with modern science and technology. Practices that have been used for a long time, like growing a variety of crops, raising animals along with crops, using natural fertilizers and collecting rainwater, are combined with new technologies such as precision farming, weather prediction, genetic improvements and digital tools that help make decisions. This mix makes CSA methods more effective and easier for farmers to accept.

Digital tools are becoming more important in making Climate-Smart Agriculture work. Technologies like artificial intelligence, satellite imaging, drones, sensors, mobile apps that give advice and digital models help monitor crops, soil, and weather in real time. These tools help farmers make better-informed decisions, use resources more efficiently, reduce the risks of farming and be more ready to deal with climate changes. Support from policies and institutions is very important for making CSA work.

Policies that provide funding for climate projects, insurance against crop loss, support for farmers through advice, carbon trading and financial incentives help spread CSA practices more widely. Strong organizations ensure that all the people involved like farmers, scientists, government officials and business people work together, which helps CSA become more common.

Overall, Climate-Smart Agriculture is a way to create food systems that are both sustainable and resilient as the climate continues to change. By combining better production, stronger adaptation to climate changes, and lower emissions into one plan, CSA offers a realistic and adaptable way to achieve food security, environmental care and climate goals at different levels from local to global.

Objectives of Climate-Smart Agriculture

1. Ensure Food Security

The main goal of Climate-Smart Agriculture is to provide enough food for the increasing number of people around the world, even as the climate changes. It focuses on increasing the productivity of crops, livestock, fish, and tree-growing systems in a way that doesn't harm the environment. By making sure crops produce consistently, growing a variety of crops, and using farming methods that can handle the climate, CSA helps keep food available, accessible, and useful. It also helps farmers earn more money and live better lives, which makes rural areas stronger and less likely to face food shortages (Ben *et al.*, 2021)^[2].

2. Enhance Climate Resilience

One of the main goals of CSA is to help farmers and communities deal with changes in the climate and extreme weather like droughts, floods, heatwaves, and pest problems. This is done through strategies such as using crops that can handle stress, managing water and soil more efficiently, mixing different types of farming, and offering advice and early warnings about weather changes. Building resilience helps lower the risk of losing crops and ensures farming stays sustainable in the long run.

3. Mitigate Climate Change

CSA also aims to fight climate change by cutting down greenhouse gas emissions and storing more carbon in the land used for farming. This includes using better ways to manage nutrients to reduce emissions of harmful gases, improving how livestock are fed and how manure is handled to lower methane, and using farming techniques that add more carbon to the soil and trees. These steps help farming systems become part of climate efforts at the national and global level (World Bank, 2023)^[7].

4. Promote Sustainable Resource Use

Another important part of CSA is managing natural resources like soil, water, biodiversity, and energy in a way that lasts. It encourages methods that improve soil health, save water, protect wildlife, and use energy more efficiently. Techniques like using water only when needed, managing nutrients carefully, using farm waste wisely, and using clean energy all help prevent waste and reduce harm to the environment. This not only helps fight climate change and build resilience but also keeps farming productive and eco-friendly for future generations.

Key Principles of Climate-Smart Agriculture (CSA)

1. Productivity

Productivity is a central part of Climate-Smart Agriculture and

aims to increase agricultural output in a sustainable way to meet rising food needs even as the climate changes. CSA supports sustainable intensification, which means getting more food, fodder, fiber, and bio-energy from each unit of land, water, and energy, while keeping the soil healthy, protecting biodiversity, and maintaining ecosystem services. Improving productivity under CSA doesn't rely on using too many external inputs. Instead, it uses efficient, science-backed methods that respond to the climate, ensuring that farms remain profitable over the long term and that natural resources are preserved (Ali *et al.*, 2017) [1].

Major ways to boost productivity through CSA

Better crop varieties

Developing and using crop types that can withstand drought, heat, salt, flooding, and new pests and diseases. These varieties help maintain steady harvests even when the weather is tough, lowering the risks for farmers.

Smart use of nutrients and water

CSA encourages applying fertilizers and water only where and when they are needed, using tools like soil tests, fertigation, drip and sprinkler irrigation, and sensors to schedule watering. This improves how efficiently inputs are used, reduces waste, and boosts crop yields while saving water and nutrients.

Combined farming systems

Mixing crops, livestock, fisheries, trees on farms, and other related activities helps recycle resources, brings in more income, and makes the whole system more resilient. Byproducts and waste from one part of the system are used in another, cutting down the need for outside inputs and increasing overall farm output.

Digital tools for decision making

Using weather forecasts, mobile apps, satellite data, GIS, AI tools and other digital systems helps farmers decide the best time to plant, water, fertilize, control pests and harvest. These technologies help reduce risks, make operations more efficient, and improve productivity in changing climate conditions.

2. Resilience (adaptation)

Resilience, also known as adaptation, is a key part of Climate-Smart Agriculture. It helps strengthen the ability of farming systems, communities, and natural resources to deal with changes in the climate and extreme weather. Resilience means being able to predict, handle, recover from, and adjust to challenges like droughts, floods, heatwaves, cold snaps, salty soil, and more pests and diseases.

By improving resilience, Climate-Smart Agriculture helps farmers deal with climate risks better and keeps their farming and livelihoods stable, even when the weather is unpredictable and changing. Some ways to build resilience in Climate-Smart Agriculture are:

Diversified farming systems

Growing a variety of crops through methods like crop rotation, intercropping, mixed farming, planting trees with crops, and using legumes and cover crops helps reduce reliance on just one crop. This spreads out the risk from climate problems. Diverse farming also improves soil quality, helps the soil hold nutrients, reduces pests and diseases, and gives farmers other income sources, making their farming more stable.

Using climate-resilient crop varieties

Choosing seeds that can handle tough conditions like dry spells, floods, heat, salty soil, and pests helps keep crop production steady. These kinds of seeds are specially bred to survive and bounce back from extreme weather, making farming more reliable.

Keeping soil moisture

Techniques like mulching, less tilling, leaving crop residue on the field, farming along the contours of the land, planting on raised beds, using cover crops, and collecting rainwater help the soil hold more water. This makes it easier for crops to handle dry periods and extreme temperatures, helping them adapt better.

Getting early warnings and advice

Using weather forecasts, climate alerts, monitoring pests and diseases, and getting agricultural advice through information and communication technology lets farmers make better decisions before problems happen. Knowing about droughts, floods, heat stress, or pest infestations in advance helps reduce crop loss and improves how well farmers can prepare and recover.

3. Mitigation

Mitigation is a key part of Climate-Smart Agriculture that aims to cut down greenhouse gas emissions from farming and boost carbon storage, helping the world fight climate change.

Farming produces a lot of methane, nitrous oxide, and carbon dioxide. Climate-Smart Agriculture encourages methods that lower emissions without harming farm productivity or the ability to handle climate challenges.

Climate change mitigation in agriculture includes Cutting methane emissions from rice and livestock

Methane from flooded rice fields can be reduced by using techniques like alternate wetting and drying, the system of rice intensification, better water management, and carefully using organic materials. For livestock, reducing methane comes from improving feed quality, giving balanced diets, using feed additives, managing animal health better, and handling manure more efficiently. These steps cut down on the gas released during digestion.

Lowering nitrous oxide emissions with precise fertilizer use

Using too much nitrogen fertilizer causes high nitrous oxide emissions. Climate-Smart Agriculture pushes for nutrient management that's tailored to the field, applying fertilizers based on soil tests, using slow-release and controlled-release fertilizers, adding nitrification inhibitors, and applying fertilizers more precisely. These methods make nitrogen use more efficient, reduce waste, and cut down on nitrous oxide.

Building soil organic carbon through conservation farming

Practices like minimal or no tillage, keeping crop residue, using cover crops, rotating crops, and adding organic material help build soil carbon. Soils rich in carbon not only store carbon but also improve soil structure, fertility and water retention, which helps increase productivity and make farms more resilient.

Encouraging renewable energy in farming

Using solar-powered irrigation pumps, biogas systems, wind power, and efficient farm machinery reduces reliance on fossil fuels. These on farm renewable energy systems lower carbon

dioxide emissions, cut costs, and make energy more reliable for farmers.

Climate Resilience Technology in Agriculture Concept and Scope

Climate Resilience Technology, or CRT, is a wide range of tools, practices, methods, and innovations designed to help agricultural systems better handle changes in climate and extreme weather events. These technologies are meant to lower the risk of damage from climate issues, keep farming stable, and support the livelihoods of people in areas that face droughts, floods, extreme temperatures, salinity, and more pests and diseases.

CRT helps crops; animals, soil, water, and farming communities adapt better to these challenges. While many Climate Resilience Technologies are part of Climate-Smart Agriculture, they can also be used on their own. They can be applied at different levels, from individual farms to communities, landscapes, and even national agriculture plans.

Scope of Climate Resilience Technology in agriculture Crop and genetic technologies

Developing and using crop varieties and hybrids that can survive drought, floods, heat, salinity, and new pests and diseases. Techniques like advanced breeding, biotechnology, and marker-assisted selection help improve how resilient crops are.

Soil and water management technologies

Tools like micro-irrigation, rainwater harvesting, soil moisture sensors, mulching materials, reduced tillage equipment, and soil conditioners improve water use and protect soil health. This helps crops grow even during extreme weather.

Climate information and decision-support systems

Using weather models, risk assessment tools, GIS, remote sensing, AI, and mobile-based farming advice allows farmers to predict and manage climate risks better. It helps them make smart decisions when needed.

Pest, disease, and stress management technologies

Systems for early detection, climate-based pest predictions, natural pest control methods, and integrated pest management tools help lower crop losses when the climate is changing.

Farm mechanization and energy technologies

Using machines that work well in tough weather, solar-powered irrigation pumps, energy-saving equipment, and renewable energy solutions improve farming efficiency and reduce reliance on fossil fuels.

Institutional and community level technologies

CRT also includes crop insurance, climate-friendly infrastructure, community seed banks, water user groups, and training programs that build the resilience and ability of communities to recover from climate impacts.

Relationship between CSA & Climate Resilience Technology (CRT)

Climate-Smart Agriculture (CSA) and Climate Resilience Technology (CRT) are closely connected and work together to deal with the effects of climate change on farming. CSA is a big picture approach that includes three main goals: making farming more productive, helping farmers adapt to changing conditions, and reducing greenhouse gas emissions. It looks at things from a

wide angle, including how policies are made, support for farming organizations, how land is managed, and what farmers do on their own fields. CSA gives a clear plan for developing agriculture in a way that is sustainable even as the climate changes, making sure that money, environment, and society all work together.

On the other hand, Climate Resilience Technology is about the specific tools, techniques, and methods that help make farming more resilient. It focuses on making farms able to handle shocks, reduce risks, and recover quickly from extreme weather. Examples include crops that can handle stress, efficient irrigation systems, services that give advice based on weather forecasts, and systems that warn farmers about upcoming weather events. While CSA sets the big picture of what needs to be done and why, Climate Resilience Technology shows how to actually do it, helping create farming systems that are resilient, productive and sustainable.

Water Management Technologies for Climate Resilience Efficient Irrigation Systems

Efficient irrigation systems are important for building climate resilience because they help use water better, save energy, and keep crop production stable even when there's not enough water or the climate changes (Shukla *et al.*, 2025) ^[6].

Micro-Irrigation Systems (Drip and Sprinkler Irrigation)

Micro-irrigation systems send water directly to the part of the plant where the roots are, in a controlled and exact way. This helps reduce the amount of water lost during transportation, from evaporation, and from runoff.

Drip Irrigation

Drip irrigation uses low pressure to send water through small parts called emitters that are placed close to the base of plants. This method spreads water evenly in the area where the roots are, helping the plants absorb it more effectively.

- This type of irrigation uses 30 to 50% less water than traditional flood irrigation.
- It can also increase crop yields by 20 to 40% because it provides the right amount of moisture and nutrients to the plants.
- When used with fertigation, which is adding fertilizer through the irrigation system, it makes fertilizer use more efficient.
- It also helps control weeds and prevent soil erosion by only wetting the area around the roots.
- This system works well for crops that need a lot of water and take a long time to grow, like sugarcane, fruits, and vegetables.

Sprinkler Irrigation

Sprinkler systems spray water in a way that mimics rain, and they can be used for many different types of soil and crops. They can spread water evenly even on land that has different elevations. Compared to methods like surface irrigation, sprinkler systems can save 25 to 40% of water. They also reduce the need for manual labor and allow farmers to water their crops on time. Sprinklers are especially good for lighter soils and for crops that need regular, light watering.

Rainwater Harvesting for Climate-Resilient Agriculture

Rainwater harvesting is an important way to manage water by collecting, storing, and reusing rainwater. This helps ensure there's enough water available during dry times. It helps reduce

the amount of water that runs off the land, lessens the effects of drought, improves groundwater levels, and makes farms more resilient to changing weather patterns, especially when there are unpredictable or heavy rains (Shukla *et al.*, 2025) ^[6].

Farm Ponds

Farm ponds are small or medium-sized structures built on individual farms to collect and store rainwater and runoff from the land. These ponds store rainwater during the monsoon season, which can then be used for irrigation during dry periods. This supports crops and helps keep them alive and productive even during droughts or if the monsoon is delayed. They also support extra irrigation, which is especially useful for high-value crops, seedlings, and managing sugarcane crops. Farm ponds can be used in combination with other farming activities like raising fish, watering animals, and growing fruits and vegetables. These ponds also help reduce soil erosion by trapping runoff at the field level.

Ponds made with materials like HDPE or concrete lose less water through seepage, while ponds without lining help to recharge groundwater. Farm ponds are affordable, easy to scale, and are a good option for small and marginal farmers, especially with support from government programs focused on watershed development and efficient irrigation.

Check Dams

Check dams are small barriers erected across seasonal streams, drainage channels, or nallahs to slow down the flow of water and encourage it to soak into the ground. They reduce the speed of water flow, which helps prevent erosion and flooding in downstream areas. These dams also help recharge groundwater by allowing more water to seep into the soil. They improve water availability for nearby wells and borewells. Check dams also help maintain a steady flow of water in streams during the dry season, improving the water supply for farming and supporting the local environment. Check dams work especially well in dry and drought-prone areas and are often part of wider programs to manage watersheds and adapt to climate changes.

Percolation Tanks

Percolation tanks are larger systems designed mainly to recharge groundwater instead of directly storing water on the surface. They collect runoff from large areas and allow water to slowly seep into underground water sources. These tanks can significantly raise the water table in nearby villages and farmlands. They ensure a steady water supply from open wells and tube wells during dry seasons. They also help with irrigation, drinking water, and maintaining the environment. These tanks reduce reliance on external water sources and help cope with the effects of drought. Percolation tanks are especially effective in areas with good soil and rock conditions and they help ensure long-term water security.

Overall Benefits of Rainwater Harvesting

- Rainwater harvesting helps ensure there is more water available during dry periods caused by climate change.
- It improves the groundwater supply and helps keep the soil moist.
- It reduces the risk of floods and land damage during heavy rains.
- It boosts agricultural production and helps farms deal with varying weather conditions.

Precision Water Application for Climate-Resilient Agriculture

Precision water application is about giving the right amount of water, at the right time and in the right place. This is done using data and sensors to make sure water is used efficiently. It helps reduce waste, makes better use of water and helps crops handle changes in the climate and water shortages.

AI-based irrigation scheduling

AI-based irrigation scheduling uses artificial intelligence and machine learning to look at various data sources and decide the best times to water crops. It takes into account weather predictions, how wet the soil is, the stage of crop growth, past harvest data, and previous irrigation records. This helps predict how much water the crops need under different weather conditions and suggests when and where to water. It can adjust watering plans as needed during heat waves, heavy rain, or droughts. This way, it prevents over- or under-watering, saving 20 to 40 percent of water while keeping or improving crop yields. It also helps make farming more efficient, especially on large farms, in irrigation areas, and in research projects for crops like sugarcane. Using AI for scheduling helps make farming more resilient to climate changes by ensuring water is available when crops need it most and helps reduce the effects of unpredictable weather patterns.

Soil moisture sensors

Soil moisture sensors give real-time information on how wet the soil is at different depths near the crop roots. These sensors measure either the amount of water in the soil or how tight the soil is, which helps make better decisions about when to water. They help find the best times to irrigate without causing the soil to be too dry or too wet. This helps use water more wisely without lowering crop yields. These sensors also reduce how often you need to water and lower the cost of pumping water. When used with automatic drip systems, they allow for real-time watering based on sensor inputs. Using soil moisture data for irrigation improves how efficiently water is used, helps roots grow better, and keeps yields stable even if rainfall or temperatures change.

Evapotranspiration (ET)-based models

Evapotranspiration (ET)-based models calculate how much water crops need by considering the amount of water lost from the soil through evaporation and from plants through transpiration. These models use reference evapotranspiration (ET_o), which is based on weather factors like temperature, sunlight, humidity, and wind. They then apply crop coefficients (K_c) to calculate the actual evapotranspiration (ET_c) for different growth stages of the crop. This helps plan and schedule irrigation at the field, farm, and regional levels. These models improve the accuracy of irrigation during changing weather, especially during hot periods. When combined with drip irrigation systems, they help save water and make irrigation more efficient. ET-based models are commonly used in systems that help farmers make informed decisions and support climate-smart irrigation.

The combined use of precision water application saves a lot of irrigation water while keeping or increasing crop productivity. It also lowers energy use and the cost of inputs. It helps crops withstand drought, heat, and changes in rainfall. It builds climate resilience through smart and flexible water management that is based on data.

Soil health management

Soil health management and conservation agriculture form the base of farming systems that can handle climate changes. Healthy soil helps the land deal with climate stress by improving how water moves into the ground, holds moisture, provides nutrients, and supports living organisms. Soils with a lot of organic matter are better at handling droughts, floods, and extreme temperatures, and they help maintain steady crop production. Keeping soil healthy is not just about adapting to climate change it also helps reduce it, because healthy soil can store carbon (Shukla *et al.*, 2025) ^[6].

Conservation agriculture

Conservation agriculture is key to maintaining soil health as the climate changes. Using little to no tilling helps protect the soil from being disturbed, which reduces erosion, improves soil structure, and keeps more moisture in the ground. Leaving crop residue on the soil surface helps shield the ground from extreme temperatures, stops weeds, reduces water loss, and boosts microbial activity. Together, these practices make the soil more resilient and less vulnerable to unpredictable rain and land degradation.

Crop Rotation

Rotating crops and growing a variety of plants also support conservation agriculture. Mixing crops with different root depths and nutrient needs improves soil fertility, breaks cycles of pests and diseases, and helps use nutrients more efficiently. Diverse farming systems lower the risk of poor production and offer more stability in the face of changing climate conditions, making them important for growing more food sustainably.

Carbon sequestration

Soil's ability to store carbon has two important roles in dealing with and adapting to climate change. Practices like using green manure, applying compost and farmyard manure, planting cover crops, and using biochar increase the amount of carbon in the soil. More carbon in the soil improves how well the ground holds together, holds water, and provides nutrients, while also lowering levels of carbon dioxide in the air. Soils high in carbon are more productive, resilient, and good for the environment.

Crop Management

Managing crops in a way that handles climate stress involves using plant varieties that can tolerate stress and applying farming strategies that adapt to changing conditions. Crops that can handle drought, flood, heat, and have shorter growing seasons help keep yields steady during tough weather. These varieties either avoid or withstand stress and are important for ensuring food security in areas with extreme weather.

Cropping Pattern

Growing a variety of crops and combining farming with trees also increases resilience and supports farmers' income. Methods like mixed cropping, intercropping, alley cropping, and farming with trees and livestock improve how resources are used, help control small climate conditions, boost biodiversity, and increase carbon storage. Agroforestry also provides extra income from things like fodder, fuelwood, fruits, and timber, which reduces farmers' reliance on a single crop. Creating farming systems that can handle climate stress is important for sustainable mixed farming. Using heat-tolerant animal breeds, better housing with good airflow, balanced feeding, and feed that reduces methane emissions improves animal productivity while reducing greenhouse gas emissions. These steps improve animal health,

reduce losses from climate problems, and support efforts to cut emissions.

Digital tools and smart technologies

Digital tools and smart technologies are changing how we make farming more climate-resilient.

Artificial intelligence and big data help us diagnose plant health, predict yields, forecast pests and diseases, and use satellite images, weather data, and sensors to use farm inputs more efficiently. Sensors and Internet of Things (IoT) devices give real-time data on soil moisture, nutrients, and local weather, allowing farmers to act quickly and precisely.

Advanced technologies such as drones, remote sensing, digital twins, and blockchain are strengthening how we make decisions and improve transparency. Drones help detect plant stress, spray pesticides precisely, estimate plant growth, and assess damage from disasters. Digital twins let us test different climate scenarios and farming methods before trying them in the field, while blockchain improves transparency in the food supply chain, tracks climate-smart products, ensures secure payments, and verifies carbon credits.

Even though these methods have a lot of potential, they face several challenges and need strong social, economic, and policy support. High start-up costs, limited digital tools, data shortages, and institutional barriers stop large-scale use. Future possibilities include AI-powered farms, climate-smart breeding using genetics, carbon-neutral farming, and integrated systems for food, energy, and water. Building strong skills, fair policies, gender equality and incentives for climate-smart farming will be key to fully realizing the promise of these methods for sustainable and resilient agriculture.



Fig 1: AI Based Irrigation System



Fig 2: NPK Sensor

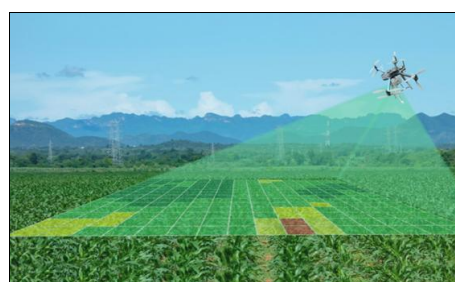


Fig 3: Drone technology for yield prediction



Fig 4: Weather station



Fig 5: Drip Irrigation system

Conclusion

Climate Smart Agriculture (CSA) and Climate Resilient Technologies (CRT) provide a complete solution to deal with the challenges of climate change and ensuring food security. These approaches combine effective water management, protecting soil health, using crops and animals that can withstand climate changes, and applying modern digital tools. This helps farming systems become more adaptable and less harmful to the environment. Healthy soils, smart use of resources, and varied farming methods work as natural defenses against extreme weather, helping maintain steady production even as climate conditions become more unpredictable.

Using smart technologies like artificial intelligence, sensors, remote sensing, and digital tools helps farmers make informed decisions quickly, improving efficiency and making farms more resilient. Also, practices like conservation agriculture and those that capture carbon help ensure long-term sustainability and reduce the effects of climate change. But for these approaches to work well, there needs to be strong support from institutions, fair policies, training, and access to affordable technologies, especially for small farmers and those in vulnerable communities.

In the future, new innovations such as climate-smart crop breeding, automated farming, and systems that connect food, energy, and water use will help make agriculture even more resilient. It is important for farmers, scientists, government officials, and businesses to work together to spread these CSA methods and create agriculture that is sustainable, strong, and able to adapt to climate changes.

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