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Integrating climate-smart agriculture for sustainable agriculture: Opportunities, challenges and future directions

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ABSTRACT

Climate-smart agriculture (CSA) has emerged as a valuable strategy to address the challenges of food insecurity, climate change, and environmental degradation. This study assesses the impact of six key CSA practices: technologies including water smart, energy smart, nutrient smart, carbon smart, weather smart, and knowledge smart for farming regarding the increasing world population and decreased shift in arable land. This paper employs a literature review and case analysis to demonstrate how these practices improve resource utilization, worsen environmental impacts and strengthen agriculture production systems. Several studies carried out in agriculture have stipulated that water-smart practices can help achieve improvements in water use efficiency by at least 30 percent, nutrient-smart practices can help increase soil health by a range of 20 percent, and carbon-smart practices could reduce greenhouse gas emissions by between 15 percent. This brings us back to the question of the role that CSA can play in support of processes that are directed at realizing the Sustainable Development Goals SDG 2 (Ending Hunger) and SDG 13 (Taking Action on Climate Change) on development processes across the world. However, inefficient and insecure land rights, water deficits, and high initial investment hinder the widespread adoption of the technologies. The consequences are that policies concerning the matters, a well-developed institutional environment, and farmer's knowledge should be introduced to eliminate these issues. As to further research, the continuous improvements of the models of CSA and the financing of the CSA also need future action research. Overall, CSA offers hope for establishing strong foundations for food security and climate-resilient agricultural systems.

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INTRODUCTION

Climate change is one of the most formidable problems in the contemporary world (Wakweya, 2023a). The term climate change refers to important changes in the mean values of the meteorological parameters, including temperature and rainfall, for which averages have been computed over a long period. The changing climate has affected the weather conditions and has increased the vulnerability to extreme events such as salinity, droughts, etc. (Malhi *et al.*, 2021), has badly affected agriculture (Praveen & Sharma, 2019) and food security across the world in the recent decade (Janni *et al.*, 2024). At the same time, the global population is growing, thus increasing the pressure on resources (Maja & Ayano, 2021) and land to produce food, which in turn results in the commercial production of crops. This shift includes the reliance on the use of chemical fertilizers and pesticides, which greatly cause greenhouse gases and degrading of the soil (Reicosky *et al.*, 2000). The emission of greenhouse effect substances like carbon, methane, and nitrous oxides through activities that raise their levels is equally affecting the globe's farming. This anthropogenic climate change will consequently alter the regional and temporal pattern of food production, food availability, and markets (Porfirio *et al.*, 2018). Climate change issues are very crucial to global agriculture as it impacts both crop and animal farming in various ways. Weather conditions, rain-fed farming, and more frequent and severe hunger lead to the decline in yields, access to food, and the financial situation of countries where agriculture is a major source of income (Wakweya, 2023). The climatic effects that are most apparent are shifts in temperature and changes in rainfall which affect crop production in a big way. The impacts of climate change including temperature increases, and fluctuations in rainfall affect crop production based on the type, location today intensity of changes in the said climate factors (Malhi *et al.*, 2021). Greenhouse gases (GHGs) emitted through human-induced activity capture heat in the atmosphere and cause changes in climate and temperature rise (Zhao *et al.*, 2023).

Warmer temperatures could increase the rate of crop production from efficient days in growth therefore reducing the growing seasons and even changing the period of planting and having the harvests (Mahato, 2014). But at the same time, high temperatures also harm crops; it strains the plants and therefore the yields can be low and the produce not as good as it should be. More specifically, if temperate and tropical areas both warm by 2°C, even total wheat, rice, and maize production is projected to decrease (Challinor *et al.*, 2014). An increase in temperature alters the plant's stress tolerance to heat, shortens growing periods, accelerates respiration rates, reduces available water, and enhances pest & disease prevalence. Higher temperatures consequently affect seed development, enhance respiration, and reduce biomass thus resulting in smaller grains, low yield, and protein levels. Similar responses have been reported for wheat under both temperature stress and drought, where the interaction between these stress factors enhanced photosynthesis and yield loss (Cogato *et al.*, 2019). Fluctuations in rainfall volume can be important for agriculture and the fields as they determine the growth of plants, the quality of the ground, and the amount of moisture (R. *et al.*, 2024). Increased precipitation in very short intervals and increased duration of the dry season will, therefore, result in frequent floods and droughts. This will increase the complexity of the process of agriculture due to instances such as erosion of the soil, water logging, and nutrient deficiencies (Fishman, 2016). On the other hand, potential areas that are characterized by drought may experience water shortages affecting the irrigation systems and requirement for watering crops (Pais *et al.*, 2020). Such variability in water availability underscores the importance of adaptive water management strategies and the development of drought-resistant crop varieties.

Pests and diseases are other effects of climate change which increase in severity by global warming beyond temperature and precipitation. Changes in temperature and humidity help pests develop favorable conditions for breeding hence, a disturbing rise in temperature causes a 10-25% increase in crop losses due to pests' attacks (Shrestha, 2019). Moreover, the yield and quality of crops produced in the field are reducing as a result of the number of pests and plant diseases that are caused by global warming (Agrimonti *et al.*, 2021). Sudden changes in climate such as heat stress, unpredictable weather, frequent droughts, floods, temperature increases, and insect invasions are examples of climate change that have negative impacts on reproduction (Mutengwa *et al.*, 2023). It is presumed that climatic changes will have an impact on pathogen reproduction and persistence, host readiness, and how diseases influence crops. This will introduce considerable shifts in disease impact, scope, the economy, and the number of diseases that affect a given crop (Elad & Pertot, 2014). Higher atmospheric levels of CO_2 will lead to a decline in the quality of pastures and the quality of available food. Where the rains intensify, the chances flashed by prices and yield are anticipated to go high, thus compounding living standards and eradicating food security (Steenwerth *et al.*, 2014). Therefore, this paper has found that climate change greatly impacts agriculture through aspects such as temperature and rainfall changes as well as pests and extreme weather vulnerabilities. Innovative practices and improved resilient farming systems can incorporate the changes occasioned by climate change and at the same time feed the ever-growing population and preserve the planet's resources for future generations.

The concept of climate-smart agriculture

Unless we change our approach to how funding for future growth and development is allocated for agriculture, we are failing to misplace capital and people resources in farming systems that are already unsustainable, and the climate is also going to pay the price. The continuously growing global population also means increased population pressure on food resources hence pressuring current and future agricultural systems and hence food security (Maja & Ayano, 2021). CSA was realized as a reliable intervention for this newly emerging climate change issue. According to the technical definition, climate-smart agriculture is agriculture that enhances an individual country's food security and development objectives in a manner that reduces or eliminates GH emissions and increases the resilience and productivity of resources (Nciizah & Wakindiki, 2015). It is a process that aims at transforming and adapting the agricultural systems to meet food security because of the emerging climate change dynamics (Lipper *et al.*, 2014). Climate-smart agriculture (CSA) focuses on three main objectives: Firstly, advancing agricultural productivity to raise incomes, food accessibility, and development; secondly, enhance climatic risk management by growing individual farm/bush farms, communities, and national system potential for resilience; and thirdly decreasing future climatic vulnerability by lessening the sector's output of greenhouse gases and becoming more effective at storing carbon in the ecosystem (Campbell *et al.*, 2014).

Climate Smart Agriculture or CSA aims to undertake the challenges in agricultural development by increasing agriculture productivity in an environment-friendly manner reducing the emission of greenhouse gases and ensuring food security domestically. CSA practices, therefore, can assist agriculture adapt to climate change, reducing climate change, and sustainably enhance productivity (Nagar *et al.*, 2023). Some of the strategies entail conservation agriculture, agroecological practices, small-scale irrigation, fish farming, agroforestry, soil and water conservation, use of proper nutrients, integrated crops and animal farming, management of landscapes and grasslands, minimum tillage practices (Chandra *et al.*, 2018). It offers or provides enablers in which specific technologies and practices can be assessed in terms of their impacts, especially relative to national development and food security in the context of the changing climate (Barasa *et al.*, 2021). Climate-smart agriculture is therefore linked with many sustainable development goals as it has an extensive impact across the spectrum, which is beyond the defined scope of climate change and adaptation (Aishwarya & Kumar, 2024). Hence this approach brings into focus how a stable food production system is possible only by integrating the agriculture sector to climate change measures since they also support the rural economy and the provision of sustainable natural resources to future generations.

Three pillars of climate-smart agriculture

The framework for evaluating current CSA methods is built on three main pillars: food security, adaptation, and mitigation. This method ensures a fair and comparable evaluation of individual tools. It is crucial to recognize that some challenges, such as sustainability, affect many pillars. For example, sustainability has substantial implications for both food security and adaptation, while its environmental components are covered by the mitigation pillar (van Wijk *et al.*, 2020).

Pillar 1: Food Security

Pillar 2: Adaptation

Pillar 3: Mitigation

Key practices and technologies in CSA

This review reviews various types of farming technologies and measures to improve adaptation and reduction of negative impacts of climate change on agriculture. These technologies aim to increase productivity, sustainability, and reliability in

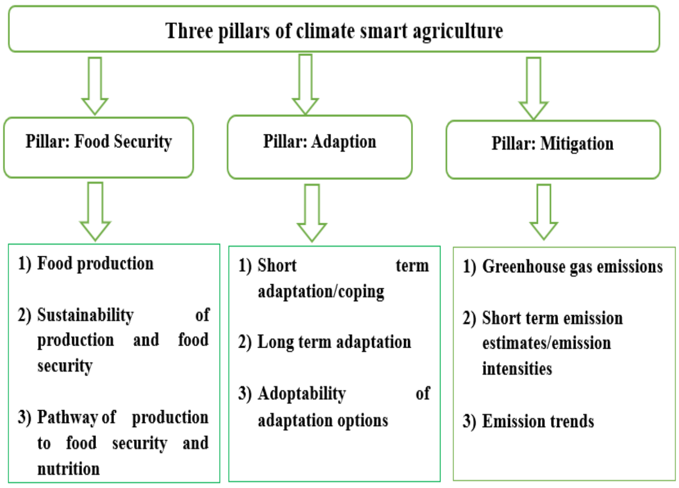

Figure 1. *Scheme of three pillars of CSA and some components (van Wijk et al., 2020).*

agriculture (Khatri-Chhetri *et al.*, 2017). Technologies such as rainwater management, efficient irrigation techniques such as drip irrigation, Laser land leveling, furrow irrigated bed planting, water control structures for improved drainage, and cover crops are some water-smart technologies that improve water efficiency and better climate shock (Zhan *et al.*, 2018). Energy-wise farming entails the provision of energy-efficient practices and minimizing the use of energy with the use of renewable energy like solar-powered irrigation systems (Yadav *et al.*, 2020). Sustainable fertilizer management and application include sites integrated nutrient management, the use of green manure, fertilizer-leaf color chart, and intercropping with legume for the wise usage of fertilizers, increase in soil fertility, cost reduction, and reduction in pollutant emission (Hou, 2023). Carbon-wise technologies such as agroforestry, concentrate feeding for animals, fodder management, integrated pest management, etc. strive to minimize the emission of greenhouse gases and foster sustainable growth (Ramachandran Nair *et al.*, 2009). Climate-smart solutions to address climate variability include climate-smart structures, weather-smart advisories, and insurance on produce (Sharma & Bhatt, 2019). Knowledge-smart technologies involve the use of research results and community knowledge in improving on and managing climatic risks, improving seed varieties, and seed and fodder banks (Bhattacharyya *et al.*, 2020). A summary of these innovations is made in the subsequent table:

CSA and food security

Climate-Smart Agriculture (CSA) has helped raise the degrees of food security as it deals with all aspects that tend to influence availability, access, and actual consumption while focusing on production in the future (Steenwerth *et al.*, 2014). CSA such as conservation agriculture, agroforestry, and integrated water management increase productivity and mitigate the unpredictability of production by maintaining production in adverse circumstances, such as unfavorable weather (Kifle, 2021). For example, drought-resistant crop varieties and IPM help minimize crop losses and make sure there is constant production and supply of food (E. Birch *et al.*, 2011; Tadesse & Anteneh, 2018). Therefore, due to the reduction in the cost and the advocacy for local community agriculture, CSA has the advantage of making food readily available and affordable, especially to the most rural populace (Ghosh, 2019; Wakweya, 2023). In this manner, crop diversification is another boost in the dimension of the quality of food and nutrient consumption hence wiping out micronutrient malnutrition (Nair *et al.*, 2016). It is eco-friendly as the practices applied in CSA do not call for the use of many chemicals hence leading to safer food (Arif *et al.*, 2020). CSA-related education and training provide nutrition and food utilization-related amenities that increase nutritional food enlightenment and safety (Zakaria *et al.*, 2020). Through CSA, societies develop the ability to adapt to change regarding climate, sustaining food security in the long run due to favorable physical characteristics of the soil, water conservation, and plant diversity (Akter *et al.*, 2022). Sustainable intensification

Table 1. Technological advances in climate smart agriculture.

Technology Adaptation	Adaptation/Mitigation Potential
Water-smart interventions	Enhance water efficiency
Rainwater Harvesting (RH)	Collection of rainwater for agricultural use in rainfed/dry areas and other purposes on-site (Velasco-Muñoz *et al.*, 2019).
Drip Irrigation (DI)	Water application directly to the root zone of crops decreases water loss (van der Kooij *et al.*, 2013).
Laser Land Levelling (LL)	Ensures equal water distribution, lowers water loss, and enhances fertilizer usage efficiency (Naresh *et al.*, 2011).
Furrow Irrigated Bed Planting (FIBP)	The approach provides better control over irrigation, drainage, and precipitation management during the monsoon, while also increasing fertilizer usage efficiency (S. Kumar *et al.*, 2020).
Cover Crops Method (CCM)	Reduces evaporation loss of soil water (also puts nutrients into the soil) (Meyer *et al.*, 2020).
Drainage Management (DM)	Removal of surplus water (flood) by water control structure (Fausey, 2005).
Energy-smart	Interventions that enhance energy consumption efficiency (Imran *et al.*, 2019).
Zero Tillage/Minimum Tillage (ZT/MT)	Reduces the amount of energy required in land preparation. In the long run, it also promotes soil water penetration and organic matter retention (Ngoma, 2018).
Nutrient-smart	Interventions that enhance nutrient utilization efficiency (Zougmoré *et al.*, 2014).
Site Specific Integrated Nutrient Management (SINM)	Optimum provision of soil nutrients throughout time and space matching the requirements of crops with the correct product, rate, time, and place (Richards *et al.*, 2015).
Green Manuring (GM)	Cultivation of legumes in a cropping system. This approach enhances nitrogen supply and soil quality (Carr *et al.*, 2020).
Leaf Color Chart (LCC)	Quantify the needed quantity of nitrogen consumption depending on the greenness of crops. It is used for split dose application in crops like rice, maize and wheat to identify nitrogen shortage (Bhusal *et al.*, 2020).
Intercropping with Legumes (ICL)	Cultivation of legumes with other principal crops in alternate rows or combined. This approach enhances nitrogen supply and soil quality (Kiwia *et al.*, 2019).
Carbon-smart	Interventions that minimize GHG emissions
Agro-Forestry (AF)	Promote carbon sequestration including sustainable land use management (Schaller *et al.*, 2017).
Concentrate Feeding for Livestock (CF)	Reduces nutrient losses and livestock requires less amount of feed (Duguma & Janssens, 2021).
Fodder Management (FM)	Promote carbon sequestration by integrating sustainable land use management (Schaller *et al.*, 2017).
Integrated Pest Management (IPM)	Reduces usage of chemicals (Roy, 2020).
Weather-smart	Interventions that provide services linked to income security and weather alerts to farmers.
Climate Smart Housing for Animals (CSH)	Protection of animals from extreme climatic occurrences (e.g. heat/cold stressors) (Mujeyi *et al.*, 2021).
Weather-based Crop Agro-advisory (CA)	Climate information-based value-added agro-advisories to the farmers (Khatri-Chhetri *et al.*, 2017).
Crop Insurance (CI)	Crop-specific insurance to cover revenue loss due to vagaries of weather (Gangopadhyay *et al.*, 2019).
Knowledge-smart	Use of a combination of science and local knowledge
Contingent Crop Planning (CC)	Climatic risk management plans to cope with major weather-related contingencies like drought, flood, and heat/cold stresses during the crop season (Muriithi *et al.*, 2023).
Improved Crop Varieties (ICV)	Crop varieties that are tolerant to drought, flood, and heat/cold stresses (Sime & Aune, 2018).
Seed and Fodder Banks (SFB)	Ensures availability of high-quality seeds and fodder amid harsh climatic circumstances (Mezgebe, 2012).

contributes to raising the productivity and production of food within the same land area as the existing one (Pretty & Bharucha, 2014). Another benefit of CSA is that it results in low greenhouse gas emissions, as well as the proper use of fertilizers which is vital in the fight against climate change and the protection of ecosystems (Abegunde *et al.*, 2022). Social enablement has remained important for the implementation of CSA where governments and relevant organizations offer required infrastructure, knowledge generation and diffusion and support services, and client education (Onyeneke *et al.*, 2018). Engaging the community and the spread of information make CSA adopt practices that fit the local environment, thus enabling the farmers to practice sustainable practices (Ma & Rahut, 2024). Thus, CSA contributes to improvements in food security, availability, access to, and utilization levels, as well as strengthens the sustainability and adaptability of agricultural production. CSA integrates aspects like better farming techniques, sustainable intensification, emission reduction, policies, and stakeholders' support to deal with the multiple factors of food insecurity under climate change.

CSA and Sustainable Development Goals (SDGs)

CSA is strongly connected with SDGs; it has focused on global issues such as food insecurity, climate change, and sustainable development (Matteoli *et al.*, 2020). Therefore, the practices of climate-smart agriculture enhance the manner of increasing output, resilience, and decreasing emissions, thus, achieving the above-mentioned objectives of the SDGs for the greater purposes of eradicating poverty, protecting the environment, and enhancing prosperity for all (Ouda & Zohry, 2022). Concepts in the CSA framework not only add to the growing productivity of agriculture or food production per capita but also improve the agricultural sector's ability to adapt to climate change and minimize or decrease GHG emissions; hence, fully aligning with sustainable development for the SDGs initiated by the UN and facilitated in thematic areas of the hunger, poverty, climate, water, and consumption (Jagustović *et al.*, 2021). CSA improves sustainable and resilient food production to feed the population thus resulting in the achievement of SDG 2: Zero Hunger (Akpabio *et al.*, 2023). Some important inputs would be improved varieties of crops, water control, and nutrient control for enhanced output. This increases yield, sustains the environment, supports climate change, and decreases food deficiency and famine (Sharma & Bhatt, 2019). The other CSA techniques, in the same manner, would lessen emissions of greenhouse gases, enhance carbon stock, and enhance the capacity to cope with climatic factors, which plays a direct role in the achievement of SDG 13: Climate Action (Arora & Mishra, 2023). Such farming practices as agroforestry, integrated pest management, and efficient use of water among others would mitigate climate change and achieve SDG 13 (Campbell *et al.*, 2018). CSA has a positive impact because of improved productivity and resilience of agricultural production hence enhancing farmers' income thus eradicating poverty, both in general and especially rural poverty supporting SDG, 1 No poverty (Khamkhunmuang *et al.*, 2022). They contribute to the creation of employment opportunities as well as decreasing the chance of being affected by climate volatility in a manner that declines poverty rates. Moreover, efficient irrigation techniques like drip irrigation and water management practices such as rainwater harvesting also enable the achievement of SDG 6: Clean Water and Sanitation (Vishnoi & Goel, 2024). Including such methods would lead to the quality of water to meet some of the human requirements and also cause a reduction of water losses while availing the water resource for agricultural and other needs. This pertains to SDG 12 entitled, Responsible Production and Consumption, and how CSA addresses wastes and optimal utilization of resources (Qureshi *et al.*, 2022). Judicious use of nutrients, no-tillage, and Integrated Pest Management are some of the practices implemented that promote sober consumption and production for sustainable development (Sharma & Bhatt, 2019).

Challenges and barriers to CSA adoption

Shrinking cropland and land tenure issues

Cropland per person is reducing as the population grows and there is less unexploited land available. The decrease in farm size has an impact on the adoption of new technology. Farmers on larger farms are more likely to adopt CSA practices because they can test new approaches on one area of their farm while using traditional techniques on the other (Josephson *et al.*, 2014). Land tenure is another challenge for smallholder farmers, discouraging them from investing (Nigussie *et al.*, 2015). Declining soil fertility and unsustainable farming practices are often linked to farmers' insecurity about land tenure. Appropriate policies are needed to encourage both individual farmers and communities to invest in sustainable long-term land management (Chiemela *et al.*, 2018).

Shortage of agricultural water resources

Currently, a scarcity of agricultural water resources impedes global food security and the sustainable development of CSA. Global water consumption is expected to increase by 55% (Lund Schlamovitz & Becker, 2021). It is expected that by 2030, the likelihood of facing agricultural water shortages will substantially rise to a medium-high level (Zhang *et al.*, 2022). Evaluation of agricultural water resources is essential for long-term management and planning. Seasonal variations in rainfall and water quality make irrigated agriculture in South Korea susceptible to water scarcity (Lee JaeMin *et al.*, 2019).

Lack of adequate knowledge and information transfer

In Ethiopia, the main barrier to implementing CSA techniques is a lack of adequate expertise and skills (Wassie & Pauline, 2018). Another problem is the ineffective transmission of knowledge, skills, and technologies from government institutions and development organizations to local farming communities (Jirata *et al.*, 2016). Farmers, particularly in developing countries, encounter challenges in implementing CSA due to a lack of knowledge and awareness, despite their interest (Autio *et al.*, 2021).

Slow return of benefit and lack of financial support

Due to high upfront costs and the substantial infrastructure and technological investment required, many farmers are unable to adopt CSA methods like precision farming (John *et al.*, 2023). As a result, farmers frequently prefer other agricultural strategies with faster production effects over using CSA (Aweke, 2017). Market issues arise when demand is low, making it harder for farmers to find markets for CSA products without support (Dong Huan *et al.*, 2019). However, there are concerns about financial and institutional support. Informal lenders frequently charge exorbitant interest rates, making it difficult for small-scale farmers to repay loans on time. Formal financial providers typically help commercial farmers while disregarding smallholders (Aweke, 2017).

Information resource integration

In CSA, precise product information and data support are critical for production, management, transportation, and sales. However, concerns such as poor consistency, insufficient data collection, and inaccuracy present substantial challenges. Real-time information sharing is difficult, so data security is a big problem. Furthermore, CSA faces the challenge of information overload; incorrect information might stymie long-term progress. Ensuring reliable and secure agricultural information is critical to the success of CSA (Zhao *et al.*, 2023).

Agricultural GHGs emissions

Agricultural greenhouse gas emissions, driven by increased fossil fuel use, land use changes, and deforestation, hinder sustainable growth in CSA (Raihan & Tuspekova, 2022).

Agricultural ecosystems are the world's second-greatest source of human-caused greenhouse gas emissions, accounting for 56% of total non-CO_2 emissions (Zhao *et al*., 2023). More than half of the world's soil emissions and 49% of its agricultural emissions are due to seven countries. Argentina, Australia, Brazil, Canada, Chile, China, India, and the United States (Maraseni & Qu, 2016). Agricultural operations affect the environment by leaving large nitrogen and water footprints in addition to producing greenhouse gas emissions (Chen *et al*., 2020).

Climate variability and climate change

Climate variability and change have shifted the distribution of light, heat, water, and other agricultural resources. This has had a significant impact on smallholder farmers, affecting crop yields, income, and food security (McKinley *et al*., 2021). Climate change and variability pose a challenge to Climate-Smart Agriculture (CSA) by reducing agricultural productivity and altering regional climates (Kogo *et al*., 2021). According to a survey from Ghana, climate variability has a significant impact on subsistence farming. It also makes eating anxious for 58% of families and makes it difficult for 62% of households to obtain the right quantity and quality of food Asare-Nuamah, 2021). Climate change has a direct impact on agriculture by increasing average temperatures, extending the growing season, increasing the number of hot days and nights, more variable precipitation patterns, and elevated CO_2 concentrations (Janowiak *et al*., 2016). Farmers may face policy and regulatory issues while attempting to implement CSA. For example, some technologies may be prohibited, and government agencies may fail to offer necessary funds or technical help (Wakweya, 2023). Farmers may be hesitant to embrace new technology or techniques that go against their traditional practices due to social and cultural practices (Annes *et al*., 2021)

Opportunities and future prospects of climate-smart agriculture

The growing global population, coupled with the adverse effects of climate change, significantly threatens agricultural output and food security. To counter these challenges, the application of environmental and sustainable approaches like Climate Smart Agriculture is critical in preventing such consequences and guaranteeing a sustainable agricultural industry (Bibi & Rahman, 2023). In this context, Climate-smart agriculture (CSA) is an innovative and comprehensive approach that focuses on the complex problems of climate change and their solution in the framework of the agricultural sector (Raihan, 2024). CSA offers a revolutionary solution by properly implementing the use of ICTs, environment-friendly approaches, and socio-economic coping strategies in the design of robust crop-growing techniques to feed the world in this era of globalization. This holistic strategy seeks to prevent the negative impacts of climate change, respond to their occurrences, and consequently enhance the probability of improved efficiency in agricultural activities (Balogun *et al*., 2024). The development of CSA in the future will greatly depend on technological innovations, new methods in cropping systems and management, combined services of “Internet + Weather,” and agricultural weather index insurance (Raihan, 2024). The following are the key drivers: technological developments, where precision agriculture is expected to dominate through the uptake of technologies. Remote sensing techniques are important in CSA as they offer quick, widespread information on crop states, yield estimates, area, pests, diseases, wildlife, water and weather conditions, and animals. This option provides distinct aspects of crop health and yields, tracing effective CSA management by satellites and drones (Kumar *et al*., 2024). The use of various sources of RS data has made it effective in capturing dynamic changes in crop growth more effectively (Udayar Pillai *et al*., 2024). In the same way, the Internet of Things alters agriculture through the networking of devices and sensors to gather data from the surrounding environment as well as the crops. IoT applications assist in facilitating the best practices in farming by availing data on the calculation of temperature, humidity, pH of the soil, and others; systems have to be smart, effective, and safe (Jusoh *et al*., 2021). IoT is a system that feeds data into AI so that the images can be integrated for analysis and other functionalities to be predicted. Challenges such as pest control and post-harvest management can thus be easily solved if IoT technology is to be used effectively (Adli *et al*., 2023). Artificial intelligence (AI) and machine learning (ML) are considered to be part of the CSA perspectives for development. AI comprises machines including digital computers that imitate, fortify, and extend intelligence to help them sense the world and learn relevant information (Subeesh & Mehta, 2021). AI will improve the accuracy of gains from sales, predictions of weather and pests, as well as numbers of yields. One is that it has great potential in CSA and it is also characterized by the abilities in the fields of data analysis and even predictive capability (Wildan, 2023).

Besides, technological practice and development in cropping systems of cropping techniques, including crop rotation, crop diversification, and conservation agriculture, can significantly improve agriculture by minimizing greenhouse gas emissions (Abdul & Bature, 2024). Vertical farming and controlled environment agriculture (CEA) are two sustainable intensification emerging technologies in urban agriculture that will enhance the optimal growing conditions and rid of transport expenses with carbon footprints (Barui *et al*., 2022). Also, many systems such as the water-efficient systems of aquaponics and hydroponic will reduce water consumption and establish several loops by incorporating fish farming into crop farming (Kalantari *et al*., 2018). Modern-day agriculture requires mechanized and industrial forms of farming and hence requires enhanced meteorological services. Thus, the establishment of a comprehensive vertical meteorological service system can be made by deploying Internet technology to nest these services into the needs of farmers. Utilizing this so-called Internet + Weather approach in terms of human-computer interface integration with multiple automated weather stations to strengthen the forecast and monitoring capability of meteorological disasters and early warning mechanisms will support CSA objectives (Zhao *et al*., 2023). Agricultural weather index-based insurance works with current agrometeorological data that serve as prompts for compensation and one type of natural source that lessens the adverse effects of natural risks on agriculture without having to evaluate every loss individually (Raihan, 2024). It means it serves as insurance based on the effective use of financial instruments, invites social funds, and becomes the new approach to transfer risks for farmers (Zhao *et al*., 2023). Finally, CSA depends on partnerships outside policy instruments through scientific institutions, agricultural research and extension, financial institutions, farmers' organizations, non-governmental and international organizations, private firms, and the media. Cooperation through coordinated platforms, common projects, and integrated use of resources is crucial. Hence enhancing these institutions enables the farmers to acquire knowledge and embrace climate-smart practices, increase climate resilience, and improve the sustainable food system (Safdar *et al*., 2024).

Conclusion

Climate-smart agriculture refers to all agricultural activities on climate change. In addition to an increase in agricultural productivity, the practices have food security, adaptation, and mitigation aspects. With an increasing population and a resultant decrease in the land under agricultural production, the integrated approach remains vital for food security and the conservation of the environment. We found that water-smart, energy-smart, nutrient-smart, carbon-smart, weather-smart, and knowledge-smart CSA practices are very important in optimizing resource use, reducing environmental impacts, and enhancing the resilience of farming systems. All these practices can be well combined to support sustainable intensification in meeting the dual challenges of human population growth and preserving planetary health. Besides the perspective that CSA would be more aligned with the SDGs for development, such as SDG 2 (zero hunger) and SDG 13 (climate action), the argument is also based on the common belief in the potential vast impact of CSA towards reaching global development targets. However, our study also identified several challenges to the implementation of CSA: insecure land rights, water scarcity, high costs of investment, and the need for good policies and robust societal engagement. Therefore, dealing with these challenges through coordination, policy reform, and farmer support is quite important to adopt CSA with the ultimate goal of making agricultural systems more resilient, productive, and sustainable, contributing to enhanced food security and environmental sustainability.

DECLARATIONS

Author contribution statement

Conceptualization: B.N. and J.R.; Methodology: B.B.; Software and validation: B.N., B.B., and G.J.; Formal analysis and investigation: L.G.; Resources: G.J.; Data curation: J.R.; Writing—original draft preparation: B.N.; Writing—review and editing: L.G.; Visualization: B.N.; Supervision: B.N.; Project administration: G.J. All authors have read and agreed to the published version of the manuscript.

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REFERENCES

Abdul, A., & Bature, A. (2024). *Combating Climate Change with Good Agricultural Practices (GAP)* (pp. 118–134).

Abegunde, V. O., Sibanda, M., & Obi, A. (2022). Effect of climate-smart agriculture on household food security in small-scale production systems: A micro-level analysis from South Africa. *Cogent Social Sciences*, *8*(1), 2086343. https://doi.org/10.1080/23311886.2022.2086343

Adli, H., Remli, M. A., Nizar, K., Ismail, N. A., González Briones, A., Corchado, J., & Mohamad, M. (2023). Recent Advancements and Challenges of AIoT Application in Smart Agriculture: A Review. *Sensor Review*, *23*. https://doi.org/10.3390/s23073752

Agrimonti, C., Lauro, M., & Visioli, G. (2021). Smart agriculture for food quality: Facing climate change in the 21st century. *Critical Reviews in Food Science and Nutrition*, *61*(6), 971–981. https://doi.org/10.1080/10408398.2020.1749555

Aishwarya, & Kumar, P. (2024). A Perspective Way to Climate Smart Agriculture. In P. Kumar & Aishwarya (Eds.), *Technological Approaches for Climate Smart Agriculture* (pp. 9–24). Springer International Publishing. https://doi.org/10.1007/978-3-031-52708-1_2

Akpabio, E. S., Akeju, K. F., Omotoso, K. O., Ohunakin, F., & Ogundokun, R. O. (2023). Climate Smart Agriculture and Nigeria's SDG 2 Prospects: A Review. *2023 International Conference on Science, Engineering and Business for Sustainable Development Goals (SEB-SDG)*, *1*, 1–6. https://ieeexplore.ieee.org/abstract/document/10124557/

Akter, A., Geng, X., Endelani Mwalupaso, G., Lu, H., Hoque, F., Kiraru Ndungu, M., & Abbas, Q. (2022). Income and yield effects of climate-smart agriculture (CSA) adoption in flood prone areas of Bangladesh: Farm level evidence. *Climate Risk Management*, *37*, 100455. https://doi.org/10.1016/j.crm.2022.100455

Annes, A., Wright, W., & Larkins, M. (2021). 'A Woman in Charge of a Farm': French Women Farmers Challenge Hegemonic Femininity. *Sociologia Ruralis*, *61*(1), 26–51. https://doi.org/10.1111/soru.12308

Arif, M., Jan, T., Munir, H., Rasul, F., Riaz, M., Fahad, S., Adnan, M., Mian, I. A., & Amanullah. (2020). Climate-Smart Agriculture: Assessment and Adaptation Strategies in Changing Climate. In V. Venkatramanan, S. Shah, & R. Prasad (Eds.), *Global Climate Change and Environmental Policy: Agriculture Perspectives* (pp. 351–377). Springer. https://doi.org/10.1007/978-981-13-9570-3_12

Arora, N. K., & Mishra, I. (2023). Sustainable development goal 13: Recent progress and challenges to climate action. *Environmental Sustainability*, *6*(3), 297–301. https://doi.org/10.1007/s42398-023-00287-4

Asare-Nuamah, P. (2021). Climate variability, subsistence agriculture and household food security in rural Ghana. *Heliyon*, *7*(4). https://www.cell.com/heliyon/fulltext/S2405-8440(21)01031-8

Autio, A., Johansson, T., Motaroki, L., Minoia, P., & Pellikka, P. (2021). Constraints for adopting climate-smart agricultural practices among smallholder farmers in Southeast Kenya. *Agricultural Systems*, *194*, 103284.

Aweke, M. G. (2017). Climate-smart agriculture in Ethiopia: CSA country profiles for Africa series. *International Center for Tropical Agriculture: Washington, DC, USA*.

Balogun, O., Nwahia, O., & Nwebor, E. (2024). Climate-Smart Agriculture for Sustainable Agricultural Development in Nigeria: An Empirical Review. *Journal of Applied Sciences and Environmental Management*, *28*, 1853–1858. https://doi.org/10.4314/jasem.v28i6.26

Barasa, P., Botai, C., Botai, J., & Mabhaudhi, T. (2021). A Review of Climate-Smart Agriculture Research and Applications in Africa. *Agronomy*, *11*, 1255. https://doi.org/10.3390/agronomy11061255

Barui, P., Ghosh, P., & Debangshi, U. (2022). VERTICAL FARMING - AN OVERVIEW. *PLANT ARCHIVES*, *22*(2), 223–228. https://doi.org/10.51470/PLANTARCHIVES.2022.v22.no2.038

Bhattacharyya, P., Pathak, H., & Pal, S. (2020). Dimensions of Climate-Smart Agriculture. In P. Bhattacharyya, H. Pathak, & S. Pal (Eds.), *Climate Smart Agriculture: Concepts, Challenges, and Opportunities* (pp. 33–39). Springer. https://doi.org/10.1007/978-981-15-9132-7_3

Bhusal, A., Khatri, L., Bhandari, B., Sherpa, L., & Neupane, G. (2020). *Climate-smart agriculture (CSA): Training manual*. http://hdl.handle.net/10625/61175

Bibi, F., & Rahman, A. (2023). *An Overview of Climate Change Impacts on Agriculture and their mitigation strategies*. https://doi.org/10.20944/preprints202307.1352.v1

Campbell, B. M., Hansen, J., Rioux, J., Stirling, C. M., & Twomlow, S. (2018). Urgent action to combat climate change and its impacts (SDG 13): Transforming agriculture and food systems. *Current Opinion in Environmental Sustainability*, *34*, 13–20.

Campbell, B. M., Thornton, P., Zougmore, R., Van Asten, P. J. A., & Lipper, L. (2014). Sustainable intensification: What is its role in climate smart agriculture? *Current Opinion in Environmental Sustainability*, *8*, 39–43. https://doi.org/10.1016/j.cosust.2014.07.002

Carr, P. M., Cavigelli, M. A., Darby, H., Delate, K., Eberly, J. O., Fryer, H. K., Gramig, G. G., Heckman, J. R., Mallory, E. B., Reeve, J. R., Silva, E. M., Suchoff, D. H., & Woodley, A. L. (2020). Green and animal manure use in organic field crop systems. *Agronomy Journal*, *112*(2), 648–674. https://doi.org/10.1002/agj2.20082

Challinor, A. J., Watson, J., Lobell, D. B., Howden, S. M., Smith, D. R., & Chhetri, N. (2014). A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change*, *4*(4), 287–291. https://doi.org/10.1038/nclimate2153

Chandra, A., McNamara, K. E., & Dargusch, P. (2018). Climate-smart agriculture: Perspectives and framings. *Climate Policy*, *18*(4), 526–541. https://doi.org/10.1080/14693062.2017.1316968

Chen, Z., Xu, C., Ji, L., Feng, J., Li, F., Zhou, X., & Fang, F. (2020). Effects of multi-cropping system on temporal and spatial distribution of carbon and nitrogen footprint of major crops in China. *Global Ecology and Conservation*, *22*, e00895.

Chiemela, S. N., Noulekoun, F., Zenebe, A., Abadi, N., & Birhane, E. (2018). Transformation of degraded farmlands to agroforestry in Zongi Village, Ethiopia. *Agroforestry Systems*, *92*(5), 1317–1328. https://doi.org/10.1007/s10457-017-0076-7

Cogato, A., Meggio, F., De Antoni Migliorati, M., & Marinello, F. (2019). Extreme Weather Events in Agriculture: A Systematic Review. *Sustainability*, *11*(9), Article 9. https://doi.org/10.3390/su11092547

Dong Huan, D. H., Campbell, B., & Rabinowitz, A. N. (2019). *Factors impacting producer marketing through community supported agriculture*. https://www.cabidigitallibrary.org/doi/full/10.5555/20193379422

Duguma, B., & Janssens, G. P. J. (2021). Assessment of Livestock Feed Resources and Coping Strategies with Dry Season Feed Scarcity in Mixed Crop–Livestock Farming Systems around the Gilgel Gibe Catchment, Southwest Ethiopia. *Sustainability*, *13*(19), Article 19. https://doi.org/10.3390/su131910713

E. Birch, A. N., Begg, G. S., & Squire, G. R. (2011). How agro-ecological research helps to address food security issues under new IPM and pesticide reduction policies for global crop production systems. *Journal of Experimental Botany*, *62*(10), 3251–3261. https://doi.org/10.1093/jxb/err064

Elad, Y., & Pertot, I. (2014). Climate Change Impacts on Plant Pathogens and Plant Diseases. *Journal of Crop Improvement*, *28*(1), 99–139. https://doi.org/10.1080/15427528.2014.865412

Fausey, N. R. (2005). Drainage management for humid regions. *International Agricultural Engineering Journal*, *14*(4), 209–214.

Fishman, R. (2016). More uneven distributions overturn benefits of higher precipitation for crop yields. *Environmental Research Letters*, *11*(2), 024004. https://doi.org/10.1088/1748-9326/11/2/024004

Gangopadhyay, P. K., Khatri-Chhetri, A., Shirsath, P. B., & Aggarwal, P. K. (2019). Spatial targeting of ICT-based weather and agro-advisory services for climate risk management in agriculture. *Climatic Change*, *154*(1), 241–256. https://doi.org/10.1007/s10584-019-02426-5

Ghosh, M. (2019). Climate-smart agriculture, productivity and food security in India. *Journal of Development Policy and Practice*, *4*(2), 166–187.

Hou, D. (2023). Sustainable soil management for food security. *Soil Use and Management*, *39*(1), 1–7. https://doi.org/10.1111/sum.12883

Imran, M. A., Ali, A., Ashfaq, M., Hassan, S., Culas, R., & Ma, C. (2019). Impact of climate smart agriculture (CSA) through sustainable irrigation management on Resource use efficiency: A sustainable production alternative for cotton. *Land Use Policy*, *88*, 104113. https://doi.org/10.1016/j.landusepol.2019.104113

Jagustović, R., Papachristos, G., Zougmoré, R. B., Kotir, J. H., Kessler, A., Ouédraogo, M., Ritsema, C. J., & Dittmer, K. M. (2021). Better before worse trajectories in food systems? An investigation of synergies and trade-offs through climate-smart agriculture and system dynamics. *Agricultural Systems*, *190*, 103131.

Janni, M., Maestri, E., Gulli, M., Marmiroli, M., & Marmiroli, N. (2024). Plant responses to climate change, how global warming may impact on food security: A critical review. *Frontiers in Plant Science*, *14*, 1297569. https://doi.org/10.3389/fpls.2023.1297569

Janowiak, M. K., Dostie, D. N., Wilson, M. A., Kucera, M. J., Skinner, R. H., Hatfield, J. L., Hollinger, D., & Swanston, C. W. (2016). *Adaptation resources for agriculture: Responding to climate variability and change in the midwest and northeast*. https://ageconsearch.umn.edu/record/320856/

Jirata, M., Grey, S., & Kilawe, E. (2016). *Ethiopia climate-smart agriculture scoping study*. https://www.sidalc.net/search/Record/dig-fao-it-20.500.14283-I5518E/Description

John, D., Hussin, N., Shahibi, M. S., Ahmad, M., Hashim, H., & Ametefe, D. S. (2023). A systematic review on the factors governing precision agriculture adoption among small-scale farmers. *Outlook on Agriculture*, *52*(4), 469–485. https://doi.org/10.1177/00307270231205640

Josephson, A. L., Ricker-Gilbert, J., & Florax, R. J. (2014). How does population density influence agricultural intensification and productivity? Evidence from Ethiopia. *Food Policy*, *48*, 142–152.

Jusoh, F., A, M., M. Firdaus, Krishnan, K., & Katimon, A. (2021). An overview of the internet of things (IoT) and irrigation approach through bibliometric analysis. *IOP Conference Series: Earth and Environmental Science*, *756*, 012041. https://doi.org/10.1088/1755-1315/756/1/012041

Kalantari, F., Tahir, O. M., Joni, R. A., & Fatemi, E. (2018). Opportunities and Challenges in Sustainability of Vertical Farming: A Review. *Journal of Landscape Ecology*, *11*(1), 35–60. https://doi.org/10.1515/jlecol-2017-0016

Khamkhunmuang, T., Punchay, K., Promburom, P., & Wangpakapattanawong, P. (2022). Developing Climate-Smart Agriculture Indicators for SDG 1 and Environmental Implications in Northern Thailand. *EnvironmentAsia*, *15*, 1–13. https://doi.org/10.14456/ea.2022.43

Khatri-Chhetri, A., Aggarwal, P. K., Joshi, P. K., & Vyas, S. (2017). Farmers' prioritization of climate-smart agriculture (CSA) technologies. *Agricultural Systems*, *151*, 184–191. https://doi.org/10.1016/j.agsy.2016.10.005

Kifle, T. (2021). Climate-Smart Agricultural (CSA) practices and its implications to food security in Siyadebrina Wayu District, Ethiopia. *African Journal of Agricultural Research*, *17*(1), 92–103.

Kiwia, A., Kimani, D., Harawa, R., Jama, B., & Sileshi, G. W. (2019). Sustainable Intensification with Cereal-Legume Intercropping in Eastern and Southern Africa. *Sustainability*, *11*(10), Article 10. https://doi.org/10.3390/su11102891

Kogo, B. K., Kumar, L., & Koech, R. (2021). Climate change and variability in Kenya: A review of impacts on agriculture and food security. *Environment, Development and Sustainability*, *23*(1), 23–43. https://doi.org/10.1007/s10668-020-00589-1

Kumar, D., Pradhan, A., Jain, R., Kumar, V., Murmu, S., Samal, I., & Chaurasia, H.

(2024). *Remote Sensing in Precision Agriculture: Current Status and Applications* (pp. 23–41). https://doi.org/10.1007/978-981-97-0341-8_2

Kumar, S., Rao, D. U. M., Thombare, P., & Kale, P. (2020). Small and marginal farmers of Indian agriculture: Prospects and extension strategies. *Indian Research Journal of Extension Education*, *20*(1), 35–41.

Lee JaeMin, L. J., Kwon EunHye, K. E., & Woo, N. C. (2019). *Natural and human-induced drivers of groundwater sustainability: A case study of the Mangyeong River Basin in Korea.* https://www.cabidigitallibrary.org/doi/full/10.5555/20193438386

Lipper, L., Thornton, P., Campbell, B. M., Baedeker, T., Braimoh, A., Bwalya, M., Caron, P., Cattaneo, A., Garrity, D., Henry, K., Hottle, R., Jackson, L., Jarvis, A., Kossam, F., Mann, W., McCarthy, N., Meybeck, A., Neufeldt, H., Remington, T., … Torquebiau, E. F. (2014). Climate-smart agriculture for food security. *Nature Climate Change*, *4*(12), 1068–1072. https://doi.org/10.1038/nclimate2437

Lund Schlamovitz, J., & Becker, P. (2021). Differentiated vulnerabilities and capacities for adaptation to water shortage in Gaborone, Botswana. *International Journal of Water Resources Development*, *37*(2), 278–299. https://doi.org/10.1080/07900627.2020.1756752

Ma, W., & Rahut, D. B. (2024). Climate-smart agriculture: Adoption, impacts, and implications for sustainable development. *Mitigation and Adaptation Strategies for Global Change*, *29*(5), 44. https://doi.org/10.1007/s11027-024-10139-z

Mahato, A. (2014). *Climate Change and its Impact on Agriculture*. *4*(4).

Maja, M. M., & Ayano, S. F. (2021). The Impact of Population Growth on Natural Resources and Farmers' Capacity to Adapt to Climate Change in Low-Income Countries. *Earth Systems and Environment*, *5*(2), 271–283. https://doi.org/10.1007/s41748-021-00209-6

Malhi, G. S., Kaur, M., & Kaushik, P. (2021a). Impact of Climate Change on Agriculture and Its Mitigation Strategies: A Review. *Sustainability*, *13*(3), Article 3. https://doi.org/10.3390/su13031318

Malhi, G. S., Kaur, M., & Kaushik, P. (2021b). Impact of Climate Change on Agriculture and Its Mitigation Strategies: A Review. *Sustainability*, *13*(3), Article 3. https://doi.org/10.3390/su13031318

Maraseni, T. N., & Qu, J. (2016). An international comparison of agricultural nitrous oxide emissions. *Journal of Cleaner Production*, *135*, 1256–1266.

Matteoli, F., Schnetzer, J., & Jacobs, H. (2020). Climate-Smart Agriculture (CSA): An Integrated Approach for Climate Change Management in the Agriculture Sector. In W. Leal Filho, J. Luetz, & D. Ayal (Eds.), *Handbook of Climate Change Management* (pp. 1–29). Springer International Publishing. https://doi.org/10.1007/978-3-030-22759-3_148-1

McKinley, J. D., LaFrance, J. T., & Pede, V. O. (2021). Climate change adaptation strategies vary with climatic stress: Evidence from three regions of Vietnam. *Frontiers in Sustainable Food Systems*, *5*, 762650.

Meyer, N., Bergez, J.-E., Constantin, J., Belleville, P., & Justes, E. (2020). Cover crops reduce drainage but not always soil water content due to interactions between rainfall distribution and management. *Agricultural Water Management*, *231*, 105998. https://doi.org/10.1016/j.agwat.2019.105998

Mezgebe, H. (2012). Forage Seed Production and Supply in Tigray. *Forage Seed Research and Development in Ethiopia*, 219.

Mujeyi, A., Mudhara, M., & Mutenje, M. (2021). The impact of climate smart agriculture on household welfare in smallholder integrated crop–livestock farming systems: Evidence from Zimbabwe. *Agriculture & Food Security*, *10*(1), 4. https://doi.org/10.1186/s40066-020-00277-3

Muriithi, C., Mwongera, C., Abera, W., Chege, C. G. K., & Ouedraogo, I. (2023). A scalable approach to improve CSA targeting practices among smallholder farmers. *Heliyon*, *9*(10). https://doi.org/10.1016/j.heliyon.2023.e20526

Mutengwa, C. S., Mnkeni, P., & Kondwakwenda, A. (2023). Climate-Smart Agriculture and Food Security in Southern Africa: A Review of the Vulnerability of Smallholder Agriculture and Food Security to Climate Change. *Sustainability*, *15*(4), Article 4. https://doi.org/10.3390/su15042882

Nagar, A., Namdeo, S., Verma, B., Shrivastava, S., & Sarkar, R. (2023). Role of Climate -Smart Agriculture towards Sustainable Food Production. *International Journal of Environment and Climate Change*, *13*, 465–472. https://doi.org/10.9734/ijecc/2023/v13i123703

Nair, M. K., Augustine, L. F., & Konapur, A. (2016). Food-based interventions to modify diet quality and diversity to address multiple micronutrient deficiency. *Frontiers in Public Health*, *3*, 277.

Naresh, R. K., Gupta, R. K., Kumar, A., Prakesh, S., Tomar, S. S., Singh, A., Rathi, R. C., Misra, A. K., & Singh, M. (2011). Impact of laser land leveller for enhancing water productivity in Western Uttar Pradesh. *International Journal of Agricultural Engineering*, *4*(2), 133–147.

Nciizah, A., & Wakindiki, I. (2015). Climate Smart Agriculture: Achievements and Prospects in Africa. *Journal of Geoscience and Environment Protection*, *3*, 99–105. https://doi.org/10.4236/gep.2015.36016

Ngoma, H. (2018). Does minimum tillage improve the livelihood outcomes of smallholder farmers in Zambia? *Food Security*, *10*(2), 381–396. https://doi.org/10.1007/s12571-018-0777-4

Nigussie, A., Kuyper, T. W., & de Neergaard, A. (2015). Agricultural waste utilisation strategies and demand for urban waste compost: Evidence from smallholder farmers in Ethiopia. *Waste Management*, *44*, 82–93.

Onyeneke, R. U., Igberi, C. O., Uwadoka, C. O., & Aligbe, J. O. (2018). Status of climate-smart agriculture in southeast Nigeria. *GeoJournal*, *83*(2), 333–346. https://doi.org/10.1007/s10708-017-9773-z

Ouda, S., & Zohry, A. E.-H. (2022). *Climate-Smart Agriculture: Reducing Food Insecurity*. Springer International Publishing. https://doi.org/10.1007/978-3-030-93111-7

Pais, I. P., Reboredo, F. H., Ramalho, J. C., Pessoa, M. F., Lidon, F. C., & Silva, M. M. (2020). Potential impacts of climate change on agriculture—A review. *Emirates Journal of Food and Agriculture*, 397. https://doi.org/10.9755/ejfa.2020.v32.i6.2111

Porfirio, L. L., Newth, D., Finnigan, J. J., & Cai, Y. (2018). Economic shifts in agricultural production and trade due to climate change. *Palgrave Communications*, *4*(1), 1–9. https://doi.org/10.1057/s41599-018-0164-y

Praveen, B., & Sharma, P. (2019). A review of literature on climate change and its impacts on agriculture productivity. *Journal of Public Affairs*, *19*(4), e1960. https://doi.org/10.1002/pa.1960

Pretty, J., & Bharucha, Z. P. (2014). Sustainable intensification in agricultural systems. *Annals of Botany*, *114*(8), 1571–1596.

Qureshi, M. R. N. M., Almuflih, A. S., Sharma, J., Tyagi, M., Singh, S., & Almakayeel, N. (2022). Assessment of the Climate-Smart Agriculture Interventions towards the Avenues of Sustainable Production–Consumption. *Sustainability*, *14*(14), Article 14. https://doi.org/10.3390/su14148410

R., L., Thomas, J., & Joseph, S. (2024). Impacts of recent rainfall changes on agricultural productivity and water resources within the Southern Western Ghats of Kerala, India. *Environmental Monitoring and Assessment*, *196*(2), 115. https://doi.org/10.1007/s10661-023-12270-x

Raihan, A. (2024). *A review of recent advances, challenges, and potential future directions of climate-smart agriculture*.

Raihan, A., & Tuspekova, A. (2022). Dynamic impacts of economic growth, energy use, urbanization, tourism, agricultural value-added, and forested area on carbon dioxide emissions in Brazil. *Journal of Environmental Studies and Sciences*, *12*(4), 794–814. https://doi.org/10.1007/s13412-022-00782-w

Ramachandran Nair, P. K., Mohan Kumar, B., & Nair, V. D. (2009). Agroforestry as a strategy for carbon sequestration. *Journal of Plant Nutrition and Soil Science*, *172*(1), 10–23. https://doi.org/10.1002/jpln.200800030

Reicosky, D. C., Hatfield, J. L., & Sass, R. L. (2000). Agricultural contributions to greenhouse gas emissions. In K. R. Reddy & H. F. Hodges (Eds.), *Climate change and global crop productivity*. (1st ed., pp. 37–55). CABI Publishing. https://doi.org/10.1079/9780851994390.0037

Richards, M. B., Butterbach-Bahl, K., Lipinski, B., & Ortiz-Monasterio, I. (2015). *Site -Specific Nutrient Management (SSNM) provides guidance relevant to the context of farmers' fields. SSNM maintains or enhances crop yields, while providing savings for farmers through more efficient fertilizer use. By minimizing fertilizer overuse, greenhouse gas emissions can be reduced, in some cases up to 50%.*

Roy, N. (2020). Modern Strategies of Integrated Pest Management: A Review. *JAST*, *4*.

Safdar, M., Shahid, M. A., Yang, C., Rasul, F., Tahir, M., Raza, A., & Sabir, R. M. (2024). *Climate Smart Agriculture and Resilience* (pp. 28–52). https://doi.org/10.4018/979-8-3693-4864-2.ch002

Schaller, M., Barth, E. I., Blies, D., Röhrig, F., & Schümmelfeder, M. (2017a). *Climate smart agriculture (CSA): Climate smart agroforestry*. https://cgspace.cgiar.org/bitstream/10568/82727/2/CSA_ClimateSmart_Agroforestry_2017.pdf

Schaller, M., Barth, E. I., Blies, D., Röhrig, F., & Schümmelfeder, M. (2017b). *Climate Smart Agriculture (CSA): Improved Fodder Management*.

Sharma, A., & Bhatt, R. (2019). Climate-Smart Technologies for Sustainable Farming. *Turkish Journal of Computer and Mathematics Education (TURCOMAT)*, *10*(3), Article 3. https://doi.org/10.61841/turcomat.v10i3.14400

Shrestha, S. (2019). Effects of Climate Change in Agricultural Insect Pest. *Acta Scientific Agriculture*, *3*(12), 74–80. https://doi.org/10.31080/ASAG.2019.03.0727

Sime, G., & Aune, J. B. (2018). Sustainability of Improved Crop Varieties and Agricultural Practices: A Case Study in the Central Rift Valley of Ethiopia.

Agriculture, *8*(11), Article 11. https://doi.org/10.3390/agriculture8110177

Steenwerth, K. L., Hodson, A. K., Bloom, A. J., Carter, M. R., Cattaneo, A., Chartres, C. J., Hatfield, J. L., Henry, K., Hopmans, J. W., Horwath, W. R., Jenkins, B. M., Kebreab, E., Leemans, R., Lipper, L., Lubell, M. N., Msangi, S., Prabhu, R., Reynolds, M. P., Sandoval Solis, S., & Jackson, L. E. (2014a). Climate-smart agriculture global research agenda: Scientific basis for action. *Agriculture & Food Security*, *3*(1), 11. https://doi.org/10.1186/2048-7010-3-11

Steenwerth, K. L., Hodson, A. K., Bloom, A. J., Carter, M. R., Cattaneo, A., Chartres, C. J., Hatfield, J. L., Henry, K., Hopmans, J. W., Horwath, W. R., Jenkins, B. M., Kebreab, E., Leemans, R., Lipper, L., Lubell, M. N., Msangi, S., Prabhu, R., Reynolds, M. P., Sandoval Solis, S., & Jackson, L. E. (2014b). Climate-smart agriculture global research agenda: Scientific basis for action. *Agriculture & Food Security*, *3*(1), 11. https://doi.org/10.1186/2048-7010-3-11

Subeesh, A., & Mehta, C. (2021). Automation and digitization of agriculture using artificial intelligence and internet of things. *Artificial Intelligence in Agriculture*, *5*. https://doi.org/10.1016/j.aiia.2021.11.004

Tadesse, A., & Anteneh, M. (2018). *Drought Tolerance Mechanisms in Field Crops*.

Udayar Pillai, S., V Naga Kumar Kommireddi, C., & Samuel, M. (2024). *Remote Sensing in Precision Agriculture* (pp. 201–223). https://doi.org/10.1007/978-3-031-43548-5_7

van der Kooij, S., Zwarteveen, M., Boesveld, H., & Kuper, M. (2013). The efficiency of drip irrigation unpacked. *Agricultural Water Management*, *123*, 103–110. https://doi.org/10.1016/j.agwat.2013.03.014

van Wijk, M. T., Merbold, L., Hammond, J., & Butterbach-Bahl, K. (2020). Improving assessments of the three pillars of climate smart agriculture: Current achievements and ideas for the future. *Frontiers in Sustainable Food Systems*, *4*, 558483.

Velasco-Muñoz, J. F., Aznar-Sánchez, J. A., Batlles-delaFuente, A., & Fidelibus, M. D. (2019). Rainwater Harvesting for Agricultural Irrigation: An Analysis of Global Research. *Water*, *11*(7), Article 7. https://doi.org/10.3390/w11071320

Vishnoi, S., & Goel, R. K. (2024). Climate smart agriculture for sustainable productivity and healthy landscapes. *Environmental Science & Policy*, *151*, 103600. https://doi.org/10.1016/j.envsci.2023.103600

Wakweya, R. B. (2023a). Challenges and prospects of adopting climate-smart agricultural practices and technologies: Implications for food security. *Journal of Agriculture and Food Research*, *14*, 100698. https://doi.org/10.1016/j.jafr.2023.100698

Wakweya, R. B. (2023b). Challenges and prospects of adopting climate-smart agricultural practices and technologies: Implications for food security. *Journal of Agriculture and Food Research*, *14*, 100698. https://doi.org/10.1016/j.jafr.2023.100698

Wakweya, R. B. (2023c). Journal of Agriculture and Food Research. *Journal of Agriculture and Food Research*, *14*, 100698.

Wassie, A., & Pauline, N. (2018). Evaluating smallholder farmers' preferences for climate smart agricultural practices in Tehuledere District, northeastern Ethiopia. *Singapore Journal of Tropical Geography*, *39*(2), 300–316. https://doi.org/10.1111/sjtg.12240

Wildan, J. (2023). A Review: Artificial Intelligence Related to Agricultural Equipment Integrated with the Internet of Things. *Journal of Advanced Technology and Multidiscipline*, *2*, 47–60. https://doi.org/10.20473/jatm.v2i2.51440

Yadav, D., Wati, L., Yadav, D. B., & Kumar, A. (2020). Long-term influence of conservation tillage on soil organic carbon and microbial diversity. *The Indian Journal of Agricultural Sciences*, *90*(7), Article 7. https://doi.org/10.56093/ijas.v90i7.105604

Zakaria, A., Azumah, S. B., Appiah-Twumasi, M., & Dagunga, G. (2020). Adoption of climate-smart agricultural practices among farm households in Ghana: The role of farmer participation in training programmes. *Technology in Society*, *63*, 101338. https://doi.org/10.1016/j.techsoc.2020.101338

Zhan, L., Chen, J., Zhang, C., Wang, T., Li, L., & Xin, P. (2018). A major waterfall landscape maintained by fog drip water. *Hydrology and Earth System Sciences Discussions*, 1–34. https://doi.org/10.5194/hess-2018-37

Zhang, Y., Li, H., Sun, Y., Zhang, Q., Liu, P., Wang, R., & Li, J. (2022). Temporal stability analysis evaluates soil water sustainability of different cropping systems in a dryland agricultural ecosystem. *Agricultural Water Management*, *272*, 107834.

Zhao, J., Liu, D., & Huang, R. (2023a). A Review of Climate-Smart Agriculture: Recent Advancements, Challenges, and Future Directions. *Sustainability*, *15*(4), Article 4. https://doi.org/10.3390/su15043404

Zhao, J., Liu, D., & Huang, R. (2023b). A review of climate-smart agriculture: Recent advancements, challenges, and future directions. *Sustainability*, *15*(4), 3404.

Zougmoré, R., Jalloh, A., & Tioro, A. (2014). Climate-smart soil water and nutrient management options in semiarid West Africa: A review of evidence and analysis of stone bunds and zaï techniques. *Agriculture & Food Security*, *3*(1), 16. https://doi.org/10.1186/2048-7010-3-16