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A Review of Digital Agriculture toward Food Security and Environmental Sustainability

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Abstract: Recent advancements in digital agriculture, with various tools and management techniques, aim to mitigate climate risks and alleviate food insecurity. Climate change and its effects on agricultural production and food security are major global concerns. The purpose of this study is to present an overview of the possible impact of digital agriculture technology and practices that may mitigate greenhouse gas emissions and boost productivity while maintaining food security. Through an extensive review of existing literature, it was discovered that climate change has adversely affected food security by diminishing agricultural yields, impeding animal growth rates, and reducing livestock productivity. This is primarily due to global warming, changed patterns of precipitation, and a rise in extreme events. The examined studies also show that adopting digital technology in agriculture is vital to alleviate the consequences of climate change and food poverty. In addition, topics surrounding developing sustainable agricultural food systems, limiting environmental pollution, boosting yields, ensuring equal and equitable distribution of food, and lowering hunger leading to food security were explored in detail. It was proven that while digital agriculture plays a significant role in reducing climate change and guaranteeing food security, it takes a concerted effort from policymakers, academics, and farmers to ensure that digitalization's benefits are achieved sustainably and fairly.

Keywords: Digital agriculture, Precision agriculture, Climate change, Food security, Climate-smart agriculture, Environmental sustainability.

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1. Introduction

The adoption of control and automation platforms, analytical software, applications for the web, and mobile tools have transformed farming operations in the past 30 years with the primary purpose of boosting productivity from the lands and resources (Javaid *et al*., 2022). Until 2010, farmers had to rely on Global Positioning System (GPS), satellite maps, ground-based sensing platforms, and local sensing equipment such as data recorders to monitor their crops and discover flaws. With the introduction of Unmanned Aerial Vehicles (UAV), low-powered long-range wireless sensors, Internet of Things (IoT) devices, and robotics, digital agriculture (DA) and smart farming approaches evolved toward digitization (Basso and Antle, 2020). They helped foster economic growth and sustainability of farming. Figure 1 depicts the fundamental process in precision agriculture (PA) whereas Figure 2 presents the building elements of digital farming. PA leverages raw data from many sources, including satellite photos, in situ sensors, and mobile sensing platforms, to diagnose inadequacies and improve crop productivity via improved management of the resources (for example, variable rate technology).

On the contrary, DA encompasses a broader range of technological innovations including robotics, wireless systems, drone technology, IoT-based automation, and smartphone applications to continually monitor, assess, and regulate soil health, water availability, and weather patterns on the agricultural land to improve field productivity while lowering operating expenses (Sparrow and Howard, 2021). Applications involve employing satellites with high-resolution UAV imaging for monitoring crop water levels and quality, estimating soil moisture including soil salinity, making NVDI and yield maps, as well as wellness evaluation and crop stress identification (Guimarães et al., 2024). On the automated side, wireless sensors and IoT devices have been key to installing smart irrigation, water loss management, as well as continual detection of soil nutrient concentrations in remote places (Sinha and Dhanalakshmi, 2022).

The principles for DA began to take shape around 2010, with some of the core technologies, such as the IoT and UAV, getting prominence, which changed the current ideals of PA and smart farming. This released the human labor force from arduous field work and created additional benefits for the sustainable production of food. Climate change, rising temperatures, as well as water scarcity harm productivity in agriculture and can severely lower crop harvests (Muluneh, 2021). Reports estimate that almost one-quarter of the global greenhouse gas (GHG) emissions are caused by crop agriculture and livestock farming. The inputs and outputs of DA that have grown using streams of data along with flexible data-sharing services have been facilitating mitigation measures for climate change by giving a variety of scientific approaches towards minimizing the use of pesticides and chemical fertilizers and limiting energy demands (Smith *et al*., 2020). With the developments in wireless networking and outstanding performance data processing gear, future farms are likely to be networked. In this context, DA has considerable potential for substituting traditional farming techniques with innovative technologies that cut GHG emissions (Javaid *et al*., 2022).

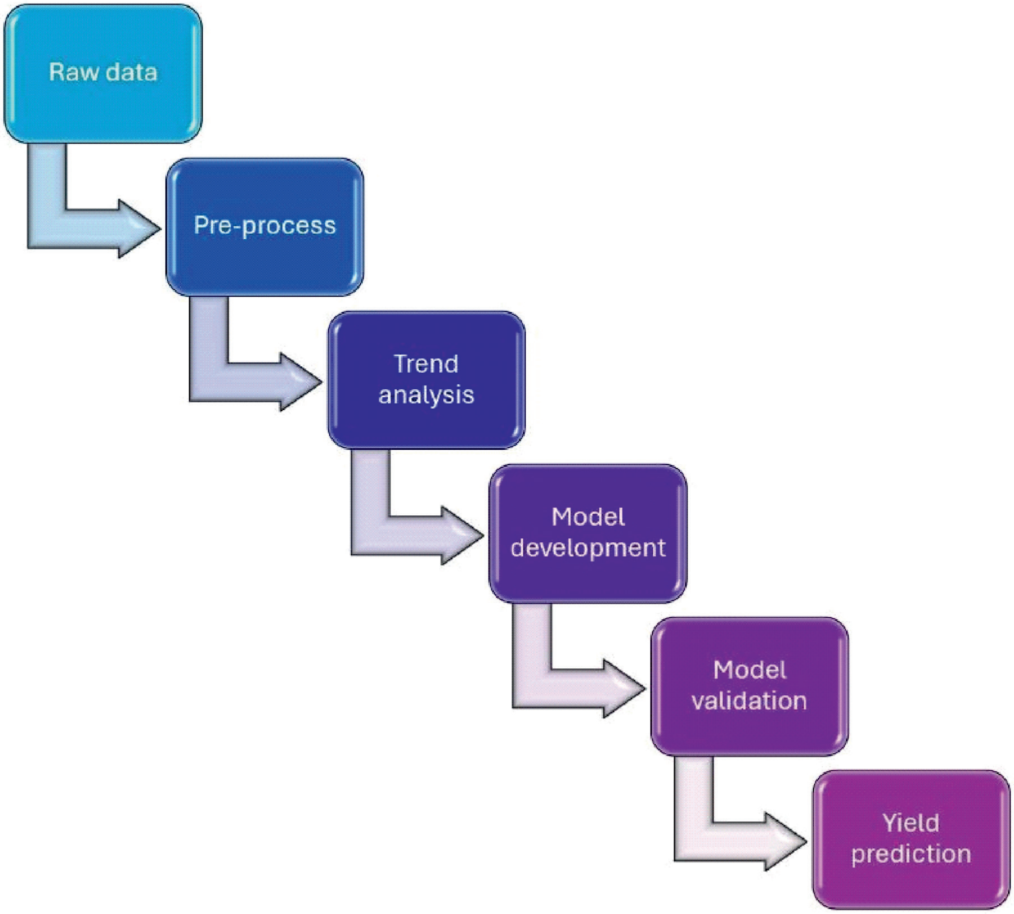


Figure 1: The workflow of precision agriculture

Climate change covers both global warming as well as massive variations in weather patterns. The GHG effect is the principal factor responsible for global warming. Utilizing fossil fuels for energy is a vital cause of GHG emissions alongside farming, clearing forests, and manufacturing. Climate change's key concerns include increasing temperature along with carbon dioxide (CO_2) levels,

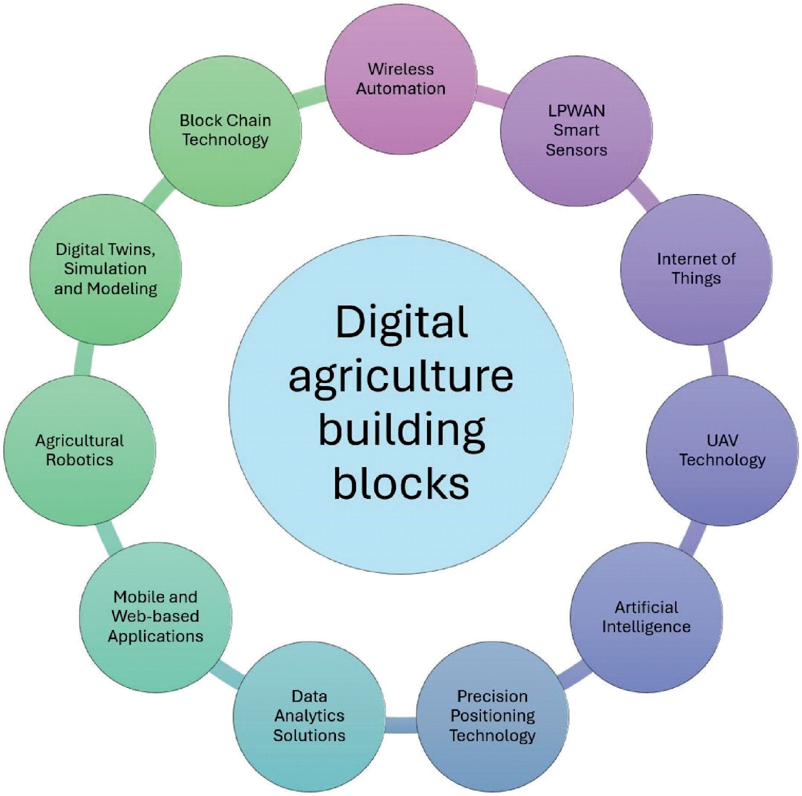


Figure 2: Digital agriculture building blocks in present days

including variations in rainfall. The atmospheric CO_2 accumulation rate was 2.3 ppm per year throughout 2009–18 as opposed to 0.6 ppm per year in the 1960s, with a present worldwide atmospheric CO_2 concentration of 409.8 ppm in 2019. Increased CO_2 emissions into the atmosphere have led the Earth's mean surface temperature to climb by 1.18 ◦C since the late 19th century (Gaffney and Steffen, 2017).

Similarly, due to fluctuations in atmospheric water vapor, the water cycle is anticipated to strengthen with rising temperatures, thereby increasing the severity of intense rains and the risk of flooding (Tabari, 2020). These elements are significant drivers of agriculture, and the extent of change in those parameters will significantly jeopardize food production. Changing climate is a primary force affecting agricultural output as well as food security globally (Lee *et al.*, 2024). In recent decades, the variety of plant and animal species with their seasonal behavior has varied due to climate change. It can affect agriculture in numerous ways, such as, productivity, quality, crop development, moisture as well as the availability of nutrients alongside uptake, transpiration and photosynthesis rate, changed length, and so on (Bibi and Rahman, 2023). In addition, global warming's immediate repercussions, such as hurricanes, floods, droughts, disease expansion, and ecosystem alterations, will indirectly influence agriculture production (Rawat *et al.*, 2024). In this scenario, food production as well as security will stand out as serious issues with ever-growing needs from the growing populace.

Digital agriculture not only offers new technology, but the utilization of these technologies offers an improved and more precise farm management system and information fusion. In addition to higher profits owing to efficient operations and the rise of technology in agriculture, digital agriculture offers multiple advantages, involving boosted product quality, enhanced sustainability, less risk in the governance structure, security of food via product traceability, safeguarding the environment, and rural development. Therefore, the present study aims to provide an overview of the role of digital agriculture as a climate-smart technology in promoting food security, as well as highlighting the limitations and issues in key food production and management sections.

2. Climate Change's Effects on Agriculture

A serious, long-term worldwide problem that affects both the present and future state of the world is climate pattern alteration. While there are many ways to interpret climate change, it is generally understood to occur when atmospheric CO_2 levels rise above 400 ppm. This can lead to a number of changes in climate, including increases in air temperature, notable and sudden shifts in annual, seasonal, and daily temperatures, variations in the dry and wet cycles, severe frost, and an extension of the drought period. Many facets of agriculture, such as crop productivity, soil characteristics, biodiversity, usage of water, livestock, and fisheries, are predicted to be significantly impacted by climate change (Srivastav *et al.*, 2021). The effects of shifting climatic trends on cattle, marine life, soil health, and crop productivity and production are covered in the following sections.

2.1. Impact on Crop Productivity

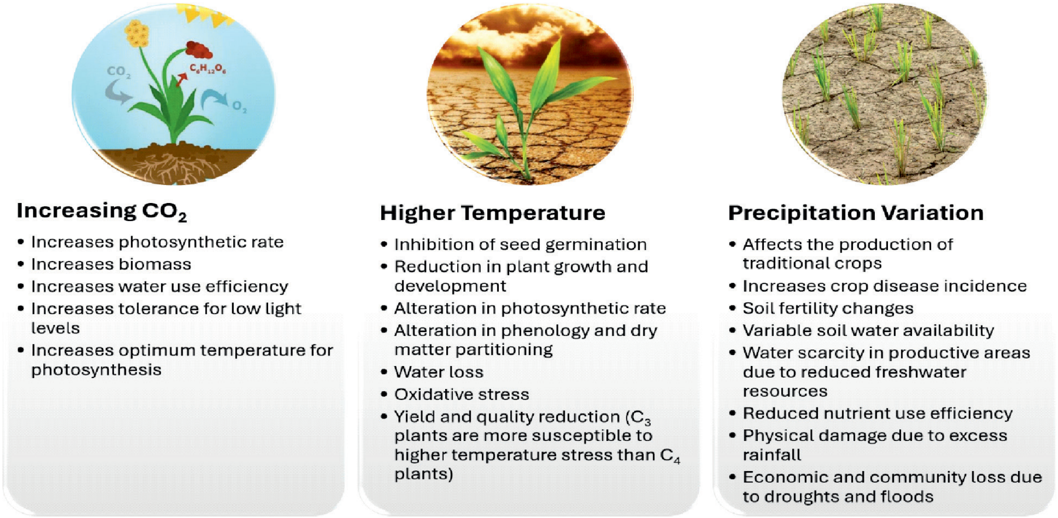
The world's growing population drives the food demand to its utmost. Increasing crop output per unit of land area is the most sustainable way to attain food security. Unfortunately, because of a variety of unfavorable factors and inadequate management techniques, we are unable to reach the maximum production of many crops worldwide. Under the current conditions, changes in the surrounding environment are essential to achieve increased agricultural output. Crop yield is largely affected by weather-related issues such as rising temperatures, CO_2 levels, and heavy precipitation. Numerous experts have projected future changes in the climate, considering both their immediate and subsequent impacts on crops (Jagannathan *et al.*, 2023).

Crop production can be greatly impacted by climate change, which can modify the conditions for the growth of crops and affect where and when to plant and harvest them. A few of the ways that climate change may affect crop productivity are modifications to temperature and precipitation patterns; a rise in the frequency and intensity of extreme weather events like storms, floods, and droughts; an increase in pests and diseases; adjustments to soil temperature and moisture content; and changes to water availability. Farmers may suffer financial losses as a result of these adjustments and a decline in food security. Plant-microbe interactions are also influenced by climate, which has an impact on agricultural crop development, growth, production, and quality (Fadiji *et al.*, 2023). Furthermore, it influences how a pathogen interacts with plants, impacting their life cycle, the development of host resistance, the severity of the disease, the emergence of new varieties, pathogenicity, and others. Figure 3 lists the negative effects of several meteorological factors on crops, all of which reduce crop yields in various manners for a wide variety of crop species.

Food insecurity is ultimately caused by the current slower rate of productivity growth compared to population increase. By 2100, global production of staple cereal crops—rice, wheat, and corn—will have decreased by 20–30 %, 45 %, and 50 %, respectively, due to climate change. By 2030, the significant decline in crop production (12 %, 23 %, 13 %, and 8 %) and the sharp rise in average prices of maize, rice, wheat, and various other crops (90 %, 89 %, 75 %, and 83 %) were also identified as consequences of climate change. All things considered, climate change possesses the power to drastically modify agricultural systems, resulting in lower crop yields and less food security. Mitigation and adaptation measures are required to lessen the detrimental effects of climate change on crop productivity (Wijerathna-Yapa and Pathirana, 2022).

2.2. Impact on the Soil

As a natural supply of vital plant nutrients, healthy soils are key for increasing agricultural output. Over time, a variety of complicated elements, including parent material, organisms, climate, relief, and other factors, interact to generate soils. The climate factor, on the other hand, has the greatest influence



Increasing CO_2

- Increases photosynthetic rate
- Increases biomass
- Increases water use efficiency
- Increases tolerance for low light levels
- Increases optimum temperature for photosynthesis

Higher Temperature

- Inhibition of seed germination
- Reduction in plant growth and development
- Alteration in photosynthetic rate
- Alteration in phenology and dry matter partitioning
- Water loss
- Oxidative stress
- Yield and quality reduction (C_3 plants are more susceptible to higher temperature stress than C_4 plants)

Precipitation Variation

- Affects the production of traditional crops
- Increases crop disease incidence
- Soil fertility changes
- Variable soil water availability
- Water scarcity in productive areas due to reduced freshwater resources
- Reduced nutrient use efficiency
- Physical damage due to excess rainfall
- Economic and community loss due to droughts and floods

Figure 3: Weather-related effects on the development and growth of crops

on soil formation and management, having a major impact on the structure of the soil, stability, retention of water, nutrient status, as well as erosion (Rodrigues *et al.*, 2023). The primary projected effects of climate change are higher temperatures and weather extremes (such as severe rainfall, drought conditions, frost conditions, storms, and sea level rise), all of which pose major risks to soil productivity, health, and compactness (Bolan *et al.*, 203). Figure 4 enumerates the anticipated effects of climate change on several soil processes.

The effects of rising temperatures, fluctuating precipitation, and rising CO_2 levels on soil can be profound and far-reaching. These alterations may have an impact on soil fertility, structure, and capacity to sustain plant development, all of which have an impact on food security, and biodiversity, hence the health of the planet as a whole. A decrease in soil fertility and an impact on plant growth can result from soil acidification, which is caused by an increase in CO_2 (Ferdush *et al.*, 2023) This may have significant effects on biodiversity, water availability, and food security. A vital part of preserving soil health is the diversity and number of soil organisms, which can be impacted by soil acidity. Consequently, it is essential to mitigate the effects of rising CO_2 levels on soil in order to maintain sustainable methods of land use and ecosystem preservation (Kalogiannidis *et al.*, 2023). Temperature increases have the potential to modify soil nutrient levels and structure by quickening the pace of decomposition and nutrient cycling. Raising soil temperatures can also result in a decrease in soil

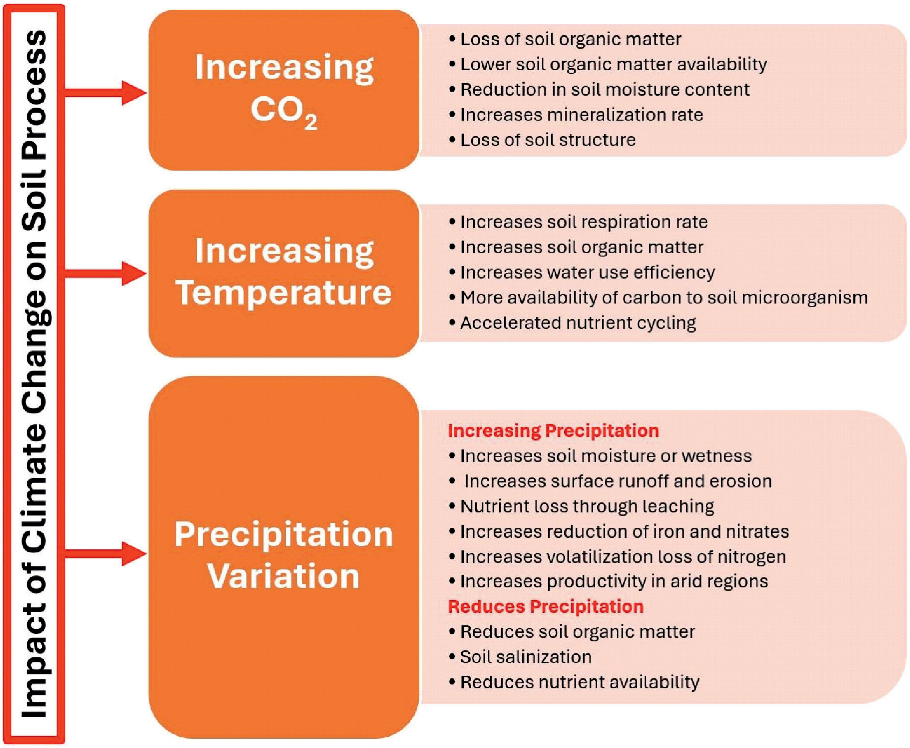


Figure 4: The potential impact of changing temperatures on soil activity

moisture, which can worsen soil erosion and impair soil health (Furtak and Wolińska, 2023).

Elevated temperatures can also have a notable effect on the variety and arrangement of soil microorganisms, which are essential for preserving the fertility and health of the soil. Increased runoff, reduced water infiltration into the soil, and soil erosion can all be consequences of changes in rainfall patterns, such as more frequent and intense rainstorms or protracted droughts. This can cause the soil to become less healthy and capable of storing less water and nutrients, as well as cause degeneration of the soil. The distribution and variety of soil microorganisms can vary as a result of altered precipitation patterns, which can have a substantial effect on the fertility and health of the soil (Furtak and Wolińska, 2023).

Furthermore, the process of soil salinization is impacted by climate change (Corwin, 2021). In semi-arid or arid agricultural areas that get irrigation, the process of soil salinization develops close to the plant's root zone, decreasing the amount of water accessible and increasing the transfer of available salts from low-lying water levels (Hailu and Mehari, 2021). This may lead to more saltwater intrusion and the reuse of deteriorated waters. It has been demonstrated that notable rainfall levels—whether excessive or insufficient—can have a major impact on the root zone's soil salinity. It has been shown that the water table rose as a result of the increased rainfall brought on by climate change (Mayowa *et al*., 2015). Research findings indicated that the capillary rising phenomenon is responsible for the salt's inclination from the water level to the soil surface when the water level is less than or equal to two meters below the soil surface. When there is little rainfall at the root zone during the dry season, this water movement may cause salt to accumulate close to or at the soil's surface.

In a similar vein, salinity, water motions, and levels of water in the soil surface and water table can all be affected by drought (Hailu and Mehari, 2021). The decrease in water supply during a drought leads to a notable increase in land, which is something that should be observed. Consequently, when upward water flow happens as a result of the capillary rising from the lower water table, salt deposition is seen on the soil surface. Conversely, drought influences the build-up of minerals and salt in the root zone during water from wells over-drafting for agricultural purposes from a non-salty aquifer situated adjacent to a saline aquifer or close to a coastal zone (Corwin, 2021). Moreover, recycling degraded water in agricultural regions that are experiencing drought—such as drainage and municipal waters—may cause the root zone's salinity to rise (Singh, 2021). As a result, it's critical to comprehend and keep an eye on how rising CO_2 levels, temperatures, and fluctuations in precipitation affect soil, as well as to put policies in place to lessen their detrimental effects and enhance soil health.

3. Climate Change's Effects on Fisheries and Livestock

With about 40 % of the total agricultural GDP coming from the cattle industry, it is the main driver of agriculture. Global demand for items with animal origins is expected to treble by 2050, mostly as a result of growing living standards (Daszkiewicz, 2022). One of the main obstacles to effective cattle production is extreme weather. Animal productivity and efficiency will be greatly impacted by disease outbreaks, heat stress, shifting feed crop varieties and quality, and increasing human rivalry for finite natural resources. Warming winters may encourage the occurrence and spread of diseases in cattle that can last all year and grow more contagious as temperatures rise (Koirala and Bhandari, 2019). The main way that heat stress impacts animals is through its effects on their ability to produce milk and meat, their ability to reproduce, and their general health. However, variations in precipitation, temperature, and CO_2 all have an impact on the quantity and quality of fodder (Seibert *et al*., 2021). Figure 5 shows how livestock are affected by climate change.

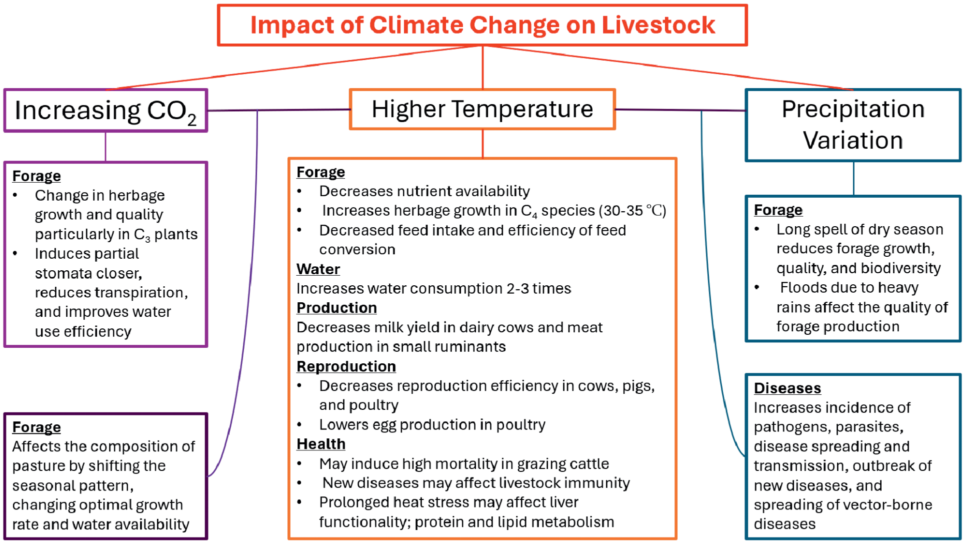
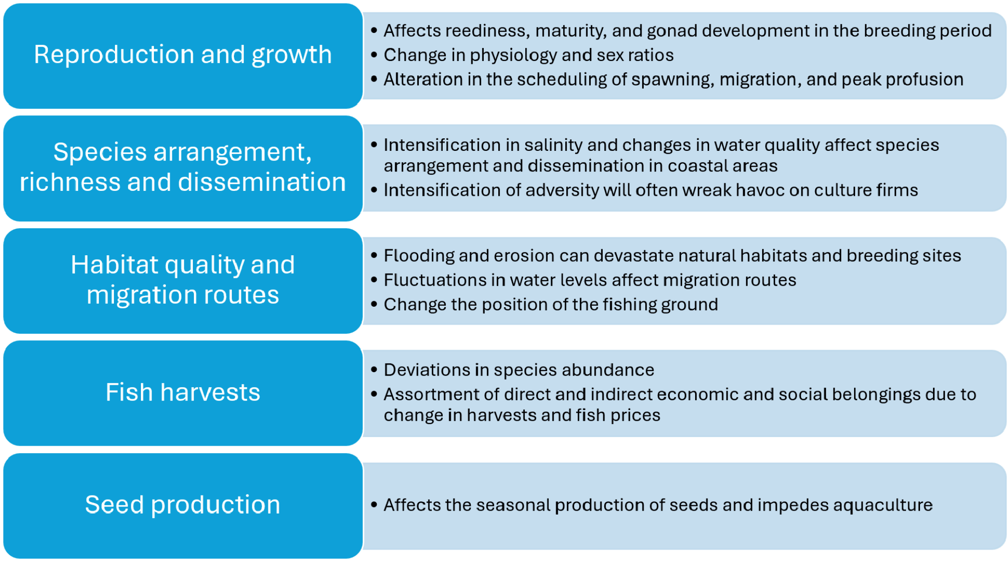


Figure 5: The effects of climate change on livestock productivity

The production and health of livestock are being impacted by the changing precipitation patterns and rising temperatures brought on by the increase in CO_2 levels in the environment. In addition to lowering feed quality and raising the degree of heat stress in animals, CO_2 can also lower feed intake and growth rates (Sammad *et al*., 2020). Furthermore, the intensity and frequency of heat waves are changing due to the rise in global temperatures, which can have a negative effect on the productivity and health of cattle. Reduced development rates, greater susceptibility to disease, decreased fertility, and decreased feed intake are all consequences of heat stress in cattle (Sammad *et al*., 2020). Modifications in the frequency and intensity of droughts and heavy precipitation events can have an impact on the availability and quality of fodder for livestock. Drought circumstances can lead to decreased feed availability and forage production, which can inhibit cattle development and weight increase.

However, excessive rain can also damage grasslands and create flooding, which lowers the pastures' quality and makes them less useful for feeding livestock. Livestock productivity and health are generally being negatively impacted by the combination of rising CO_2 levels, rising temperatures, and variable precipitation. Therefore, in order to maintain the health and sustainability of their livestock operations, farmers and ranchers need to modify their management strategies (Holechek *et al*., 2020).

Fish populations and fishermen will be significantly impacted by the impacts of climate change on the marine ecosystem, notably those related to warmth, acidity, and sea level rise. Furthermore, it is changing the range and productivity of freshwater and marine fish species. Studies on the effects of climate change indicate that populations of marine invertebrates and fish are moving to deeper waters and higher altitudes. The relative abundance of some species may change when specific settings become less favorable for them (Theuerkauf *et al*., 2022). By 2100, it is predicted that fish production will decline by 6 % globally and by 11 % in tropical regions. Additionally, it projected an 85 % decrease in terrestrial and marine production, especially in the coastal nations under analysis (Lam *et al*., 2020). Figure 6 illustrates the specific impact of climate change on fisheries.



Reproduction and growth

- Affects reediness, maturity, and gonad development in the breeding period
- Change in physiology and sex ratios
- Alteration in the scheduling of spawning, migration, and peak profusion

Species arrangement, richness and dissemination

- Intensification in salinity and changes in water quality affect species arrangement and dissemination in coastal areas
- Intensification of adversity will often wreak havoc on culture firms

Habitat quality and migration routes

- Flooding and erosion can devastate natural habitats and breeding sites
- Fluctuations in water levels affect migration routes
- Change the position of the fishing ground

Fish harvests

- Deviations in species abundance
- Assortment of direct and indirect economic and social belongings due to change in harvests and fish prices

Seed production

- Affects the seasonal production of seeds and impedes aquaculture

Figure 6: The impacts of changing climate on fisheries

Ocean warming is one of the specific effects of climate change on fisheries. Fish species' range, abundance, and migration habits may all alter as a result of this. Growth as well as reproduction of fish can be impacted by warmer seas, which could result in variations in the quantity and caliber of captures. Ocean acidification is a particular effect of climate change that arises from rising atmospheric CO_2 levels. The biology as well as physiology of marine animals, such as shellfish, fish, and other species that are crucial for both commercial and subsistence fishing, may be greatly impacted by this (Tai et al., 2021). Many marine species require calcium carbonate to create their shells and skeletons, and acidification can restrict this supply (Gold and Vermeij, 2023). Changes in patterns of ocean circulation brought on by climate change may have an impact on fish as well as other marine species' abundance and distribution. The shifting of fish stocks as a result of these modifications may have an effect on fishing communities whose livelihoods depend on particular species. Fisheries may also be severely impacted by the rising frequency and power of extreme weather events like typhoons and hurricanes. These occurrences have the potential to interfere with fishing operations and harm ports, infrastructure, and fishing gear (Muhala *et al*., 2021).

4. Enhancing Climate Resiliency with Precision and Digital Agriculture Techniques

In recent years, food security and agricultural productivity have been gravely threatened by climate change. One of the key strategies for achieving greater productivity in the face of changing climate circumstances is to achieve climate resilience by cutting GHG emissions and improving the efficiency of the resources that are already available. The agricultural system's resilience to harm and quick recovery are aided by adaptation and mitigation techniques. In this sense, achieving greater output with fewer inputs will be made possible by precision and digital methods that combine various tools and management techniques. With a potential to contribute to global warming of 28–36 and 265–298 times that of CO_2 over a 100-year time horizon, respectively, methane (CH_4) and nitrous oxide (N_2O) are the principal anthropogenic GHGs resulting from agriculture (Vallero, 2019). One of the main causes of CH_4 and N_2O is improper watering and nutrient management techniques. Emissions of these gases can be somewhat reduced by using water and fertilizers wisely. At this point, cutting emissions and increasing resource efficiency are mostly dependent on precise water and nutrient management (Hassan *et al*., 2022).

4.1. *Precision nutrient management*

Based on crop needs and supply capability, site-specific nutrient management (SSNM) is required to maximize fertilizer use and crop output. The main causes of anthropogenic GHG emissions in the form of N_2O are excessive fertilizer application and unbalanced plant nutrition. One of the best chances to achieve climate resilience in recent years is to increase nitrogen utilization efficiency (NUE). Based on crop species, current climate, soil health, and additional crop management techniques, the NUE now varies between 30 % and 50 %. Precision nutrient management in this context will help achieve higher efficiency, especially with nitrogen fertilizers, by choosing the proper source, amount, place, and application method. This will lower N_2O emissions, which in turn will mitigate GHG emissions. Furthermore, by using fewer inputs, precise approaches can contribute to increased nutrient utilization efficiency. Figure 7 lists and presents the many technologies and decision-making tools that can be used to improve the NUE via SSNM.

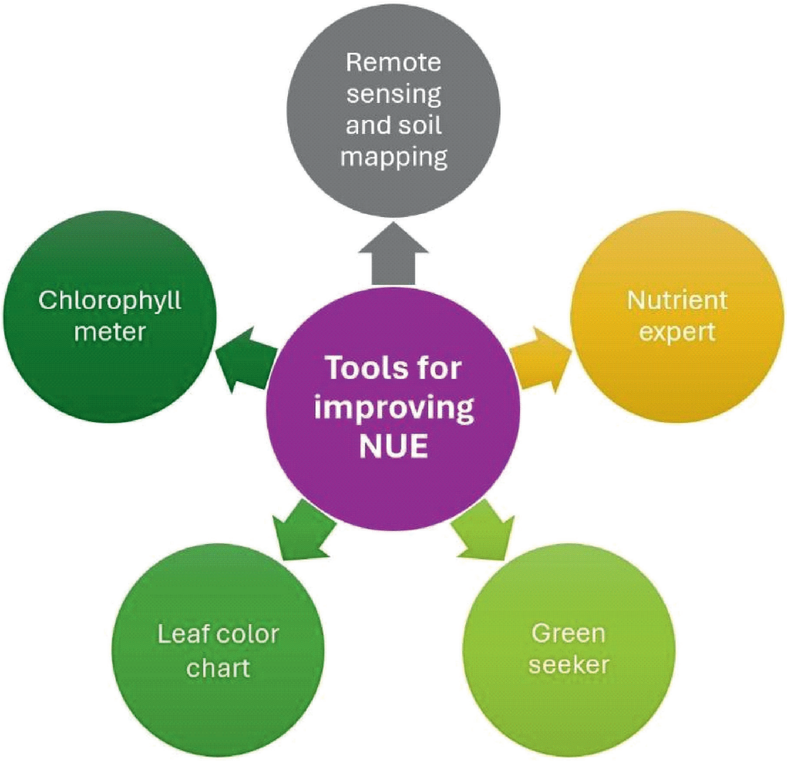


Figure 7: Methods for increasing nutrient efficiency

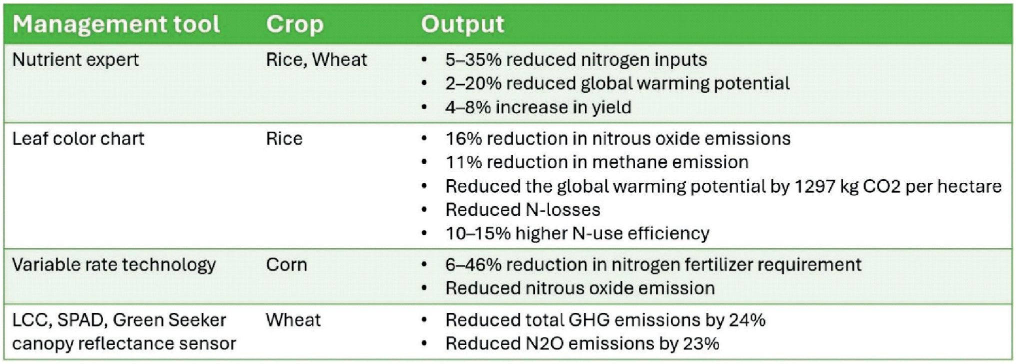
As previously indicated, the purpose of employing the SSNM system is to guarantee the crop's nutrient requirements to meet a particular growing environment or area. It is an amalgamation of nutrient management systems (Chivenge *et al*., 2022). Despite all of SSNM's efforts to increase farm trail productivity, the organization's acceptance rate remains unremarkable.

Furthermore, a lot of extension agents think that the SSNM is complicated and difficult to apply, therefore using it is necessary to comprehend the idea and obtain knowledge about the field and crop (Chivenge *et al*., 2022). In order to increase crop yield, a variety of nutrient decision assistance tools have been used recently. It's interesting to note that the aforementioned tools have been customized using the rules and values of SSNMs.

As shown in Figure 7, there are numerous technologies available to enhance the efficiency of fertilizer use in agriculture, such as soil mapping, remote sensing, green seekers, nutrient experts, chlorophyll meters, and leaf color charts. With the use of these instruments, farmers may apply fertilizer more intelligently, lowering input costs, increasing yields, and lessening the environmental effect of their operations (Sharma and Bali, 2018).

One of the previously mentioned computer-based decision tools, Nutrient Expert (NE), for example, can assist producers and plant growth consultants in creating the optimal plans for managing various nutrients, such as N, P, and K, for any cereal crop and in any location. Based on an algorithm developed from a series of on-farm trial statistics, the necessary quantity of fertilizers is computed utilizing the SSNM principle as well as guidelines. It's interesting to note that the crops in SSNM have different needs for fertilizer (N, P, and K) depending on the connection across nutrients and balancing uptake at harvest grain yield (Rodriguez, 2020). A similar precision instrument used in agriculture is the Leaf Color Chart (LCC). The timing and rate of nutrient demand have been greatly aided by this useful instrument, and numerous studies have shown that using LCC kits can boost yield improvement and nutrient utilization efficiency. This set includes a range of hues that, under the same lighting circumstances, could be contrasted with leaves (Rao and Das, 2023). This non-destructive technique is frequently used to assess intelligent and effective nitrogen management under a range of conditions, such as soil, climate, crop type, and management (Bhusal and Thakur, 2022).

One essential tool for site-specific PA is variable rate technology (VRT). Reduced environmental damage and more efficient use of inputs are the outcomes of applying the VRT technology, which allows for the application of varied doses of nutrients within an agricultural field depending on the geographical variation of soil and crop (Pawase *et al*., 2023). While any crop or field input could benefit from this kind of management, grain crops, and fertilization operations have historically made use of VRT (Fabiani *et al*., 2020). A portable tool called a chlorophyll meter quantifies the amount of chlorophyll present in crops, giving an accurate indication of their nutritional status and overall health. Using a chlorophyll meter, farmers are able to quickly determine the nutrients that their crops need. By modifying fertilizer applications accordingly, they may improve nutrient use efficiency and reduce waste (Ali, 2020; Chivenge *et al*., 2021). A device called Green Seeker employs near-infrared (NIR) technologies to determine how much chlorophyll is present in crops. By using this data, managers can apply fertilizer more precisely and at a given spot, increasing efficiency in using nutrients and decreasing waste (Sharma and Bali, 2018). Using satellite and aerial pictures, remote sensing is a technique that collects information on crop conditions, particularly soil health and nutrient status. By using this data, managers can apply fertilizer more precisely and at a given spot, increasing the utilization of nutrients and decreasing waste (Chivenge *et al*., 2021). Making a thorough map of the nutrient status and soil properties in a particular field is a tool known as "soil mapping." By using this data, managers can apply fertilizer more precisely and at a given spot, increasing the utilization of nutrients and decreasing waste (Sharma and Bali, 2018). Figure 8 shows the possibilities for reducing GHG emissions from various crop management techniques.



Management tool	Crop	Output
Nutrient expert	Rice, Wheat	• 5–35% reduced nitrogen inputs • 2–20% reduced global warming potential • 4–8% increase in yield
Leaf color chart	Rice	• 16% reduction in nitrous oxide emissions • 11% reduction in methane emission • Reduced the global warming potential by 1297 kg CO2 per hectare • Reduced N-losses • 10–15% higher N-use efficiency
Variable rate technology	Corn	• 6–46% reduction in nitrogen fertilizer requirement • Reduced nitrous oxide emission
LCC, SPAD, Green Seeker canopy reflectance sensor	Wheat	• Reduced total GHG emissions by 24% • Reduced N2O emissions by 23%

Figure 8: Different management strategies and their ability to reduce GHG emissions (Sapkota *et al*., 2021)

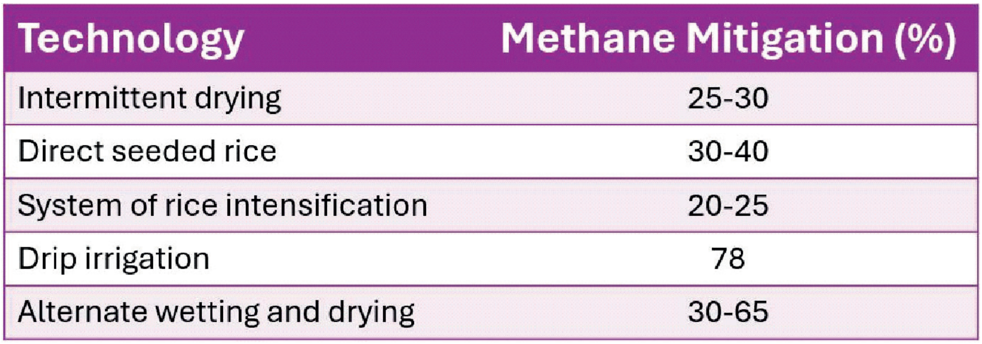
By improving nutrient management in agricultural practices, precision and digital agriculture technologies can contribute to the development of climate resilience. Increasing efficiency, reducing waste, and optimizing fertilizer application are some of the main advantages of precision nutrient management. By integrating data from soil as well as plant sensors, farmers can tailor their nutrient management techniques to the specific requirements of their crops and soil, leading to greater production and fewer expenses for inputs (Higgins *et al*., 2019). Precision nutrient management also has the benefit of lessening negative effects on the environment and agriculture. By reducing fertilizer consumption and optimizing application, PA may assist prevent nutrient runoff and pollution, which can have detrimental effects on ecosystem health and water quality (Sishodia *et al*., 2020). Precision nutrient management does have several disadvantages, too. For example, utilizing PA technologies may be costly and necessitate large investments in hardware, software, and data administration.

Additionally, there might be a learning curve associated with employing these technologies, meaning that farmers along with other agricultural experts would need to receive additional training (Barnes *et al*., 2019). In general, a number of variables, such as farming methods, soil, and climate conditions, as well as the accessibility of technology and training, will affect how successful precision nutrient management is at boosting climate resilience. To evaluate the efficacy of these measures, agriculturalists, researchers, and business experts will need to work together and conduct ongoing monitoring and analysis (Higgins *et al*., 2019). Future recommendations may include expanding farmers' access to technology and training, creating best practices and standardized protocols for data collection and analysis, and advocating for laws and incentives that support sustainable nutrient management techniques in order to optimize the advantages of precision nutrient management over climate resilience. In addition, to guarantee that these tactics continue to be applicable and successful in the face of changing environmental conditions, continuous research and development of PA technology will be necessary.

4.2. Precision water management

The world's need to increase climate resilience through digital and precision agriculture strategies—like precision water management—is growing as the impacts of climate change worsen. By maximizing irrigation techniques and cutting down on water wastage, precision water management can assist farmers in adapting to changing climates as well as extreme weather events, such as floods and droughts. It makes use of cutting-edge technologies to track crop water requirements, soil moisture levels, and meteorological conditions in real-time. These technologies include sensors, analytics of data, and control systems. Precision water management reduces waste and increases crop yields by assisting farmers in making educated decisions regarding when and what quantity of water to apply to crops through the collection and analysis of this data (Bhakta *et al*., 2019). Furthermore, by reducing the impacts of water stress on crops, farmers can increase their crops' resistance to drought as well as other extreme weather events through the use of precision water management. It also lessens the environmental impact of agriculture and contributes to the conservation of water resources for future generations. Precision water management may assist in safeguarding aquifers, rivers, and additional water supplies by cutting down on water waste and improving irrigation techniques, guaranteeing that these resources will remain accessible during dry spells. Precision nutrient and water management techniques, the use of climate-resilient cultivars, slow-releasing fertilizers, laser land leveling, rainwater harvesting, minimum tillage techniques, crop diversification, carbon sequestration, and sustainable land use and management will all be crucial in achieving climate resilience in the current climate change scenario (Jat *et al*., 2022).

Applying irrigation water precisely contributes to both decreased GHG emissions and increased crop productivity. With rice production accounting for 1.5 % of all anthropogenic GHG emissions worldwide, it is the primary source of CH_4 and N_2O emissions (Wang *et al*., 2023). The majority of rice grown worldwide is under-puddled transplanted rice, which uses less water. In this sense, implementing various irrigation management strategies and rice crop farming techniques will aid in achieving increased water usage efficiency and lowered methane emissions. By preserving rice productivity, irrigation management techniques including spray irrigation, drip irrigation, and alternate soaking and drying instead of floods will lower GHG emissions. Figure 9 shows the methane mitigation percentage for various irrigation techniques. Lowering the carbon footprint of rice farming and guaranteeing a viable rice farming industry require an understanding of the mitigation proportion of CH_4 under various irrigation techniques. This paper investigates the proportion of CH_4 mitigation under five distinct irrigation techniques: drip irrigation, direct seeded rice, intermittent drying, drip irrigation, as well as alternate drying and wetting. Every technique has a different amount of mitigation; for example, drip irrigation reduces GHG emissions by 80 %, direct seeded rice reduces emissions by 30–40 %, intermittent drying reduces emissions by 20–25 %, and alternate wetting with drying reduces emissions by 30–60 %. The decrease in GHG emissions can be attributed to various variables, including decreased water consumption, enhanced water management, accurate use of water, and aerobic decomposition of organic waste. However, the percentages of CH_4 that are mitigated by various irrigation techniques fluctuate based on a variety of parameters, including soil composition, climate, and management techniques (Win *et al*., 2020; Hiya *et al*., 2020; Islam *et al*., 2020; Sikka *et a*l., 2022).



Technology	Methane Mitigation (%)
Intermittent drying	25-30
Direct seeded rice	30-40
System of rice intensification	20-25
Drip irrigation	78
Alternate wetting and drying	30-65

Figure 9: Methane mitigation percentages for various techniques of irrigation (Win *et al*., 2020; Hiya *et al*., 2020; Islam *et al*., 2020)

There are a number of benefits to using precision water management in conjunction with digital and precision agriculture initiatives. By giving precise information about the soil's moisture and its crop water demands, it can reduce the amount of water used for irrigation, which is one of the major advantages (Neupane and Guo, 2019). Additionally, it can aid in preventing overwatering, which can lead to nutrient leaching, waterlogging, and soil erosion. Ultimately, this can improve crop yields and reduce water waste. Farmers can also benefit from precise water management by using the technology to help mitigate the consequences of climate change, including floods and droughts (Srivastav *et al*., 2021). Precision water management can assist farmers in making knowledgeable decisions about water use during droughts and preventing flooding by giving precise details on the moisture content of the soil and crop needs for water (den Besten *et al*., 2021). But there are some disadvantages to precision water management as well. One of its biggest drawbacks is that it requires a large infrastructure and technological investment, which can be very costly for small-scale farmers with little funding. Moreover, variables like soil variability as well as calibration of sensors might affect the precision of water management, leading to erroneous data and even erroneous management choices (Brahmanand and Singh, 2022). Regarding recommendations for the future, more study is required to evaluate the economic feasibility and efficacy of precision water management in many agricultural systems and geographical areas. Furthermore, more user-friendly and reasonably priced technology is required in order to deliver precise data and enable efficient water management choices. Moreover, farmers can fully profit from this technology by encouraging the adoption of precise water management techniques through educational and training initiatives (Brahmanand and Singh, 2022).

4.3. Precision Land use Management

Sustainable land use practices aim to minimize the negative environmental effects of land usage while promoting economic and social growth. They may also assist in lowering emissions, enhancing carbon sequestration, and promoting ecosystem resilience to the impacts of climate change (Everest *et al.*, 2021). These practices can contribute to a number of benefits, such as enhanced biodiversity, enhanced soil health, minimized soil erosion, elevated soil fertility, and upgraded food security, all while decreasing carbon. Reducing GHG emissions can also help communities become more resilient to the effects of climate change. There are numerous instances of climate change mitigation strategies that involve sustainable land use. For example, regenerative agriculture uses techniques like rotational grazing, cover crops, and agroforestry to improve soil health, lower GHG emissions from agriculture, and store carbon in the soil (Vasu *et al*., 2018; Everest *et al*., 2021). On the other side, selective logging, lowering deforestation and degradation, as well as promoting forest regeneration—all of which assist lessen climate change—are examples of sustainable forest management techniques. Reducing GHG emissions and promoting carbon storage can be achieved through sustainable land use planning that takes into account the potential for sequestering carbon on various types of land. Finally, fostering denser, walkable communities and restricting urban sprawl can help cut down on emissions from energy consumption, transportation, and other sources (Vasu *et al*., 2018).

By empowering land managers to make better-educated choices on the appropriate use of their land, precision as well as digital agriculture techniques hold significant promise for fostering climate resilience. The ability of a specific land use to satisfy the needs of a specific region while accounting for variables like soil type, accessibility to water, and climate conditions is referred to as land use appropriateness. Land managers can evaluate land use suitability more accurately and decide which land uses are most suited for a given area by utilizing precision as well as digital agriculture techniques (Hussain *et al.*, 2024). The application of precision irrigation technologies, which can lower water consumption and boost crop production efficiency, is one instance of precision plus digital agriculture tactics in action. These systems monitor the moisture content of the soil using sensors and other technology, then modify the amount of water applied. Land managers can help boost water availability in areas susceptible to drought as well as water shortages by implementing these techniques to reduce water usage (Akpoti *et al*., 2019; Everest *et al*., 2021).

Analyzing crop growth patterns and soil health using digital technologies like machine learning algorithms and satellite data is another example. Land managers can use these techniques to pinpoint places that are vulnerable to nutrient depletion, soil erosion, and other problems that might affect crop productivity and worsen climate change. They can then utilize this data to create more focused land management plans that deal with these problems and promote climate resilience.

Increased crop output, better soil quality, less water use, and increased climate resilience are just a few benefits of the land use appropriateness method. Farmers may optimize crop yields and reduce environmental impact by determining the best varieties of crops, nutrient management strategies, and irrigation techniques for each unique region (Taghizadeh-Mehrjardi *et al*., 2020). This approach's major upfront costs for equipment and data collection are one of its disadvantages. To make well-informed judgments on the suitability of their land use, farmers need to have the ability to access high-quality soil mapping, and weather data, including crop models (Meyfroidt *et al*., 2022). Furthermore, this strategy might not work in places with poor access to technology or in climate-wildly inconsistent locations. Measuring the effectiveness of land use appropriateness policies can be difficult from an evaluation perspective. Gathering information on crop yields, water use, and soil quality may be necessary for farmers to assess the success of their precision agriculture tactics. Additionally, in order to guarantee that the chosen land use methods continue to be effective over time, this technique might need regular monitoring and modifications (Everest *et al*., 2021). Future proposals for land use suitability techniques include encouraging cooperative research efforts amongst farmers, scientists, and policymakers, creating user-friendly instruments for supporting decisions, and increasing utilization of technology as well as data collection techniques. Furthermore, by providing monetary rewards for sustainable land utilization and making investments in infrastructure to facilitate data collection and analysis, authorities can encourage the use of precision agriculture tactics (Akpoti *et al*., 2019).

5. Adoption of Digital Agriculture

Using technological advances in agriculture offers a significant chance to reduce the consequences of climate change and end hunger and poverty (Anser *et al*., 2023). Since connectivity and the instantaneous processing of enormous volumes of information allow for more efficient operations, more economic exchange, higher benefits for the environment, and improved conditions for employees in the field, digitalization will modify every link in the agri-food production chain. To adopt and implement creative solutions, governments will need to support the growth of rural communities as well as small companies as well as bolster the infrastructure in rural areas in order to carry out these changes. Research carried out in the United States evaluated the viewpoints on digital agriculture deployment and found that perceptions of the resulting benefits vary and are contingent on the agricultural practices (Thompson *et al.*, 2019). It's critical to comprehend farmers' perceptions of the advantages technology can offer them for the purpose of better understanding their adoption decisions—or lack thereof.

Prior research on digital agriculture highlights how it helps farmers make better decisions by providing systematic analysis of agricultural systems and digital solutions related to robotics along with artificial intelligence (Subeesh and Mehta, 2021). They do, however, emphasize that in order to facilitate a future generation of farmers who are keen to learn and use current agricultural technologies, it is imperative that more comprehensive user training be coordinated. They believe that now is the ideal moment for society to develop toward modern, sustainable agriculture, enabling it to demonstrate the full force of data-driven agricultural management in order to meet the issues facing food production in the twenty-first century.

A questionnaire was distributed to all businesses in the region that deal with sugar and alcohol as part of research done in Sao Paulo to look into the use of digital agriculture technologies in sugarcane production (Silva *et al.*, 2011). According to the study's findings, businesses that have embraced and implemented these technologies have demonstrated to benefit from them in the form of enhanced management, increased productivity, less expenses, less environmental impact, and better sugarcane quality. Additionally, another study by Borghi *et al.* (2016) examined how manufacturers and suppliers of services in various Brazilian agricultural regions used and adopted digital agriculture technologies, and it discovered a correlation between the rise in technology adoption and agricultural economic gains. The primary barriers preventing the widespread use of these innovations in the field were identified as financial concerns and the challenges associated with utilizing the software and equipment given by field teams' deficiency of technical training (Bolfe *et al.*, 2020). According to this study, at least one digital technology, including software, digital platforms, mobile apps, GPS, remote sensing, as well as field sensors, is used by Brazilian farmers in their production system. As a result, the percentage drops as the technological complexity of the application rises (Bolfe *et al.*, 2020).

By increasing the sustainable management of natural resources, increasing agricultural productivity, and lessening the adverse effects on the environment, digital agriculture has promised (Borghi *et al*., 2016). The lack of technology and digital infrastructure in some areas, the lack of knowledge and comprehension of digital agriculture across farmers and land managers, as well as the high costs of setting up and sustaining digital agriculture systems all pose obstacles to expanding its use. Inadequate data quality and availability for creating precise models and algorithms, integration issues between digital agriculture technologies and current farm management techniques alongside practices, worries about data security and privacy, and doubts about the efficiency of digital agriculture in reducing climate change and enhancing sustainability are some of the other difficulties (Bolfe *et al*., 2020).

Land managers will have a number of difficulties in the future because of the changing environment and technological advancements. A variety of technologies can be utilized for implementing digital agriculture as a means of mitigating the effects of climate change, which has increased both the severity and frequency of extreme weather events including heatwaves, floods, and droughts that can cause crop failure including soil erosion (Malhi *et al*., 2021; Abbass *et al*., 2022). Crop yields will be impacted by temperature and precipitation patterns, and ecosystem functions will be impacted by shifting vegetation zones and altered temperatures. Land managers also have to deal with the spread of diseases, pests, and invasive species, which can have a detrimental effect on livestock and crop productivity as well as the general health of ecosystems. There may be a disconnect between land managers and technology due to farmers' and land managers' lack of awareness and comprehension of digital agriculture. Other difficulties include the lack of sufficient data quantity and accessibility to create precise models and algorithms, as well as the integration of digital agriculture technology with current farm management procedures and systems (Kayad *et al*., 2020).

Land managers are investigating a variety of technology options to tackle these issues. Climate-smart agriculture practices, like agroforestry, which integrates trees and crops to improve ecosystem services while lowering GHG emissions, must also be used. Precision agriculture technologies, like soil sensors, drones, as well as satellite imagery, must be utilized to track soil alongside crop conditions along with optimizing fertilizer and water usage. Finally, alternative energy sources, like biogas and biofuels, must be created to lessen dependency on fossil fuels while offering alternative energy sources (Cherwoo *et al*., 2023; Mignogna *et al*., 2023).

6. Structure of Climate-Smart Agriculture

Agriculture is a climate-sensitive industry; therefore, climate change and its variability have a significant impact on it, albeit the effects vary by region, crop, and degree of resilience and adaptability in the farming industry. Low-latitude and developing nations are more vulnerable to climate change because of factors like poverty, unstable income, and a lack of capacity for adaptation. A lot of emphasis is placed on climate-smart agriculture (CSA) as a means of achieving food security in the face of climate change issues. The three main goals of the CSA are to reduce GHG emissions from various inputs and results in the cultivation procedure, adapt and build resilience to both short- and long-term risks and stresses, and achieve nutritional and food security through increased productivity and the efficient use of available resources (Everest, 2021). These three goals are integrated by CSA in terms of the economic, social, and environmental aspects in order to jointly address climate threats and sustainable food production. To make crops more climate resilient, climate-smart methods must be developed at every stage of agricultural production. Crop management, animal management, conservation of soil and water, energy and carbon management, and so forth are all included in the CSA. Figure 10 provides an illustration of the CSA actions. However, because local climates fluctuate throughout the world, CSA techniques are unique to some nations and areas. Together with the aforementioned management techniques, prompt distribution of weather-based agro-advisory services and

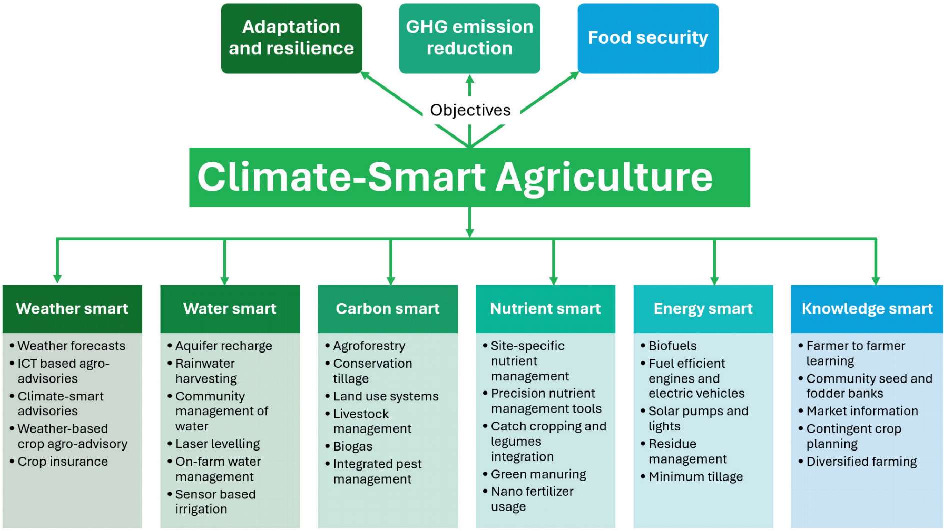


Figure 10: The framework for CSA's goals and treatments in multiple contexts

enhanced farmer understanding of CSA practices might help them get greater yields in the context of climate change. There is a thorough discussion of the significance of fundamental CSA practices and how they affect the reduction of GHG emissions.

Climate-smart agriculture can benefit greatly from the technologies and practices employed in digital agriculture, such as robots, IoT sensors, and AI-based processing of data software. The invention and application of robotic mechanical weeding is one example, as are devices utilizing variable rate technology that apply pesticides and fertilizers just where necessary, minimizing the quantity of chemicals delivered to the soil. This can lessen the possibility of contaminating the soil and water as well as GHG emissions. In a similar vein, precision irrigation methods can maximize crop growth and minimize water waste. Farmers can modify irrigation plans to make sure crops receive the ideal quantity of water by employing digital sensors to monitor soil moisture levels as well as weather patterns. IoT sensors have made it possible for farmers in closed-field agriculture, such as dairy farming and greenhouses, to anticipate changes in the outside weather and employ the best control strategies to use less energy for heating and cooling. In order to determine which crops are most suited to their local environment and which would perform best under future climatic conditions, growers may now simulate how various crops will perform under various climate scenarios thanks to mathematical crop models. Reducing the requirement for inputs like energy, water, as well as fertilizer through crop selection increases resilience to climate change. Conversely, digital platforms can help farmers, scientists, and policymakers work together to create novel approaches to climate change, like crop types that are more resistant to extreme weather.

6.1. Crop Management

Crop management that is climate-smart is essential to CSA. The objective is to reduce the environmental impact of agriculture by managing resources and conserving them through the use of innovative and sustainable agricultural practices, technology, and regulations. Climate-smart crop management aims to increase crop resistance for altering climate conditions and boost agricultural system productivity. Precision agriculture is one of the main components of climate-smart crop management. Information and communication technologies (ICTs) are used in precision agriculture to monitor and manage crops more efficiently. For instance, precision irrigation systems employ sensors to gather information on crop growth, weather, and soil moisture. They then use that data to automatically modify water usage, making sure the proper amount of water is applied at the right time to the right spot. This helps farmers save water resources and adjust to evolving climate conditions by lowering water waste and increasing irrigation efficiency. Employing agronomic techniques that encourage water-use efficiency and drought-tolerant crop types is a crucial component of climate-smart crop management. For instance, mulching and conservation tillage can help to retain moisture in the soil, decrease water evaporation, and improve water-use efficiency. Crop rotation techniques that optimize water utilization and reduce crop stress can also be implemented by farmers. This can lessen the negative impacts of water stress on crops, increasing their resistance to the adverse consequences of drought as well as harsh weather conditions. Climate-smart crop management includes various agronomic techniques as well as the creation and execution of beneficial policies and initiatives. For instance, governments can provide financial assistance to farmers that wish to invest in sustainable land use practices and precision agriculture technology and techniques. Furthermore, they have the option to allocate resources towards research and development in order to facilitate the wider adoption of these methods and technologies by farmers.

The field's GHG emissions can be reduced, and weather anomalies can be tolerated with the use of practices including crop rotation, improved storage and processing methods, drought including heat-tolerant varieties, short-duration varieties, enhanced storage and processing systems, and crop diversification. For instance, switching to rice-wheat cropping systems from rice-rice cropping systems can help cut down on GHG emissions overall, especially CH_4, as rice contributes significantly to CH_4 emissions because of constant flooding. In comparison to their solo crops, maize and soybean intercropping systems resulted in lower N_2O emissions, according to a Chinese study by Shen *et al*. (2018). Similarly, less tillage and residue mulching in the maize plus wheat intercropping system contributed to decreased carbon emissions (Gou *et al*., 2021). As a result, implementing appropriate crop management techniques will be crucial to lowering GHG emissions and increasing yields.

6.2. Livestock Management

One essential component of agriculture that aims to assist farmers in adapting to the effects of climate change on the production of livestock is climate-smart livestock management. Climate change is impacting cattle productivity through altered temperature and precipitation patterns, as well as heightened occurrence and intensity of extreme weather events. These effects are having an influence on the welfare, production, and health of cattle as well as posing new management issues for farmers. Climate-smart livestock management aims to assist farmers in implementing cutting-edge, sustainable methods and technologies to maintain their livestock, preserve resources, and lessen the environmental effect of livestock production. Farmers can, for instance, adopt enhanced cattle genetics to make their animals more resistant to the diseases and heat stress brought on by climate change. Furthermore, agroforestry systems can lessen the environmental damage caused by cattle production and contribute to the creation of more resilient landscapes (Grossi *et al*., 2019). The incorporation of climatic data into decision-making procedures is a crucial component of climate-smart livestock management. When deciding when to feed, drink, and relocate their cattle, farmers can use climatic forecasts and meteorological data to make well-informed decisions.

Furthermore, by monitoring and managing livestock more skillfully, remote sensing technology might lessen the negative effects of disease outbreaks and extreme weather on animal productivity and health. Governments and the commercial sector must collaborate to encourage the creation and application of climate-smart livestock management techniques in addition to these doable steps. This entails giving farmers financial support, making investments in animal management techniques that are sustainable, and implementing land use methods that are sustainable. Furthermore, it is imperative that they allocate resources towards research and development in order to promote the adoption of these techniques by farmers (Grossi *et al*., 2019).

Since livestock releases GHGs through enteric fermentation, it is necessary to adopt climate-smart improved feeding techniques, grazing rotation, forage crop diversity, conservation and regeneration of grasslands, manure management, improved animal health, as well as improved animal husbandry practices. A diet high in protein will cut down on the amount of CH_4 that animals emit (Bačėninaitė *et al*., 2022). Raising calves that are resistant to illness and the heat will boost productivity and lower animal mortality.

6.3. *Soil, Water, and Nutrient Management*

Climate-smart strategies for managing soil, water, and nutrients are essential for reducing the negative effects of climate change on agriculture and guaranteeing food security amid a changing climate. These methods are intended to help crops adjust to shifting climatic conditions by enhancing fertilizer efficiency, preserving water, and improving soil health. They improve farming systems’ resistance to the effects of climate change and aid in the reduction of GHG emissions from agriculture. Crop rotation, conservation of soil, harvesting water, and the use of cover crops to increase soil fertility and lessen soil erosion are examples of climate-smart agricultural techniques. By enhancing soil health, farmers can lessen their reliance on pesticides and fertilizers, which increases GHG emissions (Yang *et al*., 2024).

Furthermore, effective water management techniques like micro-irrigation and rainwater collection can lower water usage and contribute to the preservation of this essential resource. Using nutrient management techniques, such as intercropping and the use of organic fertilizers, can help increase crop yields and improve soil fertility. This improves food security and farmer income in addition to lessening the effects of climate change on agriculture. An integrated strategy that includes funding for extension and research services, as well as government policy, as well as government policy is needed to implement climate-smart agricultural practices. By doing this, farmers will be better equipped to adjust to shifting climate patterns and maintain sustainable agricultural methods for upcoming generations.

Achieving higher output via climate resilience requires increasing the efficiency of water and nutrient utilization. Therefore, achieving climate resilience can be facilitated by implementing conservation farming, contour cultivating, organic modification mulching, precision watering, harvesting water, technologies that conserve water, and management of nutrient approaches. Applying biochar was found to increase soil aeration, increase its carbon content, and decrease GHG emissions as compared to treating it with crop residue. Using LCC, paddy soil test equipment, organic modification, and intermittent irrigation techniques, the CSA significantly decreased GHG emissions by 7–23% while increasing economic returns by 42–129 % (Ariani *et al*., 2018).

6.4. Carbon and Energy Management

Reducing GHG emissions, enhancing energy efficiency, and expanding the adoption of renewable energy sources are all part of climate-smart energy and carbon management. This strategy seeks to address the causes and effects of climate change and offer a way forward for a sustainable, low-carbon future. Increasing energy efficiency is one of the most important methods for lowering carbon emissions. This can be accomplished by encouraging the use of low-carbon energy sources like wind and solar power as well as by utilizing more energy-efficient technology like LED lighting and energy-efficient structures. Since renewable energy sources produce less pollutants and do not trigger climate change, developing them can also aid in the reduction of GHG emissions. Transport-related emissions reduction is a key component of climate-smart energy and carbon management. This can be done through encouraging low-carbon modes of transportation like electric cars and public transportation, as well as by employing more fuel-efficient cars and alternative fuels to increase fuel efficiency (Gołasa *et al*., 2021). Climate-smart carbon and energy management includes not only lowering emissions but also putting carbon capture, utilization, and storage technologies into practice. This entails removing CO_2 emissions from factories and power plants and storing them in a secure location. The creation of a legislative framework that encourages the application of energy management and climate-smart carbon activities is crucial, too. This involves creating rules and incentives to promote the use of low-carbon technologies and the cutting of emissions from industry and transportation.

Sustainable food production can be achieved by implementing energy- and carbon-smart strategies. By implementing the agroforestry concept of cultivating trees and plants on bunds, orchards of fruit, multipurpose timber trees, and nitrogen-fixing trees in agricultural systems, carbon sequestration can be accomplished. Additionally, by lowering soil disturbance with chemical use, minimum tillage and integrated pest control will lower carbon emissions. In terms of energy management, CSA will be made possible by utilizing energy-smart techniques including residue management, biofuels, solar-powered pumps and motors, electronic cars, biogas, better stoves and energy-producing facilities, and biogas. Developing nations must make significant changes to address concerns about food security related to climate change. To attain climate resilience in the future, agricultural production systems must incorporate proven, efficient, and climate-resilient practices. In order to effectively address climate change, policies must adopt an ecological perspective, operate at the landscape level, and guarantee intersectional and cross-sectoral collaboration.

7. Conclusion

An overview of food security, climate change mitigation, and the role of digital agriculture was given in this paper. This study comes to the conclusion that climate change has a negative impact on food security by lowering yields from agriculture, declining animal growth, and reducing livestock productivity in developing countries. This is because of global warming, changed patterns of precipitation, and an upsurge in the incidence of extreme events. The fundamental underpinnings of agriculture are at danger. On the other hand, there are currently scientific advancements that can be used to lessen the environmental impact of food production and to lessen the consequences of climate change. The results of this study indicate that food consumption-based and technology-based strategies have the most potential to reduce GHG emissions. Future food security is best addressed with the same integrated strategy. Many of the recommendations made for ensuring food security may also contribute to lowering GHG emissions from agriculture. Food security and the decrease of GHG emissions will benefit from actions that increase agricultural productivity and reduce environmental pollution. This study offers proof that increasing the use of digital technology can lessen the environmental effect of agri-food systems while also improving efficiency throughout the industry, from agricultural processes to market access. In light of this, digital agriculture technology may offer a more environmentally friendly way to achieve sustainable crop production while simultaneously meeting the growing demand of the population. Therefore, developing sustainable agricultural food systems, reducing environmental pollution, raising yields, distributing food fairly and equally, and reducing malnutrition will be the next challenge in ensuring food security for all. We could prevent climate change and improve the health of the world if we were willing to make changes and use modern technology developments.

Certain limits should be taken into account, according to research on the contribution of digital agriculture to guaranteeing food security and reducing the effects of climate change. A significant limitation is the dearth of empirical data regarding the efficacy of digital agriculture technologies for reducing GHG emissions and guaranteeing food security, especially in developing countries. Furthermore, there is an uneven distribution of access to necessary infrastructure and technology, which prevents many small-scale farmers in developing nations from making use of digital agriculture's benefits. Another drawback is the high implementation costs associated with digital agriculture technology, which may prevent small-scale farmers with limited funding from adopting it. Furthermore, in order for digital agriculture technology to work, there must be a steady source of energy, which can be difficult in rural locations with erratic electrical supplies. Furthermore, the manufacture and disposal of digital agriculture technologies may harm the environment by producing electrical trash and releasing GHGs. Digital agriculture also has ethical and social ramifications, including the possibility of more inequality, employment losses, and privacy and ownership issues with data. These drawbacks imply that although digital agriculture may help mitigate the effects of climate change and provide food security, it is not a cure-all. Its drawbacks and possible adverse effects must be carefully considered in order to guarantee that it is applied in a fair and sustainable manner.

Further studies that evaluate the capacity of digital agriculture to alleviate climate change and guarantee food security may concentrate on tackling the constraints of the current body of knowledge. In order to accomplish this goal, more empirical research is required to assess how well digital agriculture technology, particularly in poor nations, can reduce GHG emissions and improve food security. Furthermore, more investigation is needed to understand the hurdles small-scale farmers face in obtaining and using these technologies as well as the solutions to these problems. Studies might also look into the economic feasibility of digital agriculture innovations, including how affordable certain technologies and business models are. Research may also look into how much energy digital farm devices use and how best to operate them sustainably while producing the fewest GHG emissions. Future research should focus on understanding the possible ethical and social ramifications of digital agriculture as well as how to implement it in a way that is fair and sustainable. Lastly, research might look into the advantages of combining digital agriculture techniques with other sustainable farming methods like conservation agriculture and agroforestry.

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