The Role of Smart Farming Technologies in Mitigating Climate Change and Enhancing Agricultural Sustainability

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Abstract:

This research examines the function of smart farming technology in alleviating climate change and promoting agricultural sustainability. It analyzes the role of technical advancements in decreasing greenhouse gas emissions, enhancing resource efficiency, and developing climate-resilient agricultural systems.The study consolidates current literature about the use of smart agricultural technologies, including precision agriculture, IoT, AI, and renewable energy systems. It assesses their efficacy in tackling critical climate and sustainability issues via data-informed decision-making, resource optimization, and adaptive methods.Smart agricultural methods substantially alleviate the effects of climate change by enhancing water efficiency, minimizing chemical consumption, and decreasing carbon emissions. These technologies augment soil vitality, bolster agricultural resistance against severe weather phenomena, and provide real-time surveillance of environmental variables. The incorporation of renewable energy sources into agricultural practices reduces reliance on fossil fuels. Notwithstanding their promise, obstacles such as elevated implementation costs, technology disparities, and restricted access for smallholder farmers persist as significant impediments.Smart farming technologies are essential for changing agriculture into a climate-resilient and sustainable industry. Their implementation may aid in achieving global climate objectives and securing food stability. Overcoming obstacles to access and execution is crucial for the successful scaling of these technologies.The results underscore the need for governmental interventions, financial incentives, and capacity-building measures to facilitate the widespread use of smart agricultural technology. To improve agricultural output while decreasing environmental effect, governments should subsidize smart farming technology, finance research, and implement capacity-building programs. A fair distribution of precision agriculture tools, including those for smallholder farmers, requires policy that encourages data-sharing frameworks and the development of digital infrastructure.

Keywords: *smart farming, climate change, sustainability, Climate resilience, greenhouse gas emissions*

1.0 Introduction

When there is a noticeable shift in the typical patterns of weather across a large area (or the entire planet) over an extended period, scientists call climate change. The topic at hand is the impact of climate change on various regions of the planet, particularly when such differences deviate from the usual. It could be tens, hundreds, or even millions of years before these changes materialize(Mahato, 2014).Its extensive effects endanger world food supplies and go well beyond environmental issues. In light of this, it is critical to tackle the complex issues that lie ahead by comprehending the interplay between food security and climate change(Toromade et al., 2024).Fires, volcanic eruptions, and the combustion of fossil fuels (coal, oil, and natural gas) all contribute to atmospheric concentrations of carbon dioxide (CO2), a crucial gas for heat trapping and a greenhouse gas(Bolles, 2024).

According to (Arora, 2019)human activities, especially greenhouse gas (GHG) emissions, have raised the average temperature by 0.9 °C during the 19th century. Due to deforestation, GHG emissions, and soil, water, and air pollution, this increase is anticipated to reach 1.5 °C by 2050 or even higher. The enormous rise in temperature has caused droughts, floods, unpredictable precipitation patterns, heat waves, and other severe occurrences worldwide.Report from World Food Programme (WFP) indicates thatClimate change, a major cause of global hunger, affects every continent. Extreme climate change and weather calamities have afflicted 1.7 billion people in the last decade. Communities who contribute least to the climate catastrophe are most hit and have little resources to respond((WFP), 2025).

GHG Emission Source	Description
Livestock	Methane (CH_4) emissions from the digestive process of ruminants
Manure Management	Emissions from stored or treated livestock manure
Synthetic Fertilizers	Nitrous oxide (N_2O) emissions from applying synthetic fertilizers
Rice Cultivation	Methane (CH_4) emissions from flooded rice fields
Soil Management	Nitrous oxide (N_2O) emissions from soil cultivation practices
Energy Use in Agriculture	Emissions from the use of fossil fuels in agricultural machinery
Crop Residues and Burning	Carbon dioxide (CO_2) and methane (CH_4) emissions from burning crop residues

Table 1: Primary sources of GHG emissions associated with farming activities.
(Polymeni et al., 2024a)

Global warming frequently focusses on carbon dioxide, but Table 2 shows another viewpoint from agriculture. Livestock farms, rice field floods, and crop waste burning produce methane, which is the main cause. However, animal waste management, synthetic fertilizers, and soil management create nitrous oxide. Carbon dioxide is a persistent greenhouse gas, meaning it stays in the atmosphere and warms the planet. At shorter durations, methane and nitrous oxide have larger global warming potentials than carbon dioxide, making them more powerful. Recent studies have shown that methane has a 28–36 times greater than carbon dioxide over a 100-year period, while nitrous oxide has 265–298 times greater causing a much more immediate and intense warming effect despite its shorter atmospheric lifetime(Stocker, 2014).

Additionally, the Food and Agriculture Organization (FAO)findings suggest that the number of people suffering from hunger has been steadily rising since 2014, with 824 million people falling into this category alone, up from 804 million the previous year. It is still very difficult to accomplish the sustainable development goals (SDG) ambition of ending world hunger by 2030, as these publications have shown(FAO, 2025).An effort to make farming more resilient to climate change and its effects on food production is known as "climate smart agriculture" (CSA)(Zecca, 2019).

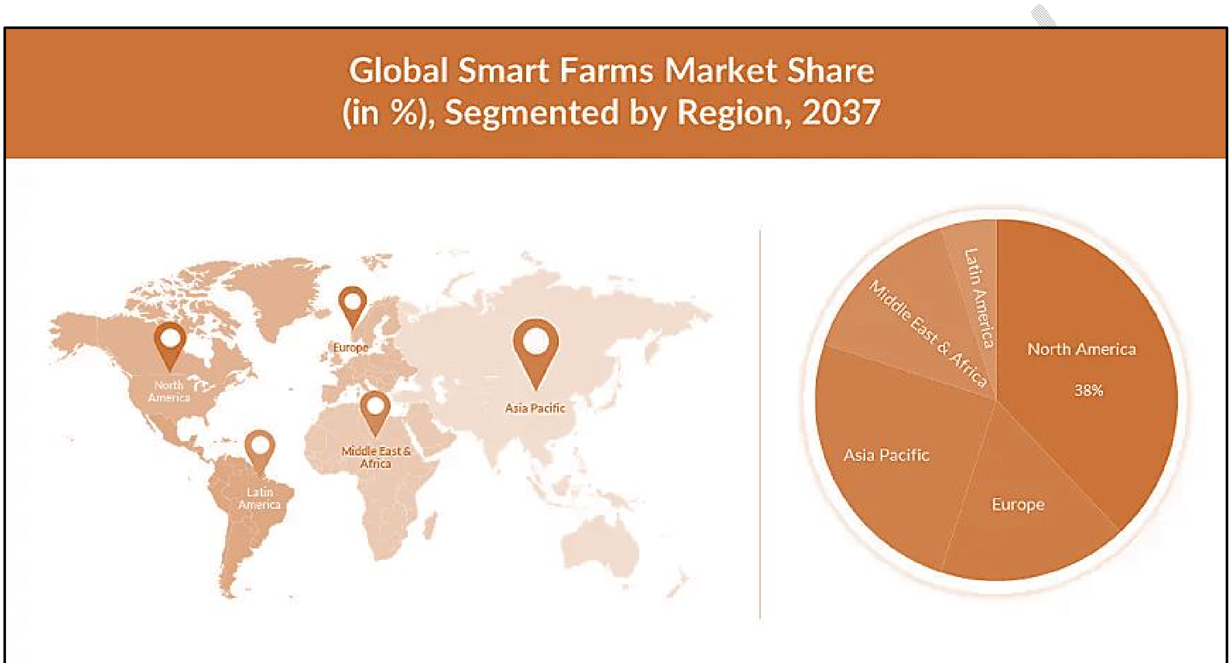


Figure 1: Global Smart Farms Market overview
Source:(Nair, 2025)

The image illustrates the **Global Smart Farms Market Share** segmented by region for the year **2037**. On the left, a world map highlights key regions—**North America, Europe, Asia Pacific, Middle East & Africa, and Latin America**—with markers indicating their involvement in the smart farming market. On the right, a pie chart visually represents market share distribution, showing **North America (38%)** and **Asia Pacific** as leading regions in adoption. Europe also holds a significant portion, while the **Middle East, Africa, and Latin America** have relatively smaller shares. This visualization suggests a strong future demand for smart farming technologies, particularly in North America and Asia Pacific.

The Internet of Things (IoT)and smart agricultural technologies in the food production sector(Brewster et al., 2017), also known as Agriculture incorporates ICT advancements into agricultural operations to boost production, quality, yield, and revenue while decreasing impact on the environment (via more accurate pesticide use, effective irrigation, etc.). The smart agricultural industry is predicted to see a yearly growth rate of 12.7%(Chen et al., 2019).The world's problems have practical answers that can be provided by modern technologies like mobile internet, the Internet of Things (IoT), and artificial intelligence (AI)(Said Mohamed et al., 2021).Problems with food production currently include rising production costs and a shrinking rural workforce. One idea for managing farms that could leverage the Internet of Things (IoT) to solve the problems with food production today is smart farming(Navarro et al., 2020).

Also, as more and more people leave the countryside for urban centers for work and live in cities, agricultural production areas and the number of people employed in agriculture are both declining. In order to ensure that people have enough to eat, it is critical to create and spread efficient manufacturing methods(Kırkaya, 2020).Sustainable and efficient farming practices have evolved with agricultural technology. Big Data, AI, robotics, IoT, and virtual and augmented reality are all parts of this digitalization and automation in business and everyday life. These technological advances are changing our lives. It leads to precision agriculture technically(Javaid et al., 2022).

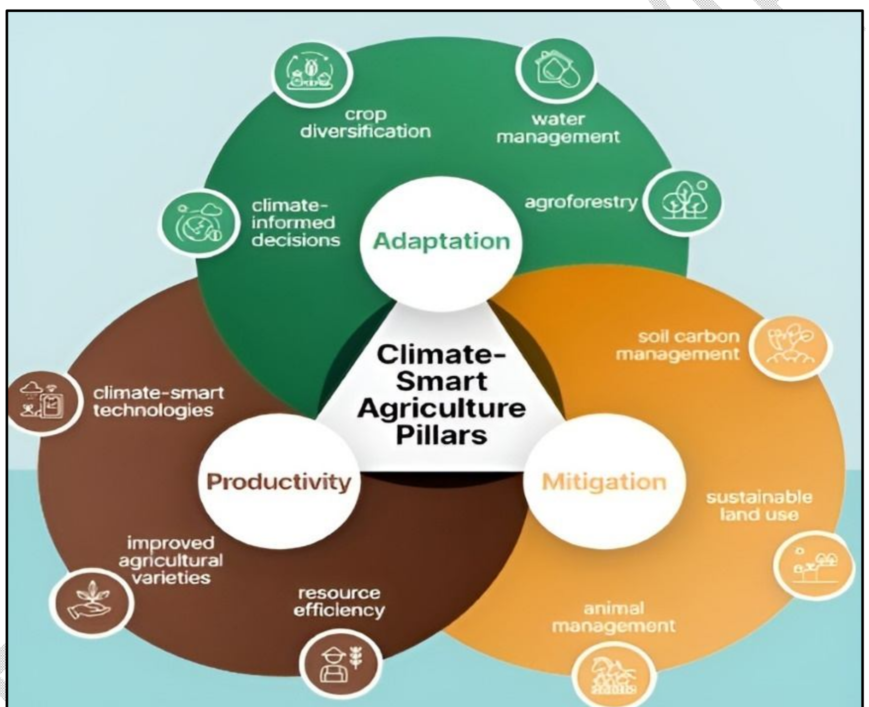


Figure 2: Pillars of Climate Smart Agriculture
Source: (Arifin, 2023)

Figure 2 illustrates the pillars of Climate Smart Agriculture (CSA) which focuses on three key objectives: increasing agricultural productivity, enhancing resilience to climate change, and reducing greenhouse gas emissions. Productivity aims to ensure food security while improving livelihoods. Resilience emphasizes adapting farming systems to climate variability and extremes through sustainable practices. Mitigation targets lowering emissions by optimizing resource use and integrating renewable energy. Together, these pillars promote sustainable, climate-resilient agriculture to address global environmental and food challenges.

2.0 Smart Farming Technologies: An Overview

Smart Farming is the new term in the agriculture sector, aiming to transform the traditional techniques to innovative solutions based on Information Communication Technologies (ICT)(Moysiadis et al., 2021). The goal of "smart farming" is to make agricultural operations more effective, efficient, and lucrative by using ICTs(O'Grady & O'Hare, 2017).According to(Virk et al., 2020)Smart Farms (SF) integrate information and communication technology with agricultural equipment and sensors for crop growing and food production. In this sophisticated technological age, internet of things (IoT) and other electronic instruments (robots and AI) with data translation and signaling capabilities have transformed smart homes, health care, and now agriculture. Today, farmers may use IoT to improve irrigation, fertilization, harvesting, and climate forecasting by monitoring using sensors to make better decisions.

By employing various and enhanced agricultural techniques, methods for planting and harvesting crops, and the use of agricultural machinery. Sticks, sickles, hand harvesting, and hunting were the tools of the prehistoric farmer. These days, farmers can keep tabs on their fields from anywhere using only their cellphones and other remote controls. In order to increase agricultural yields while decreasing pest populations, farmers are turning to genetically engineered seeds(Idoje et al., 2021).

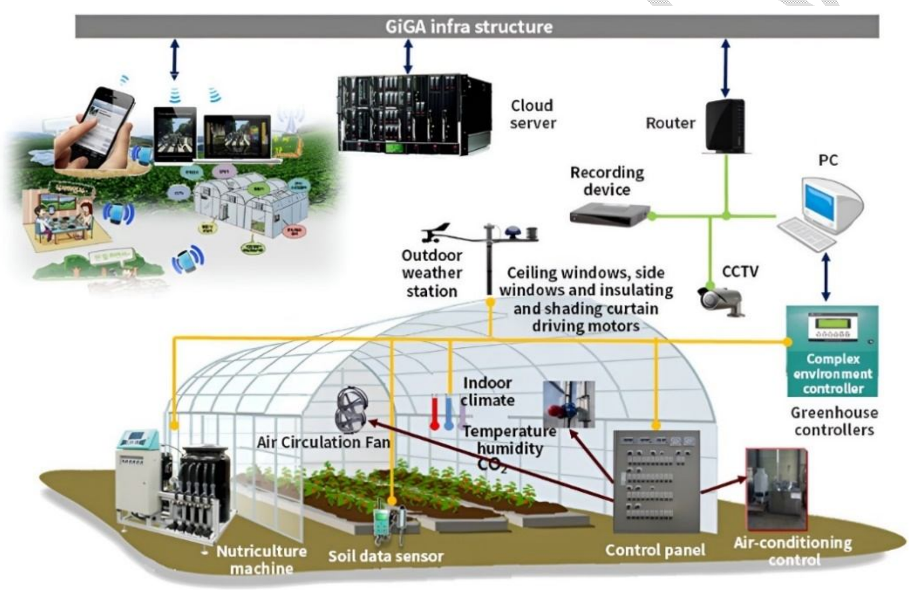


Figure 3: Smart farm concept as part of the “Smart Farm Dispersion Method” in South Korea
Source: (M. Alananbeh, 2019)

Figure 3illustratesseveral layers of the technological model that this smart farm prototype from Korea follows: First, a more convenient way to keep tabs on things from afar; second, a more effective way to manage growth; and third, the creation and implementation of smart farm integrated systems, including energy optimization and robot automation, for export. Reduced labor and agricultural material usage, improved productivity and quality, and a connection to farm family income are all goals of the initiative, which aims to address issues in farming and adjacent sectors simultaneously. Integrated administration and maintenance of smart farms is currently challenging owing to the incompatibility of scattered ICT equipment caused by varying product specifications from different companies. As a result, efforts are being made to standardize information and communication technology (ICT) equipment to provide a single format and communication technique for all sensors and controllers used in horticulture and livestock.

The Korean Rural Development Administration (RDA) is studying key elements and source-based technologies to establish the world's best Korean-style smart farm model and smarten perch production. The Korean smart farm initiative creates field-based agricultural production technologies without importing, modifying, or reproducing foreign technology. First generation remote monitoring and control, second generation intelligent precision growth management, and third generation energy optimization and robot automation increase this Korean smart farm prototype's convenience, productivity, and energy optimization. The project aims to minimize labor and agricultural materials, increase farm family income via productivity and quality, and address farming and industrial challenges(M. Alananbeh, 2019).

Smart farming represents a transformative approach in agriculture, integrating Internet of Things (IoT) sensors and Artificial Intelligence (AI) to enhance productivity and sustainability (Mandapuram et al., 2019). This evolution builds upon precision agriculture's foundations, incorporating technologies like GPS, GIS, and remote sensing to optimize resource use and increase crop yields (Khan & Babar, 2024). IoT sensors collect real-time data on soil conditions, weather, and livestock, while AI algorithms interpret this information to provide actionable insights (Balu et al., 2023). These advancements enable automated irrigation, SMS alerts to farmers, and improved field monitoring (Balu et al., 2023). The integration of IoT, AI, and robotics is shifting agriculture from a labor-intensive to a technology-native industry, potentially addressing challenges related to climate change and food security (Charania & Li, 2020). As smart farming continues to evolve, it promises to revolutionize agricultural practices, offering solutions to global sustainability challenges.

Smart farms in Korea have emerged as a key strategy to address agricultural challenges and enhance competitiveness. These farms integrate advanced technologies like IoT, AI, and robotics to improve crop management and productivity(Kim et al., 2017). The adoption of smart farms is influenced by factors such as technology compatibility, financial costs, and the changing digital environment (Yoon et al., 2020). In practice, smart greenhouses in Korea primarily cultivate fruits and vegetables, with most facilities ranging from 3,300 to 6,600 m2. Farmers report high satisfaction levels, although pest management remains a challenge (박영균 et al., 2020).

3.0 Components of Smart Farm

3.1 Internet of Things (IoT) in agriculture

The Massachusetts Institute of Technology (MIT) Auto-ID Labs network radio frequency identification (RFID) system was the first concept for the Internet of Things (IoT) in 1999(Sarma et al., 2001). A new technology known as the Internet of Things (IoT), enables remote device connections, leading to smart farming. With the goal of improving efficiency and performance in all sectors, the Internet of Things (IoT) has started to impact a wide variety of industries, including healthcare, commerce, communications, energy, and agriculture(Shi et al., 2019; Sisinni et al., 2018). The Internet of Things (IoT) is revolutionizing agriculture by enabling smart farming practices through interconnected devices and sensors(Kopawar & Wankhede, 2024; Supravi & Devadiga, 2023). These technologies allow farmers to collect and analyze data on soil conditions, crop growth, and environmental factors, leading to improved decision-making and resource management(Supravi & Devadiga, 2023; Zamir & Sonar, 2023).IoT solutions can automate irrigation systems, detect pests, and provide real-time alerts to farmers(Supravi & Devadiga, 2023).The implementation of IoT in agriculture has the potential to increase crop yields, reduce waste, and enhance overall farm efficiency(Sadiku et al., 2021; Zamir & Sonar, 2023).As a result, IoT is poised to transform the agricultural sector, contributing to improved productivity and sustainability in farming practices(Zamir & Sonar, 2023).

3.2 Precision farming tools

Precision farming utilizes advanced technologies to optimize agricultural production by managing spatial variability in fields(Weiss, 1996).It employs tools such as global positioning systems, remote sensing, and geographic information systems to improve resource efficiency and crop yields(Meena, 2021).Recent developments in soft computing and information technology have further enhanced precision farming capabilities, incorporating wireless sensor networks, artificial neural networks, and Internet of Things (IoT) technologies (Njoroge et al., 2018).These advancements enable real-time monitoring, prediction, and decision-making for improved farm management. Precision farming aims to apply the right inputs at the right time and place, potentially increasing productivity, reducing waste, and minimizing environmental impact(Meena, 2021).As a result, it offers significant potential for enhancing agricultural sustainability and profitability.

3.3 Artificial Intelligence (AI) and Machine Learning (ML) applications

Artificial Intelligence (AI) and Machine Learning (ML) are revolutionizing smart farming practices, addressing agricultural sustainability challenges and enhancing productivity. These technologies, along with the Internet of Things (IoT), are being applied in various aspects of agriculture, including crop selection, yield prediction, soil management, water management, and pest control(Akkem et al., 2023). AI and ML algorithms analyze crop data sets to classify soil fertility, optimize resource utilization, and provide real-time monitoring and control through IoT devices (Thotho & Macheso, 2024). Applications extend to livestock management, focusing on animal welfare and production(Thotho & Macheso, 2024). Image processing-based ML techniques are being used for detecting and controlling plant diseases, particularly in cotton crops(Gorati Sravan kumar, 2022).These advancements aim to reduce agricultural risks, support sustainability, and provide farmers with predictive advice for more efficient and precise farming practices (Thotho & Macheso, 2024).

3.4 Drones and robotics

Robotics and drones are revolutionizing agriculture, offering solutions to challenges like increasing food demand and labor shortages(Das, 2024). These technologies enable precision agriculture, enhancing productivity while minimizing environmental impact (Basri et al., 2021). Drones equipped with advanced sensors provide real-time data for crop monitoring and resource optimization(Das, 2024)while robots perform various tasks such as tillage, seeding, and harvesting(Basri et al., 2021). The market for drone technologies is expected to reach $12 billion by 2021(Suzuki, 2018). During the COVID-19 pandemic, drones and robots proved effective in reducing human-to-human contact and enhancing delivery service capacity(Bhardwaj et al., 2023). However, challenges such as high initial costs, technological learning curves, and regulatory hurdles impede widespread adoption (Das, 2024). Overcoming these obstacles requires strategic investments, supportive policies, and collaborations between technology developers, agricultural experts, and policymakers to drive innovation and facilitate the adoption of smart farming practices(Das, 2024).

3.5 Climate-smart irrigation systems

Climate-smart irrigation systems are emerging as crucial solutions for water conservation and sustainable agriculture in the face of climate change. These systems employ precision water management technologies, including micro-irrigation techniques like drip and sprinkler systems, which significantly improve water use efficiency (Kumar et al., 2023). Smart irrigation systems utilize environmental sensors and decision-making algorithms to determine when and where irrigation is needed, reducing water waste and energy consumption (Masaba et al., 2016). Advanced agro-techniques, such as laser land leveling and furrow-irrigated raised beds, further enhance water productivity (Kumar et al., 2023). The integration of artificial intelligence and remote-control capabilities allows for more precise water management (Durmuş et al., 2024). Additionally, rainwater harvesting and storage systems can be incorporated to supplement traditional water sources (Daniel et al., 2020). By implementing these climate-smart irrigation practices, farmers can improve crop yields, conserve water resources, and contribute to climate change mitigation efforts (Durmuş et al., 2024; Kumar et al., 2023).

3.6 Remote sensing and Geographic Information Systems (GIS)

Remote sensing and Geographic Information Systems (GIS) are complementary technologies that have become increasingly integrated for environmental and agricultural applications. Remote sensing provides up-to-date spatial data that can be directly input into GIS, enhancing the quality and availability of geographic information (Adamides et al., 2020; Louka et al., 2022). These integrated technologies offer numerous benefits for sustainable agriculture and natural resource management, including crop discrimination, growth monitoring, yield prediction, and soil moisture estimation(Kingra et al., 2016).They are particularly valuable for assessing and managing agricultural production systems, which are highly vulnerable to climate, soil, and topographic variations. The integration of remote sensing and GIS enables more effective analysis of land use, crop acreage, and the impacts of extreme weather events on a regional scale (Evsahibioglu & Ozdikililer, 2015; Kingra et al., 2016). As these technologies continue to evolve, their combined use is becoming increasingly important for addressing environmental challenges and supporting sustainable resource management (Evsahibioglu & Ozdikililer, 2015; Hinton, 1996).

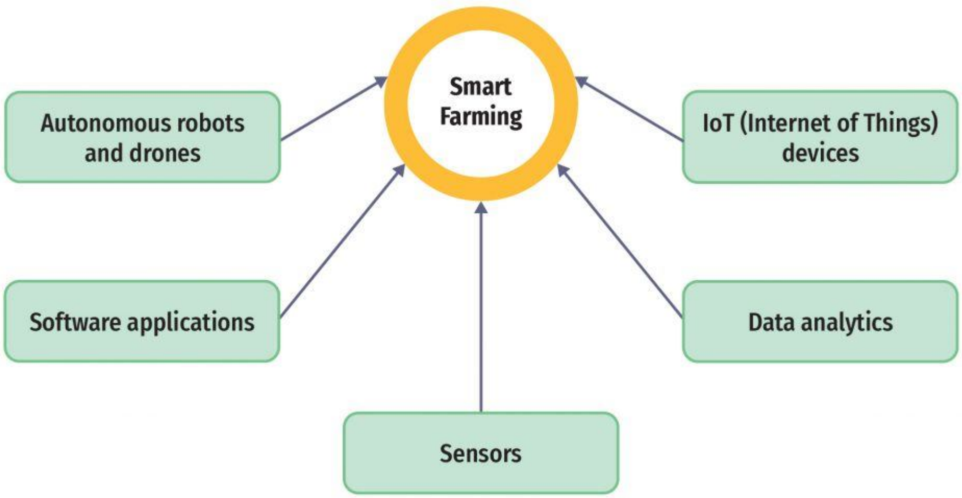


Figure 4: Components of SmartFarm Technology
Source: (IDAP, 2023)

The illustration shows a diagram of Smart Farming, emphasizing its main components. Smart Farming is at the center, with arrows pointing to five key technologies: Autonomous robots and drones, Software applications, Sensors, Data analytics, and IoT (Internet of Things) devices. These technologies enhance agricultural efficiency, optimize resource use, and improve sustainability. Autonomous robots and drones support precision farming, and IoT devices and sensors gather real-time field data for improved decision-making. Software applications and data analytics process information to deliver actionable insights, resulting in more productive and climate-resilient farming practices.

4.0 Impact of Smart Farming on Climate Change Mitigation

4.1*Reduction of greenhouse gas emissions through optimized resource use.*

Smart farming technologies offer promising solutions for mitigating greenhouse gas (GHG) emissions in agriculture. The integration of 6G-IoT enables precise resource management and advanced emission reduction technology(Polymeni et al., 2024a).Climate-smart technologies can effectively target inputs to fields, lowering GHG emissions, with livestock farming identified as the largest contributor (Panchasara et al., 2021). Circular agriculture and precision farming tools contribute to better resource use efficiency and sustainable agriculture (Tagarakis et al., 2021). Climate-smart agricultural (CSA) practices have been shown to improve farm productivity, increase incomes, enhance resilience, and reduce GHG emissions (Zheng et al., 2024). These practices lead to increased crop yields, improved technical and resource use efficiency, and reinforced food security. The adoption of CSA practices also promotes environmental sustainability by reducing emissions and improving soil quality. Overall, smart farming approaches offer a transformative solution for managing GHG emissions in agriculture while promoting sustainability.

4.2 *Role in carbon sequestration via precision land management.*

Climate-smart agriculture (CSA) practices offer significant potential for mitigating climate change through enhanced soil carbon sequestration. Conservation tillage, cover crops, and biochar applications have been shown to increase soil organic carbon (SOC) content, with biochar being the most effective (39% increase), followed by cover crops (6%) and conservation tillage (5%) (Bai et al., 2019). These practices, along with precision agriculture and integrated nutrient management, can improve soil quality, reduce erosion, and increase crop productivity (Handayani & Folz, 2021; Lal et al., 2011). Adaptive land management focusing on carbon and nitrogen cycles is crucial for maintaining food security in a changing climate (Handayani & Folz, 2021). Additionally, restoring degraded lands and implementing precision conservation management can contribute to climate change mitigation and adaptation (Bhatti & Khan, 2012). The effectiveness of CSA practices may vary depending on local environmental factors, emphasizing the importance of tailored approaches for optimal results (Bai et al., 2019)

4.3 *Sustainable energy uses through renewable-powered systems.*

Smart farming technologies and practices offer significant potential for climate change mitigation and sustainable agriculture. These approaches can reduce greenhouse gas emissions, improve resource efficiency, and enhance productivity (Bhattacharyya et al., 2020; Tagarakis et al., 2021). Precision farming techniques, such as IoT-based systems for irrigation and crop protection, can optimize resource use and reduce environmental impact (Adamides et al., 2020). Renewable energy sources, including solar, wind, and biofuels, can replace fossil fuels in agricultural operations, further reducing emissions (Bhattacharyya et al., 2020).

Specific practices like legume-based cover crops, crop rotation, and intercropping show promise in achieving climate-smart agricultural outcomes (Erekalo, Pedersen, Christensen, Denver, Gemtou, Fountas, & Isakhanya, 2024). Smart energy systems in agriculture can effectively manage energy consumption, minimize negative environmental consequences, and improve efficiency. Implementing rules and providing incentives are necessary to promote the widespread adoption of smart energy systems in the agricultural sector(Salaria & Rakhra, 2024).Smart farming practices and technologies can contribute to climate-smart agricultural outcomes like productiveGHG mitigation, and resource use efficiency(Erekalo, Pedersen, Christensen, Denver, Gemtou, Fountas, & Isakhanya, 2024).

4.4 *3D Food Production*

3D printing technology is revolutionizing the food industry by enabling personalized, on-demand food production with complex designs and improved nutritional profiles (Leontiou et al., 2023; Taneja et al., 2022).This innovative approach offers potential solutions to food scarcity and waste reduction while allowing for the integration of functional ingredients and smart packaging (Leontiou et al., 2023; Taneja et al., 2022). In smart farming, printed sensors play a crucial role in monitoring soil conditions, plant growth, and environmental factors, offering versatile and cost-effective solutions for agricultural applications (Rayhana et al., 2021).The food industry is also benefiting from artificial intelligence and machine learning technologies, which are being applied to improve food quality, processing methods, and overall efficiency across various sectors, including dairy, bakery, and beverages (Addanki et al., 2022). These advancements in 3D printing, sensor technology, and AI are driving innovation and addressing key challenges in food production and smart farming practices.

5.0 Climate Adaptation through Smart Farming

5.1*Enhancing crop resilience to extreme weather events.*

Climate change poses significant challenges to agriculture, necessitating the adoption of climate-resilient farming practices. Smart farming techniques, including precision agriculture and Internet of Things (IoT) technologies, offer promising solutions for adapting to extreme weather events and enhancing crop resilience (Adamides et al., 2020; Sarma et al., 2024). These approaches involve implementing strategies such as diversifying crop varieties, efficient water management, and site-specific nutrient management (Karri & Nalluri, 2023). Climate-smart agricultural (CSA) practices have been shown to improve net farm returns, reduce volatility, and mitigate downside risks (Tunio et al., 2024). The integration of traditional knowledge with modern scientific advancements can enhance ecosystem robustness and productivity (Sarma et al., 2024).

Additionally, the Smart Farming as a Service (SaaS) paradigm has demonstrated potential for reducing irrigation needs and optimizing pesticide use efficiency, particularly benefiting small-scale farmers (Adamides et al., 2020). The current research indicates a potential reduction of up to 25% on total production cost due to the optimization of irrigation and pest control applications, which amounts to EUR 4500 per acre. An increase in farmers' income up to 10% is projected to be achieved, due to the improved product quality and yield, which corresponds to EUR 11,200 per acre(Louka et al., 2022).The adoption of climate-smart agriculture as an adaptation strategy in coastal Bangladesh is influenced by various socio-demographic, economic, ecological, and adaptive behavioral factors(Saroar & Filho, 2016).

5.2*Real-time monitoring of climatic conditions and crop health.*

Smart farming leverages Internet of Things (IoT) technologies to enhance agricultural sustainability and productivity through real-time monitoring of environmental conditions and crop health. IoT-enabled sensors collect data on soil moisture, weather patterns, and crop status, allowing farmers to optimize irrigation, fertilization, and pest management (Adamides et al., 2020; Joshi, 2023; Kakamoukas et al., 2019; Pooja et al., 2017). These systems can reduce water usage by up to 22% and improve pesticide efficiency (Adamides et al., 2020). The MQTT protocol enables efficient data transmission for continuous analysis of field conditions (Pooja et al., 2017). Advanced architectures incorporating wireless sensor networks, meteorological stations, and unmanned aerial vehicles provide comprehensive monitoring and decision support (Kakamoukas et al., 2019). By integrating machine learning and cloud computing, these systems offer adaptive solutions for various crop types, helping farmers make informed decisions about planting, harvesting, and crop protection (Joshi, 2023) Overall, smart farming techniques present significant potential for climate change adaptation and sustainable agricultural practices.

5.3*Diversification and optimization of cropping systems using AI.*

Artificial intelligence (AI) and smart farming techniques offer promising solutions for adaptation to climate change in agriculture. AI-based models can analyze historical climate data and crop performance to predict yields and suggest optimal adaptation strategies (Zidan & Febriyanti, 2024). These technologies enable real-time data collection on irrigation and plant protection, potentially reducing irrigation needs by up to 22% and optimizing pesticide use (Adamides et al., 2020). Climate-Smart Agriculture (CSA) integrates AI to enhance productivity, adaptability, and sustainability in farming practices (Gryshova et al., 2024).

On-farm diversification is another effective strategy for climate adaptation, particularly for smallholder farmers in tropical and subtropical regions. A seven-step decision-making process can guide farmers in diversifying their cropping, pasture, and agroforestry systems, considering constraints such as risk aversion and limited access to information (van Zonneveld et al., 2020). These approaches collectively contribute to more resilient and sustainable agricultural systems in the face of climate change.The proposed smart farming system using AI and IoT can improve the efficiency and environmental impact of farming.The useof IoT sensors to collect data on various physical parameters to support decision-making for farmers.The system uses AI to analyze the sensor data and provides farmers with insights on crop demand, availability of inputs, and climatic conditions, and provides automated control of humidity/water levels and soil fertility using IoT(Vallakati et al., 2021)

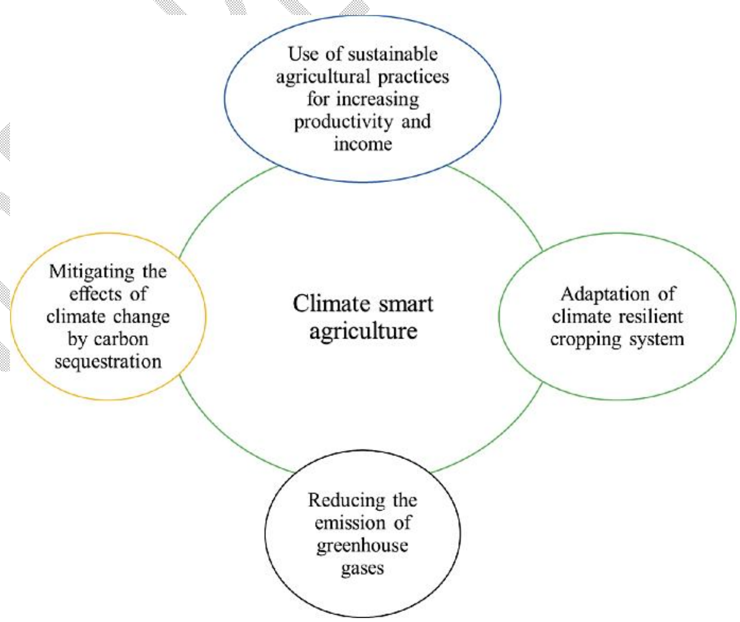


Figure 5: **Concept of Climate Adaptation through Smart Farming**
Source: (Ullah et al., 2022)

Figure 5illustrates the concept of smart agriculture that helps reduce greenhouse gas emissions by optimizing resource use and minimizing waste. Precision technologies, such as GPS-guided machinery and IoT sensors, enable efficient use of fertilizers and water, reducing nitrous oxide and methane emissions. Adoption of no-till farming and crop rotation practices enhances soil carbon sequestration. Smart systems also promote renewable energy sources, like solar-powered irrigation. These measures collectively make agriculture more sustainable while mitigating climate change impacts.

6.0 Case Studies and Success Stories

6.1 *Examples of smart farming applications in different climatic regions.*

Smart farming leverages IoT, AI, and robotics to enhance agricultural productivity and sustainability across various climatic regions. These technologies enable real-time monitoring of environmental conditions, automated irrigation, and precision farming techniques (Pal & Joshi, 2023). IoT sensors and UAVs are used to collect data on temperature, humidity, soil moisture, and crop health, facilitating informed decision-making for farmers (Islam et al., 2021). Case studies demonstrate the practical applications of smart farming, such as a prototype in Thailand using IoT devices to measure temperature and humidity for optimal water management in rice cultivation (Suanpang & Jamjuntr, 2019). Another case study in India highlights the potential of IoT-based systems to improve crop yield by providing real-time field monitoring and data-driven insights for fertilizer and pesticide application (Roopashree et al., 2021). These advancements in smart farming contribute to increased efficiency, reduced waste, and improved environmental sustainability in agriculture.

Smart farming, an evolution of precision agriculture leveraging Industry 4.0 technologies, has shown promising results worldwide. It utilizes Internet of Things (IoT) devices, artificial intelligence, and big data analytics to optimize agricultural practices, increase productivity, and enhance sustainability (Bhavika et al., 2024; Tjhin & Riantini, 2022). The SmartFarmNet platform, for instance, automates data collection from various IoT devices, filters invalid data, and provides personalized crop recommendations (Jayaraman et al., 2016). Smart farming applications have been successful in improving farm efficiency and environmental stewardship across different agricultural environments (Bhavika et al., 2024). In Africa, despite initial challenges due to limited ICT infrastructure, recent initiatives have sparked interest in digital agriculture and smart farming (Fastellini & Schillaci, 2020). As internet accessibility improves and costs decrease, the adoption of smart farming technologies is expected to increase among African farmers, who have already demonstrated willingness to embrace new technologies that simplify their economic activities (Fastellini & Schillaci, 2020).

Smart farming leverages Internet of Things (IoT) and Unmanned Aerial Vehicles (UAVs) to enhance agricultural practices through automated operations and data-driven decision-making (Islam et al., 2021). Case studies demonstrate the global application of smart farming techniques. In Africa, recent ICT developments and mobile technology adoption have facilitated the implementation of digital agriculture (Fastellini & Schillaci, 2020). In India, IoT-based systems enable real-time field monitoring, weather and soil condition analysis, and precise fertilizer application, leading to improved crop yields (Roopashree et al., 2021). Canada's "Food from Thought" project exemplifies smart dairy farming, utilizing IoT technologies to increase production quality and environmental protection(Vate-U-Lan et al., 2017). Despite its potential, smart farming faces challenges such as connectivity limitations in remote areas, which can be addressed through meshed low range wide area network(LoRaWAN) gateways and satellite communication systems (Islam et al., 2021)These case studies highlight the diverse applications and benefits of smart farming across different countries.

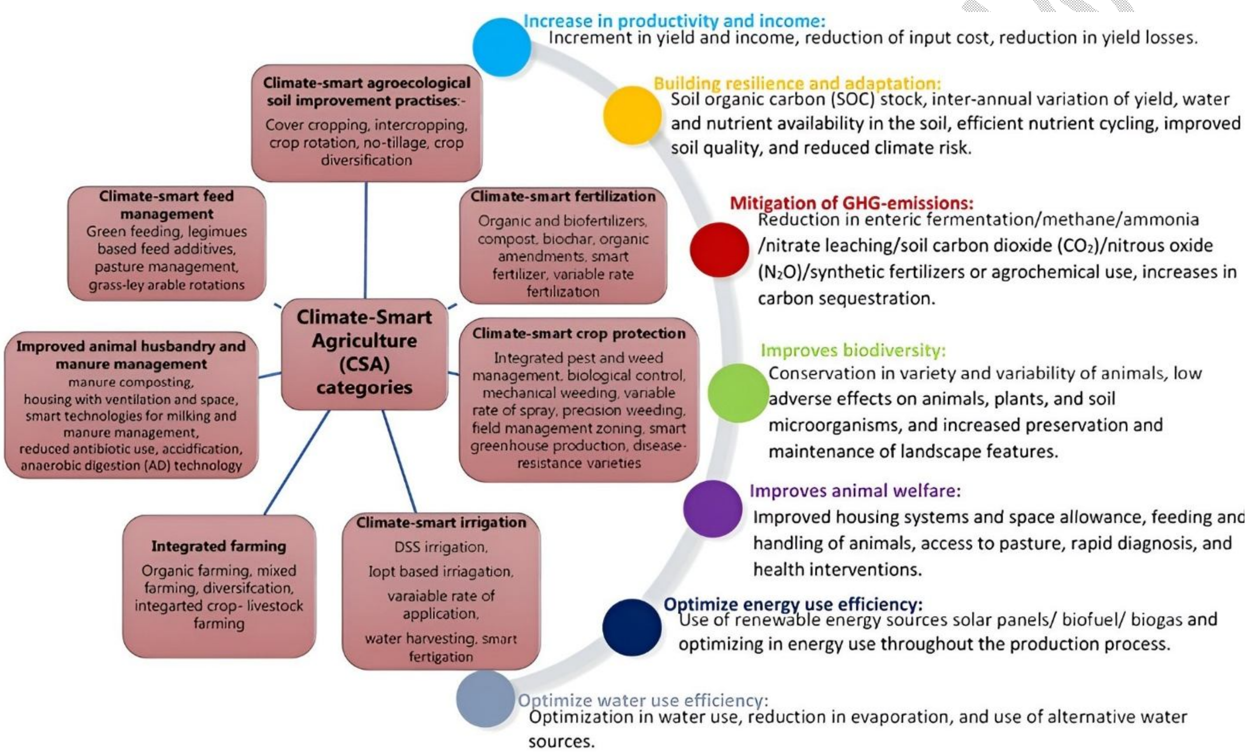
6.1 Evidence of improved yield and reduced environmental footprint.

Recent advancements in precision agriculture leverage AI and automation to enhance crop management and sustainability. AI-powered solutions have improved crop monitoring accuracy by 30-50% and increased yields by 5-15% while reducing water and fertilizer use by 25-40% and 30-40%, respectively(Hoque & Padhiary, 2024).Smart farming technologies have demonstrated significant potential in improving agricultural sustainability and productivity. Studies have shown that these technologies can reduce environmental impacts, particularly in vineyard management and rice cultivation. In vineyards, the use of on-site weather stations and decision support systems led to reduced agrochemical and water usage, although machinery use remained a critical environmental concern (Tascione et al., 2024).

For rice cultivation, variable rate nitrogen fertilization guided by remote sensing and smart apps reduced environmental impact by 11-13.6% compared to uniform application (Bacenetti et al., 2020). In the wine industry, smart farming solutions decreased pesticide use by up to 75% in Cyprus and reduced greenhouse gas emissions by 33.4% in Italy (Kasimati et al., 2024). These technologies, including IoT, AI, and big data analytics, have the potential to transform traditional farming into a more productive and sustainable industry (Bhavika et al., 2024).
Smart farming technologies have shown promising results in reducing greenhouse gas emissions from agricultural activities. A case study in Portugal demonstrated an 83.24% reduction in grid energy consumption and associated CO_2 emissions through solar energy integration on a rural farm (Santos et al., 2023).

In Greece, the implementation of smart farming practices led to significant reductions in emissions and pollutant concentrations, with NH_3 emissions decreasing by up to 60% due to reduced fuel consumption and nitrogen fertilizer use (Fragkou et al., 2022). The integration of 6G-IoT in smart agriculture offers potential for further emission reductions through precise resource management and advanced mitigation techniques (Polymeni et al., 2024b). In Australia, livestock farming is responsible for 70% of agricultural emissions, with Queensland being the largest contributor. Climate-smart technologies and best management practices are suggested as effective strategies for reducing greenhouse gas emissions in the agriculture sector (Panchasara et al., 2021)

Recent case studies demonstrate that integrated farming practices can significantly improve crop yields while reducing environmental impacts. In Australia, adopting best management practices and irrigation improvements led to economic benefits of AUD29-377 per hectare annually, along with reductions in fossil fuel use and greenhouse gas emissions (Connolly et al., 2024). The System of Rice Intensification has shown dramatic yield improvements while using less water, fertilizer, and seed (Doyle, 1998). Precision farming techniques in dairy operations have increased milk production by 70% and pasture production by 43% while reducing fertilizer costs (Yule et al., 2013). In China, an integrated cropping system incorporating intercropping, strip rotation, soil mulching, and reduced tillage increased annual crop yields by 15.6-49.9% and farm net returns by 39.2%, while decreasing environmental footprint by 17.3% compared to traditional monoculture (Chai et al., 2021)These studies highlight the potential for integrated



farming approaches to enhance productivity and sustainability simultaneously.

Figure 6: Benefits of Climate Smart Agriculture towards mitigating climate change
Source: (Erekalo, Pedersen, Christensen, Denver, Gemtou, Fountas, & Isakhanyan, 2024)

Figure 6Climate-smart agriculture (CSA) encompasses several key categories that help mitigate climate change while ensuring sustainable food production. Climate-smart agriculture (CSA) lowers greenhouse gas emissions by encouraging sustainable land management practices like conservation tillage and cover cropping, which improve soil carbon sequestration. Precision agriculture technologies enhance fertilizer efficiency, lowering nitrous oxide emissions from over-application of nitrogen. Better livestock management, such as enhanced feed efficiency and methane-reducing supplements, reduces methane emissions from ruminants. Agroforestry and reforestation in CSA sequester carbon by incorporating trees into farming systems, helping to mitigate climate change.

7.0 Challenges in Implementing Smart Farming Technologies

7.1 *Economic and infrastructural barriers*.

Smart farming technologies offer significant potential to increase agricultural productivity and sustainability, but face several implementation challenges, particularly for smallholder farmers. High initial investment and operational costs are major barriers to adoption (Assimakopoulos et al., 2024; Z et al., 2024). Poor connectivity and infrastructure hinder access to vital information and services, affecting crop yields (Z et al., 2024).The adoption of smart farming technologies faces several challenges, with high initial investment and operational costs being major barriers for smallholder farmers(Yoon et al., 2020). Limited technical skills among farmers pose difficulties in operating and maintaining smart farming tools (Assimakopoulos et al., 2024; Z et al., 2024). The integration of various technologies, including sensors, communication systems, big data, and actuators, is crucial for effective smart farming implementation (Elbeheiry & Balog, 2023). While these technologies offer benefits such as increased efficiency and improved crop yields, their implementation raises social, ethical, and environmental concerns that need addressing (Prabha et al., 2023). Overcoming these challenges requires robust support systems and initiatives to promote global adoption of smart farming practices (Prabha et al., 2023).

7.2 *Digital divide between developed and developing countries*.

The digital divide in agriculture between developed and developing countries poses challenges for food safety, competitiveness, and sustainable development (Kenney et al., 2021; Meziani et al., 2024). While smart agriculture can improve food safety and security, it may also intensify competition and lead to underinvestment in good practices by advanced countries (Meziani et al., 2024) To bridge this gap, developing countries are exploring innovative approaches such as agricultural cooperatives, outsourcing, and digital service platforms (Xie et al., 2021). However, implementing e-governance and digital technologies in developing countries faces constraints including leadership commitment, connectivity, capital costs, competencies, content creation, citizen interface, and cyber laws(Singh, 2004). Development banks can play a crucial role in facilitating an inclusive digital revolution in agriculture globally(Kenney et al., 2021). Addressing these challenges requires a shift towards service-scale operations and inclusive organizational innovation to ensure smallholder farmers benefit from digital agricultural transformation (Xie et al., 2021).

7.3 *Need for farmer training and capacity building*.

Farmer training and capacity building are crucial challenges for expanding smart farms. Research highlights the need for enhancing extension officers' skills in smart farming technologies to bridge the gap between researchers and farmers (Kresna & Hanifa, 2023). Training programs have shown to significantly increase participants' comprehension and satisfaction levels (Kresna & Hanifa, 2023). Capacity building and training opportunities are essential for sustainable agriculture development, equipping farmers with necessary skills and competencies (Indraningsih & Swastika, 2022; Yaseen et al., 2015). In underdeveloped regions, strengthening farmers' capacity through counselling, mentoring, and soft loans is vital for creating independent and productive rural economic actors (Indraningsih & Swastika, 2022). However, the adoption of smart farming technologies faces barriers such as interoperability, security, and diverse farming practices. Implementing user-centered design strategies is crucial to increase technology adoption among heterogeneous end-users, ranging from illiterate producers to farm enterprises (Talero-Sarmiento et al., 2023).

7.4 *Ethical concerns regarding data privacy and security*.

Smart farming technologies, while improving agricultural efficiency, raise significant ethical concerns regarding data privacy and security. IoT devices used in smart farming are vulnerable to cyber-attacks, potentially compromising farming operations and sensitive data (Gyamfi et al., 2024). The collection and analysis of big data in agriculture have increased privacy concerns for farmers and other stakeholders (Amiri-Zarandi et al., 2022). Key ethical challenges include data ownership and access, power distribution, and societal impacts (van der Burg et al., 2019). To address these issues, researchers have proposed frameworks for enhancing security and privacy in smart farming (Gundu & Maronga, 2019). However, discussions on these topics have not reached satisfactory conclusions, partly due to differing ideas about the purpose of digital farms in society. Future research should focus on clarifying societal and commercial goals for smart farming and exploring how they can be reconciled in various contexts (van der Burg et al., 2019).

8.0 Future Perspectives

8.1 *Integration of AI and IoT in Precision Agriculture*

Artificial Intelligence (AI) and Internet of Things (IoT) technologies are revolutionizing precision agriculture, offering solutions to increase productivity, optimize resource use, and promote sustainability in farming (Naresh et al., 2020; Sharma et al., 2023). These technologies enable data-driven decision-making through the collection and analysis of field data from various sources, including drones, sensors, and satellites (Eissa, 2024). AI-powered systems can detect crop health issues early, allowing for targeted interventions and reduced chemical use (Eissa, 2024; Naresh et al., 2020). Precision farming techniques improve water management, fertilizer application, and pest control, leading to increased crop yields and profitability while minimizing environmental impact (Raj et al., 2021; Sharma et al., 2023).Despite the potential benefits, challenges such as high implementation costs and data privacy concerns need to be addressed for widespread adoption (Eissa, 2024). Overall, AI and IoT in precision agriculture offer promising solutions for meeting growing food demands and achieving sustainable farming practices (Naresh et al., 2020; Vallakati et al., 2021).

Deep learning techniques have emerged as powerful tools in precision agriculture, offering significant improvements in crop management and yield optimization. Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs) are particularly effective for tasks such as crop yield prediction, resource optimization, and image processing (Wang, 2024). These methods have demonstrated superior accuracy compared to traditional techniques in areas like irrigation management, pest and disease detection, and yield estimation (Ganatra & Patel, 2020). Deep learning applications in agriculture span various domains, including crop classification, weed identification, and pest control (Ganatra & Patel, 2020). A bibliometric analysis of over 400 recent studies highlights the widespread adoption of deep learning in agriculture, with CNNs being the most commonly used architecture (Coulibaly et al., 2022). However, challenges remain, including the need for better integration with domain experts, rigorous statistical testing, and cross-validation of training data (Coulibaly et al., 2022).Deep learning has emerged as a valuable tool in agriculture to address various challenges, such as crop yield prediction, disease detection, weed management, irrigation optimization, and livestock monitoring(ArunabhaPal et al., 2023).

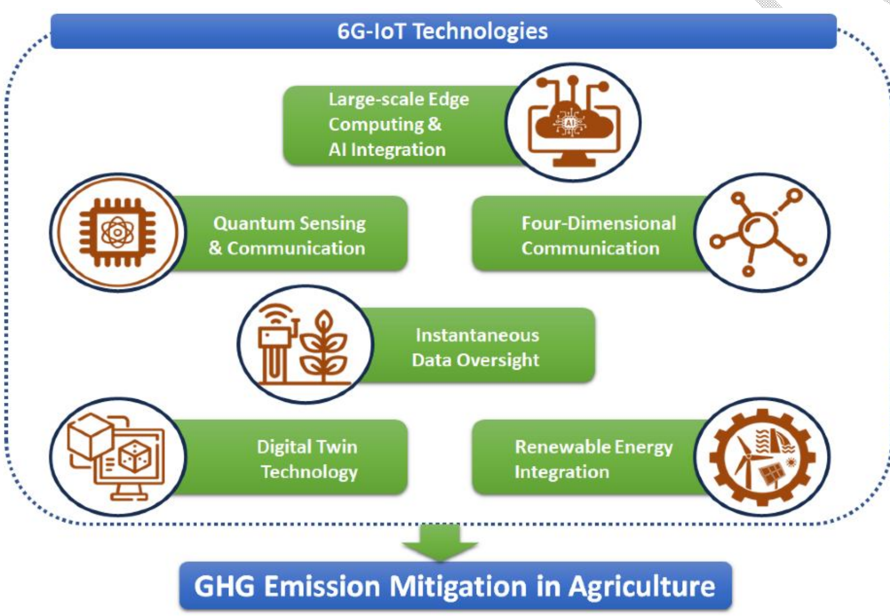


Fig 7: Mitigating Climate change through incorporating 6G-IoT Technologies
Source: (Polymeni et al., 2024a)

Figure 7 illustrates The integration of large-scale edge computing and AI will enable real-time analysis of sensor data, improving irrigation precision, fertilizer efficiency, and pest control. Quantum sensing will revolutionize agriculture by providing ultra-precise measurements of soil moisture, nutrient levels, and plant health, allowing for targeted interventions and reduced waste. Quantum communication will ensure the secure transmission of this critical data, preventing eavesdropping and manipulation. Additionally, four-dimensional communication will enhance data coverage and enable ultra-fast transmission of real-time crop health information from remote sensors, supporting efficient decision-making. Instantaneous data oversight will facilitate predictive maintenance of agricultural equipment, minimizing downtime and ensuring optimal operation. Furthermore, digital twin technology will create virtual farm models, allowing for crop yield simulations and risk mitigation strategies.

Smart farming unquestionably benefits the farming community via the provision of real-time warnings, assistance with management, and the accurate use of agricultural resources to ensure sustainable food production. Smart farming technologies are poised to revolutionize agriculture, addressing challenges like climate change, population growth, and resource scarcity (Debangshi et al., 2023). These technologies, including IoT, AI, drones, and remote sensing, enable precise crop monitoring, efficient resource management, and increased productivity (Balyan et al., 2024; Sharma et al., 2022). LoRaWAN, a low-cost, long-range communication technology, is crucial for implementing IoT in agriculture, though it faces some limitations (Citoni et al., 2019). While smart farming offers significant potential for sustainable food production and economic growth, barriers such as high implementation costs, data security concerns, and lack of digital literacy among farmers persist (Balyan et al., 2024).

Future research should focus on overcoming these challenges through data encryption, digital literacy programs, and supportive economic policies (Balyan et al., 2024). Additionally, advancements in big data analytics, machine learning, and autonomous systems are expected to further enhance smart farming capabilities (Sharma et al., 2022).However, adoption rates remain relatively low and fragmented, necessitating further research to understand and overcome barriers to implementation(Osrof et al., 2023).

9.0 Conclusion

In conclusion, smart farming represents a transformative approach to addressing the challenges of climate change in agriculture. By leveraging advanced technologies such as IoT, AI, and renewable energy, smart farms enhance resource efficiency, reduce greenhouse gas emissions, and promote sustainable practices. These innovations not only improve productivity and resilience in the face of climate variability but also contribute to global efforts to mitigate environmental impacts. Embracing smart farming on a wider scale is essential for building a sustainable and climate-resilient agricultural future.

Agricultural problems such as climate change, land degradation, and severe weather occurrences may be effectively addressed with the use of smart farming technology. Increased output and profit for farmers is one way that smart agricultural technologies integrated with the internet of things (IoT) are predicted to enhance their lives and help ensure a steady supply of food.

Smart farming technologies play a crucial role in mitigating climate change and enhancing agricultural sustainability by optimizing resource use, reducing emissions, and improving productivity. For farmers, these innovations offer cost-effective solutions to enhance yield resilience and adapt to changing climate conditions. Policymakers can leverage data-driven insights to create sustainable agricultural policies and incentives. Researchers benefit from advanced analytics to develop climate-smart strategies, while agribusinesses gain opportunities to invest in precision agriculture and sustainable supply chains. Collaboration among stakeholders is essential to scale these technologies, ensuring a resilient and climate-smart agricultural future.Current trends suggest that smart agricultural practices may help reduce the danger of agriculture becoming unsustainability.

Recommendation

The adoption of smart farms offers a promising solution to mitigate climate change by integrating technology-driven precision agriculture. These systems use IoT sensors, AI, and data analytics to monitor soil health, water usage, and crop performance, ensuring efficient resource utilization. By reducing fertilizer and pesticide overuse, smart farms minimize greenhouse gas emissions and soil degradation. Automated irrigation and climate-responsive technologies optimize water use, addressing water scarcity while enhancing crop resilience to extreme weather. Renewable energy integration, such as solar-powered machinery, further lowers carbon footprints. Additionally, real-time data enables farmers to adapt quickly to changing conditions, fostering sustainable practices. Scaling smart farming globally can significantly contribute to food security and climate resilience.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

List of Abbreviations

GHG	Green House Gasses
CO2	Carbon Dioxide
WFP	World Food Programme
FAO	Food Agriculture Organization
SDG	Sustainable Development Goals
CSA	Climate Smart Agriculture
IOT	Internet of Things
ICT	Information Communication Technology
AI	Artificial Intelligence
SF	Smart Farm
RDA	Rural Development Administration
MIT	Massachusetts Institute of Technology
RFID	Radio Frequency Identification
ML	Machine Learning
GIS	Geographical Information System
MQTT	MQ Telemetry Transport
UAV	Unmanned Aerial Vehicle
LORAWAN	Low range wide area network
AUD	Australian Dollars
KOICA	Korean International Cooperation Agency
CNN	Convolutional Neural Networks
RNNS	Recurrent Neural Networks

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