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Climate-Smart Agriculture and Food Security: A Review of Recent Approaches, Evidence, and Future Directions

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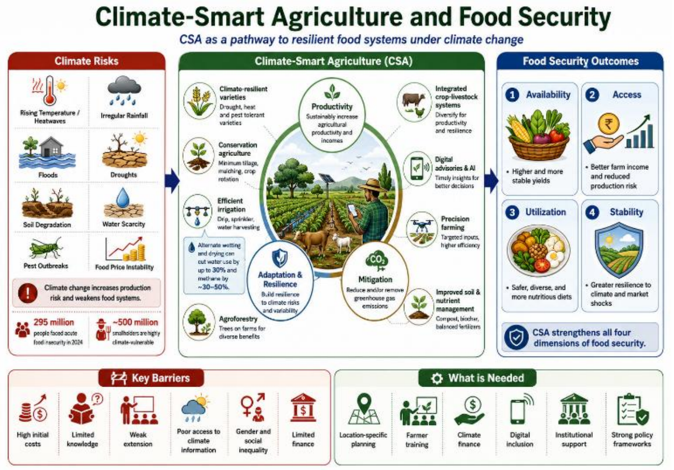
Abstract—*Climate change is increasingly reshaping global food systems by intensifying heat stress, erratic rainfall, droughts, floods, water scarcity, soil degradation, pest outbreaks, post-harvest losses, and food price volatility. These pressures are particularly severe in rain-fed and smallholder farming systems, where limited access to finance, technology, extension services, and climate information reduces farmers' capacity to adapt. Climate-smart agriculture (CSA) has emerged as a transformative approach for building resilient, productive, and sustainable food systems by integrating three core objectives: increasing agricultural productivity and income, strengthening adaptation and resilience, and reducing greenhouse gas emissions where feasible. This review examines the contribution of CSA to food security by synthesizing recent literature, institutional reports, and empirical evidence from 2020 to 2026. The paper focuses on key CSA practices, including climate-resilient crop varieties, conservation agriculture, efficient irrigation, alternate wetting and drying, agroforestry, integrated crop-livestock systems, improved soil and nutrient management, precision farming, digital advisory services, artificial intelligence, remote sensing, early warning systems, and climate finance mechanisms. The reviewed evidence shows that CSA can enhance all four dimensions of food security: food availability through improved and stable production; food access through increased income and reduced production risk; food utilization through diversified, nutritious, and safer food systems; and food stability through improved resilience to climate shocks, market disruptions, and environmental stress. Recent advances in digital agriculture, low-emission rice systems, carbon farming, biofortified crops, climate-smart livestock, and AI-based advisory platforms further demonstrate the expanding role of CSA in modern food-system transformation. However, CSA adoption remains constrained by high initial costs, weak extension services, limited credit access, poor infrastructure, digital exclusion, insecure land tenure, gender inequalities, and fragmented policy support. The review concludes that CSA can serve as a critical pathway for achieving sustainable food security under climate change, but its success depends on locally adapted implementation, inclusive farmer training, climate finance, gender-sensitive planning, digital accessibility, institutional coordination, and long-term policy commitment.*

Keywords—*Climate-smart agriculture, food security, climate change, sustainable agriculture, adaptation, resilience, digital agriculture, smallholder farmers.*



I. INTRODUCTION

Agriculture is highly sensitive to climate change because crop growth, livestock health, water availability, soil fertility, and pest dynamics are directly influenced by temperature, rainfall, and seasonal patterns. In recent years, climate change has increased the frequency and intensity of droughts, floods, heatwaves, storms, and unpredictable weather events. These changes have placed pressure on food systems by reducing crop productivity, increasing production costs, disrupting supply chains, and raising food prices. Food security is not only about producing enough food; it also includes people's physical and economic access to safe, nutritious, and culturally acceptable food at all times. Therefore, climate change affects all four dimensions of food security: availability, access, utilization, and stability.

Climate-smart agriculture has gained attention as a practical and policy-oriented approach for transforming agricultural systems under climate stress. CSA does not refer to a single technology or farming method. Rather, it is a broad approach that combines scientific knowledge, local farming practices, technology, institutional support, and environmental management. Its three central goals are to increase agricultural productivity and income, build resilience and adaptation to climate change, and reduce or remove greenhouse gas emissions where feasible. This makes CSA different from conventional agriculture because it connects food production with climate adaptation and environmental sustainability.

The problem is further intensified by climate shocks, conflict, inflation, and economic instability. The Global Report on Food Crises 2025 reported that more than 295 million people across 53 countries and territories experienced acute food insecurity in 2024, representing an increase of 13.7 million people compared with 2023 (Food Security Information Network [FSIN] & Global Network Against Food Crises [GNAFC], 2025). The report identified conflict, economic shocks, climate extremes, and forced displacement as major drivers of food crises. Climate-related disasters such as droughts, floods, heatwaves, and irregular rainfall directly reduce crop yields, damage livestock systems, disturb food supply chains, and increase food prices. At the same time, inflation reduces household purchasing power, making healthy diets unaffordable for poor and vulnerable communities (FAO et al., 2025). Therefore, climate change does not only threaten agricultural production; it also affects food access, nutrition, income stability, and long-term livelihood security.

Smallholder farmers are particularly vulnerable because they often depend on rain-fed agriculture and have limited capacity to adapt to changing climate conditions. The World Bank reports that nearly 80% of global agriculture is rainfed and produces about 60% of the world's food, but this also leaves around 500 million smallholder farmers highly exposed to erratic rainfall, drought, and water scarcity (World Bank, 2025). In contrast, irrigated agriculture covers only about 20% of farmland but contributes nearly 40% of global food production, showing the importance of reliable water access for agricultural productivity and food security (World Bank, 2025). Smallholder farmers also commonly face limited access to credit, improved seed varieties, fertilizers, mechanization, storage facilities, digital technologies, weather forecasts, and climate advisory services. These limitations reduce their ability to adopt improved farming practices and increase their vulnerability to crop failure, income loss, and food insecurity (Kumar & Doan, 2025; Omokpariola, 2025).

In this context, CSA is needed because it offers practical strategies to improve food security while responding to climate change. CSA aims to increase agricultural productivity, strengthen resilience and adaptation, and reduce greenhouse gas emissions where possible. Practices such as drought-tolerant seed varieties, efficient irrigation, conservation agriculture, agroforestry, integrated crop-livestock systems, improved soil management, climate information services, and digital advisory tools can help farmers reduce climate-related losses and improve productivity. For low-income and lower-middle-income countries, CSA is especially important because agriculture remains a major source of employment, income, and food supply. Without climate-smart transformation, food systems will remain vulnerable to repeated shocks, and progress toward ending hunger and malnutrition will remain slow and uneven.

Recent research shows that climate-smart agriculture (CSA) practices can support food security through multiple pathways, including higher productivity, better resource-use efficiency, climate adaptation, income diversification, and reduced environmental degradation. Improved seed varieties are one important example. Climate-resilient maize varieties developed through CGIAR and national breeding programs have been designed to tolerate drought, heat, low soil nitrogen, pests, and diseases, helping farmers maintain yields under stressful conditions (CGIAR, 2021; AICCRA, 2026). Similarly, stress-tolerant rice varieties and improved rice management practices are increasingly promoted in climate-vulnerable rice-growing regions to address flooding, salinity, drought, and water scarcity (CGIAR, 2021, 2025). These innovations are important because climate change is already reducing crop productivity in many large-scale and smallholder farming systems through rising temperatures and changing rainfall patterns (IPCC, 2019).

Conservation agriculture is another CSA practice that can improve food security by protecting soil health and reducing climate risk. Practices such as minimum tillage, crop residue retention, mulching, crop rotation, and cover cropping help conserve soil moisture, reduce erosion, increase organic matter, and improve long-term productivity (Kabato, 2025; Neupane, 2024). For example, in dryland and semi-arid areas, residue retention and reduced soil disturbance help crops survive longer during dry periods by improving water infiltration and reducing evaporation. These practices are especially useful for smallholder farmers who depend on rain-fed agriculture and are highly exposed to erratic rainfall.

Efficient irrigation systems also provide practical examples of CSA. In rice production, alternate wetting and drying (AWD) is a water-saving irrigation method in which rice fields are not kept continuously flooded. FAO identifies AWD as a practical innovation for reducing water use in irrigated paddy fields, while CGIAR evidence shows that AWD can reduce water use by up to 30% and methane emissions by up to 48% without necessarily reducing rice yield when properly managed (Food and Agriculture Organization of the United Nations [FAO], 2020; Richards & Sander, 2014). Recent studies have also explored the use of computer vision and sensors to monitor water levels in AWD rice fields, showing how digital tools can improve irrigation management and reduce manual measurement errors (Hasan et al., 2024). This example shows that CSA can combine traditional water-saving practices with modern digital technologies.

Agroforestry is another important CSA approach because it combines trees with crops or livestock on the same land. Trees can improve soil fertility, reduce wind and heat stress, increase biodiversity, store carbon, and provide additional income through fruits, fodder, timber, fuelwood, or other tree products. Recent research on climate-smart food systems highlights agroecological and regenerative practices, including agroforestry, as important strategies for adaptation and mitigation in climate-vulnerable regions (Mudzielwana, 2025). In West African cocoa systems, recent machine-learning-based research found that shade trees have strong potential to increase carbon storage and improve sustainability without necessarily threatening production when managed carefully (Becker et al., 2024). This suggests that agroforestry can support both farm income and environmental resilience.

Integrated crop-livestock systems also support food security by diversifying production and improving nutrient recycling. In these systems, crop residues can be used as livestock feed, while manure can be returned to fields to improve soil fertility. FAO explains that integrating crops, livestock, and trees can increase resilience, reduce economic risk, and improve resource-use efficiency, particularly in areas where uncertain weather threatens crop production (Food and Agriculture Organization of the United Nations [FAO], 2017). Recent studies on climate-smart livestock systems also emphasize that smallholder farmers need integrated strategies to protect livestock from heat stress, feed shortages, disease risks, and water scarcity (Adesogan et al., 2025). Therefore, integrated farming systems can reduce dependence on a single crop and provide households with more stable food and income sources.

Digital technologies are becoming a newer and rapidly expanding area of CSA. Mobile-based weather forecasts, remote sensing, artificial intelligence, Internet of Things-based sensors, drones, and digital advisory platforms can help farmers make timely decisions about sowing, irrigation, fertilizer use, pest control, and harvesting. For example, recent work in Bangladesh proposed a deep-learning-based agricultural recommendation system using weather forecasting to guide crop selection and warn farmers about extreme weather events (Zubair et al., 2024). Similarly, AI-based advisory services tested in Kenya and Bihar, India, used WhatsApp, mobile apps, and voice-based systems to provide smallholder farmers with localized agricultural guidance linked to weather, soil, and market information (Collis et al., 2025). These examples show that digital CSA can improve decision-making, but only when farmers have access to mobile phones, internet connectivity, local-language support, and trustworthy advisory services.

However, the benefits of CSA are not automatic. Adoption depends on farmers' awareness, affordability, access to credit, land ownership, extension services, market access, policy support, gender inclusion, and local ecological conditions. Recent reviews show that CSA adoption is often limited by high initial costs, weak institutional support, lack of technical training, poor access to climate information, and uncertainty about economic returns (Yiridomoh, 2025). Therefore, CSA should not be treated as a single universal package. It must be adapted to local farming systems, climate risks, soil conditions, water availability, farmer capacity, and market opportunities. With proper support, CSA can strengthen food availability, improve income, protect natural resources, and build more resilient food systems under climate change.

This paper reviews recent work on climate-smart agriculture and food security. It aims to explain how CSA contributes to sustainable agricultural production, climate adaptation, and food security, while also identifying the major challenges that limit its adoption.

II. MATERIALS AND METHODS

This study used a narrative literature review approach. Relevant literature was reviewed from international reports, peer-reviewed journal articles, systematic reviews, and institutional publications published mainly between 2020 and 2026. The review focused on climate-smart agriculture, food security, climate adaptation, agricultural sustainability, smallholder farming, digital agriculture, and climate-resilient food systems.

The main sources included publications from the Food and Agriculture Organization, the Intergovernmental Panel on Climate Change, the World Bank, CGIAR, and recent peer-reviewed studies on CSA adoption and food security. Search terms included "climate-smart agriculture," "CSA and food security," "climate-resilient agriculture," "CSA adoption," "smallholder farmers and climate change," "digital agriculture and food security," "agroforestry and climate resilience," "conservation agriculture," and "climate adaptation in agriculture."

The reviewed material was organized according to the following themes:

1. Concept and pillars of climate-smart agriculture.
2. Major CSA practices used in recent agricultural systems.
3. Effects of CSA on food availability, access, utilization, and stability.
4. Barriers to CSA adoption.
5. Policy and research directions for improving CSA implementation.

The analysis was descriptive and thematic. Instead of generating primary quantitative data, the paper synthesized recent evidence to identify trends, benefits, limitations, and future directions.

III. RESULTS AND DISCUSSION

CSA as an Integrated Response to Climate Risk

The reviewed evidence shows that climate-smart agriculture (CSA) is most useful when it is applied as an integrated package rather than as a single technology. Its value lies in linking three goals: higher productivity and income, stronger adaptation and resilience, and lower greenhouse gas emissions where feasible (Food and Agriculture Organization of the United Nations [FAO], 2017). This integrated approach is important because climate change affects farming through sudden shocks such as droughts, floods, heatwaves, storms and pest outbreaks, as well as long-term stresses such as soil degradation, salinity, groundwater depletion and shifting rainfall patterns.

Across recent studies, CSA practices reduce climate risk mainly through five pathways: protecting soil and water resources, improving crop and livestock tolerance to stress, diversifying production and income, strengthening farm decision-making through climate information, and lowering avoidable emissions. The strongest findings are seen where farmers combine practices such as improved varieties, conservation agriculture, efficient irrigation, crop diversification, agroforestry, integrated crop-livestock systems and advisory services rather than adopting one practice in isolation (Alobwede, 2026; Olabanji et al., 2025; Yiridomoh, 2025).

Contribution of CSA to Food Security

CSA contributes to food availability by increasing or stabilizing production under climate stress. Conservation agriculture improves soil moisture and soil structure; stress-tolerant crop varieties reduce losses from drought, heat, flood, salinity and disease; and improved water management helps farmers maintain production during dry periods. Evidence from recent reviews and country studies indicates that CSA is more effective when improved seed, soil management, water management and extension support are used together (Kabato, 2025; Traore et al., 2026).

CSA improves food access by raising farm income, reducing production risk and creating more than one source of livelihood. Agroforestry, crop diversification, kitchen gardening and livestock integration provide both food and marketable products. This is important because food insecurity is often caused not only by low production but also by poverty, inflation, weak market access and low purchasing power. Digital advisory services, market-price information and climate forecasts can further improve access by helping farmers reduce input waste, sell at better times and respond earlier to weather threats (Collis et al., 2025; Godwin & Johnson, 2025).

CSA supports food utilization when it improves the nutritional quality and safety of food. Diversified farming systems increase the availability of pulses, vegetables, fruits, milk, eggs and other nutrient-rich foods, while biofortified crops can help reduce hidden hunger in communities that depend heavily on staple foods. Food safety is also linked with CSA because climate change can increase fungal contamination and post-harvest losses. Improved drying, storage, ventilation, pest management and cold chains can reduce mycotoxin risk and protect nutritious foods after harvest (Bunny et al., 2024; Casu et al., 2024; UNEP, 2024).

CSA and Nutritional Value of Food for Human Health

CSA is closely linked with human health because it can improve not only the amount of food produced but also the nutritional value, diversity, and safety of food consumed by households. Climate change can reduce dietary quality by lowering crop yields, increasing food prices, damaging fruits and vegetables, and limiting access to animal-source foods.

TABLE 1. CSA pathways for reducing climate risk and supporting food security

CSA risk-reduction pathway	Main CSA practices	Climate-risk reduction effect	Food-security value	Key references
Protecting soil and water resources	Conservation agriculture, mulching, residue retention, crop rotation, efficient irrigation, rainwater harvesting and laser land leveling.	Improves soil moisture, reduces erosion and runoff, protects soil organic matter and improves water-use efficiency under drought and rainfall variability.	Stabilizes crop production and protects food availability during dry periods and irregular rainfall.	Kabato (2025); World Bank (2025); Wang et al. (2022)
Improving crop and livestock tolerance to stress	Drought-, heat-, flood- and salinity-tolerant crop varieties; climate-smart livestock housing, feeding, water and health management.	Reduces losses from heat, drought, flooding, salinity, pests, diseases and livestock stress.	Maintains staple crop supply, livestock products and farm income under climate pressure.	AICCRA (2026); Adesogan et al. (2025); Traore et al. (2026)
Diversifying production and income	Crop diversification, agroforestry, kitchen gardening, legumes, integrated crop-livestock systems and tree-based products.	Spreads risk across crops, livestock, trees and seasons instead of depending on one crop or income source.	Improves food access, dietary diversity and household resilience when one crop or market fails.	Alobwede (2026); Swarnam et al. (2024); Yiridomoh (2025)
Strengthening farm decision-making	Weather advisories, seasonal forecasts, early warning systems, mobile apps, AI advisory services, remote sensing and market information.	Helps farmers adjust sowing, irrigation, fertilizer use, pest control, harvesting, storage and marketing decisions before losses become severe.	Reduces production risk, input waste and income shocks, thereby supporting availability, access and stability.	Collis et al. (2025); Godwin & Johnson (2025); Machefer et al. (2025)
Lowering avoidable emissions	Alternate wetting and drying in rice, improved manure management, reduced residue burning, agroforestry, carbon farming and efficient fertilizer use.	Reduces methane, nitrous oxide and carbon losses where feasible while supporting resource efficiency.	Supports low-emission food production without weakening productivity when locally adapted.	FAO (2024); FAO (2025); Richards & Sander (2014)

TABLE 2. Crop varieties and production benefits under climate-smart agriculture

CSA crop variety / production option	Main production trait	Approximate production benefit	Food-security value	References
Climate-smart/drought-tolerant maize	Bred to tolerate drought, heat, low soil nitrogen, pests and diseases.	Helps maintain grain yield under stress and supports higher, more stable production where drought and poor soils are common.	Protects staple food supply and farm income in dry seasons.	CGIAR (2021); AICCRA (2026)
Flood-tolerant rice (Sub-1 type varieties)	Can survive temporary submergence and waterlogging better than ordinary varieties.	Recent climate-resilient rice examples report survival under about 14 days of waterlogging and yields of about 30-55 quintals per hectare under suitable conditions.	Reduces rice losses in flood-prone areas and supports household food availability.	Bihar Agricultural University (2025)
High-yield and climate-resilient wheat (PBW 826)	Shorter-duration, high-yielding wheat with moderate rust resistance and broad adaptation.	Reported average yield of 65.7 quintals per hectare in the North Western Plains Zone and 53.6 quintals per hectare in the North Eastern Plains Zone during 2024-2025 trials.	Strengthens wheat production and improves farmers' income in climate-stressed areas.	Punjab Agricultural University (2025)
Short-duration and cold-tolerant rice	Matures earlier and tolerates cold stress in climate-vulnerable rice systems.	Supports timely harvest and reduces exposure to late-season floods or cold-related crop damage.	Improves production stability in regions exposed to flash floods and seasonal stress.	CGIAR (2025)
Biofortified crop varieties	Developed to increase micronutrients such as iron, zinc and vitamin A in staple foods.	Improves the nutrient value of production without requiring major changes in daily diets.	Supports both food availability and human nutrition, especially where hidden hunger is common.	Bouis & Saltzman (2017); HarvestPlus (2025)

TABLE 3. Temperature variation and crop-yield response

Temperature variation / climate signal	Main crop-yield response	Approximate reported yield effect	Food-security value	References
+1°C increase in global mean temperature: wheat	Higher temperature shortens the growing period and affects flowering and grain filling.	Average global wheat yield loss of about 6.0% per 1°C increase, without effective adaptation.	Reduces availability of a major staple food and increases price-risk pressure.	Zhao et al. (2017)
+1°C increase in global mean temperature: maize	Heat stress reduces pollination, grain formation and water-use efficiency.	Average global maize yield loss of about 7.4% per 1°C increase, without effective adaptation.	Creates serious risk for food and feed supply in warm regions.	Zhao et al. (2017)
+1°C increase in global mean temperature: rice	High temperature affects flowering, grain quality and grain filling.	Average global rice yield loss of about 3.2% per 1°C increase, without effective adaptation.	Threatens food security in rice-dependent populations.	Zhao et al. (2017)
+1°C increase in global mean temperature: soybean	Temperature stress can reduce pod setting and seed development.	Average global soybean yield loss of about 3.1% per 1°C increase, without effective adaptation.	Affects protein and oilseed supply as well as livestock feed markets.	Zhao et al. (2017)
Extreme heat and heatwaves	Heat stress damages crops, livestock, fisheries and outdoor agricultural labour capacity.	Loss depends on timing, duration and crop stage; reproductive stages are especially sensitive.	Increases the need for heat-tolerant varieties, adjusted sowing dates, shade, irrigation and early warning systems.	FAO & WMO (2026); IPCC (2022)

TABLE 4. Nutrient deficiencies, medical-health impacts, and CSA-linked food responses

Nutritional deficiency	Main medical-health impact / disease risk	CSA-linked food response	References
Iron deficiency	Iron-deficiency anemia, fatigue, reduced work capacity, poor pregnancy outcomes, and impaired child growth and learning.	Promote iron-rich foods such as pulses, legumes, dark green leafy vegetables, biofortified beans/cereals, animal-source foods where available, and diversified diets.	CDC, 2025; NIH ODS, 2025a
Vitamin A deficiency	Night blindness, xerophthalmia, higher infection risk, poor immunity, and increased risk of child morbidity and mortality.	Support orange-fleshed sweet potato, carrots, pumpkin, mango, leafy vegetables, dairy, eggs, and biofortified vitamin A crops.	CDC, 2025; NIH ODS, 2025b
Iodine deficiency	Goiter, hypothyroidism, impaired mental development, lower work productivity, and fetal neurodevelopmental damage during pregnancy.	Improve dietary diversity with iodine sources, promote iodized salt use, and support nutrition education in vulnerable communities.	NIH ODS, 2024
Zinc deficiency	Poor growth, weakened immunity, delayed wound healing, reduced appetite, and higher risk of diarrhea and infections.	Increase legumes, nuts, seeds, whole grains, dairy, meat/fish where affordable, and zinc-biofortified cereals.	CDC, 2025; NIH ODS, 2026
Folate deficiency	Megaloblastic anemia and higher risk of neural tube defects such as spina bifida during early pregnancy.	Promote leafy vegetables, legumes, citrus fruits, fortified foods, and nutrition-sensitive kitchen gardening.	CDC, 2025; NIH ODS, 2022
Vitamin B12 deficiency	Megaloblastic anemia, fatigue, glossitis, nerve damage, memory problems, and developmental delays in infants.	Support access to animal-source foods, dairy, eggs, fish, and fortified foods, especially for pregnant women and low-intake groups.	NIH ODS, 2025c
Vitamin D deficiency	Rickets in children, osteomalacia in adults, bone pain, skeletal deformities, dental problems, and muscle weakness.	Promote vitamin D-rich or fortified foods, eggs, fish, dairy where available, and health education on safe sunlight exposure.	NIH ODS, 2025d
Protein-energy deficiency	Wasting, stunting, underweight, weak immunity, delayed recovery from illness, marasmus, and kwashiorkor in severe cases.	Promote pulses, legumes, dairy, eggs, fish, small livestock, kitchen gardens, and diversified climate-resilient farming systems.	WHO, 2024; FAO et al., 2025

It can also affect nutrient quality through heat stress, water stress, soil degradation, and higher carbon dioxide levels, which may reduce protein, iron, zinc, and other micronutrients in some staple crops. Recent nutrition research emphasizes that climate change, extreme weather, food insecurity, and malnutrition are connected problems; therefore, agricultural responses should support healthy diets as well as production (Fanzo et al., 2025). This is important because about 2.6 billion people could not afford a healthy diet in 2024, showing that food security must include nutrition quality, not only calorie supply (FAO et al., 2025).

Nutrition-sensitive CSA practices can improve human health by increasing access to diverse food groups. Crop diversification, pulses, fruits, vegetables, kitchen gardening, agroforestry, small livestock, dairy, poultry, and aquaculture can provide vitamins, minerals, protein, fiber, and essential fats that are needed for growth, immunity, pregnancy, child development, and disease prevention. Legumes improve protein intake and also add nitrogen to the soil, while fruits and vegetables provide vitamin A, vitamin C, folate, potassium, and antioxidants. Livestock and fish provide high-quality protein and micronutrients such as iron, zinc, calcium, vitamin B12, and omega-3 fatty acids. In this way, CSA can reduce hidden hunger by making diets more balanced, especially for women, children, and low-income households. Biofortified crops such as iron-rich beans, zinc wheat, vitamin A maize, vitamin A cassava, and vitamin A sweet potato are also useful where people depend heavily on staple foods (HarvestPlus, 2025; Bouis & Saltzman, 2017).

CSA also protects human health by improving food safety and reducing climate-related contamination. Warmer temperatures, humidity, drought stress, and poor storage conditions can increase fungal growth and mycotoxin contamination in crops such as maize, groundnut, cereals, and oilseeds. Mycotoxins, especially aflatoxins, are a major public health concern because contaminated food may contribute to liver disease, weakened immunity, poor child growth, and long-term health risks (Bunny et al., 2024; Casu et al., 2024). Climate-smart post-harvest practices such as timely harvesting, solar drying, hermetic storage, improved granaries, ventilation, pest control, cold chains, and moisture management can reduce these risks. Therefore, CSA improves human health when it combines production, nutrition education, safe storage, clean water, sanitation, and food safety management. The main finding is that CSA should be judged not only by yield and income, but also by whether it helps people consume safe, diverse, nutritious, and culturally acceptable food for better health outcomes.

This shows that CSA can improve human health when it moves beyond yield targets and supports diverse, micronutrient-rich, safe, and locally available foods. Therefore, nutrition-sensitive CSA should combine climate-resilient production with biofortification, food diversification, improved storage, and community nutrition education.

CSA strengthens food stability by helping food systems absorb and recover from repeated shocks. Crop diversification, agroforestry, water harvesting, efficient irrigation, climate information services, early warning systems, storage facilities and climate-resilient value chains reduce dependence on a single crop, season, market or water source. Recent food-security modelling and early warning research also shows that satellite data, vegetation indices, rainfall anomalies, conflict indicators and food-price data are becoming important tools for anticipating food crises before they become severe (Machefer et al., 2025; Pedersen, 2026).

Water-Use Efficiency as a Key CSA Finding

Water management emerged as one of the strongest and most repeated themes in the reviewed literature. The evidence indicates that drip irrigation, sprinkler irrigation, laser land leveling, rainwater harvesting and alternate wetting and drying can reduce water loss and improve production stability under water-scarce conditions. These practices are especially important because rain-fed agriculture covers most agricultural land but remains highly exposed to erratic rainfall, while irrigated agriculture contributes a large share of global food production (World Bank, 2025).

TABLE 5. CSA water practices, efficiency benefits, and food-security value

CSA water practice	Main efficiency effect	Approximate reported benefit	Food-security value	References
Drip irrigation	Delivers water near the root zone and reduces evaporation, runoff and deep percolation.	About 20-50% improvement in water productivity, depending on crop and management.	Improves yield stability during dry periods.	FAO (2021); Wang et al. (2022)
Subsurface drip irrigation	Supplies water below the surface, reducing surface evaporation.	Meta-analysis evidence reports higher yield and irrigation water productivity than surface drip irrigation.	Supports efficient production in water-scarce systems.	Wang et al. (2022)
Sprinkler irrigation	Distributes water more uniformly than traditional flood irrigation when well designed.	Application efficiency commonly ranges from about 70-95%.	Reduces field-level water wastage.	FAO (2021)
Laser land leveling	Improves field uniformity and reduces ponding, runoff and over-irrigation.	Studies report about 23-26% reduction in irrigation water use.	Lowers irrigation cost and improves water-use efficiency.	PCRWR (2017); Saleem et al. (2023)
Rainwater harvesting	Stores rainfall for later crop use, especially in rain-fed and semi-arid farming.	Benefit varies by rainfall, storage design and farm size.	Reduces drought risk and groundwater dependence.	FAO (2021)
Alternate wetting and drying in rice	Allows controlled drying before re-irrigation instead of continuous flooding.	Often saves about 20-40% irrigation water and can reduce methane emissions.	Saves water while supporting low-emission rice production.	FAO (2020); Li et al. (2024); Shah et al. (2025)

Recent Trends in CSA Research

Recent CSA research is moving beyond basic agronomic practices toward digital, low-emission and finance-supported food systems. Artificial intelligence, mobile advisory platforms, remote sensing, drones, sensors and Internet of Things-based monitoring are increasingly used to guide sowing, irrigation, fertilizer use, pest control, crop monitoring and early warning. These tools can improve decisions, but their usefulness depends on affordability, connectivity, local-language support, data privacy and farmer trust (Cantonjos & Biswas, 2025; Rufin et al., 2025; Zafar et al., 2025).

Low-emission agriculture is another major trend. Alternate wetting and drying in rice, improved livestock feeding, manure management, reduced residue burning, agroforestry, cover cropping and soil-carbon practices are being studied because they can reduce emissions while maintaining productivity. However, mitigation efforts should not weaken food security in poor farming communities. Carbon farming and digital systems must therefore be designed so that smallholders are not excluded by cost, complex measurement rules or weak institutional support (FAO, 2024; Richards & Sander, 2014; World Bank, 2024).

Barriers to CSA Adoption

The main barriers to CSA adoption are high initial cost, limited credit, weak extension services, low technical knowledge, poor infrastructure, insecure land tenure, uncertain returns, gender inequality and digital exclusion. These barriers explain why CSA benefits are uneven across regions and farming groups. For example, improved varieties cannot help farmers if seed systems are weak; digital advisories have limited value without smartphones, internet or trust; and agroforestry is difficult for tenant farmers who lack long-term land security.

Women, tenant farmers, landless workers and resource-poor households often face the greatest barriers because they may have less access to land, finance, machinery, extension services, market information and decision-making power. Therefore, CSA adoption should not be judged only by technical performance. It must also be assessed through affordability, equity, local relevance and the ability of farmers to maintain the practice over time (Food and Agriculture Organization of the United Nations [FAO], 2017; Li et al., 2025; Saran et al., 2024).

Policy and Research Implications

The findings suggest that CSA policies should promote location-specific packages instead of universal prescriptions. Drought-prone areas may need drought-tolerant seed, mulching, water harvesting and efficient irrigation, while flood-prone areas may require drainage, raised beds, flood-tolerant varieties and early warning systems. Governments and development agencies should combine CSA technologies with training, demonstration plots, farmer field schools, climate finance, insurance, market linkages and inclusive digital services.

Future research should measure the long-term effects of CSA on yield, income, nutrition, water-use efficiency, soil health, gender equity, greenhouse gas emissions and resilience. More evidence is also needed on which combinations of practices work best for specific crops, regions and farmer groups. Overall, the reviewed evidence supports CSA as a strong pathway for sustainable food security, but only when implementation is locally adapted, financially accessible and institutionally supported.

IV. CONCLUSION

Climate-smart agriculture is a promising strategy for improving food security under climate change because it addresses productivity, resilience, and environmental sustainability together. The reviewed evidence shows that CSA supports food availability by improving crop and livestock production, food access by increasing income and reducing production risk, food utilization by promoting diverse and nutritious food systems, and food stability by strengthening resilience against climate shocks. Practices such as conservation agriculture, climate-resilient varieties, agroforestry, integrated crop-livestock systems, efficient irrigation, digital advisory services, precision farming, improved storage, and early warning systems can make food systems more resilient and sustainable.

However, CSA is not a universal solution that works equally in all contexts. Its adoption depends on affordability, farmer awareness, extension services, access to credit, climate information, market linkages, gender inclusion, institutional coordination, and policy support. Smallholder farmers require locally suitable technologies, practical training, financial assistance, and reliable advisory services to benefit from CSA. Future CSA policies should promote location-specific packages, climate finance, inclusive extension, digital access, and long-term research on productivity, nutrition, resilience, and emissions. When supported through strong institutions and farmer-centered planning, climate-smart agriculture can become a key pathway for achieving sustainable food security in a changing climate.

REFERENCES

[1]. Accelerating Impacts of CGIAR Climate Research for Africa. (2026). Climate-smart maize innovations strengthen national drought resilience and food security. AICCRA.

[2]. Adesogan, A. T., Arriola, K. G., Jiang, Y., & others. (2025). Climate-smart approaches for enhancing livestock production and resilience in smallholder systems. Animal Production Science.

[3]. Alobwede, V. N. (2026). Climate-smart agriculture adoption as a pathway to food security: A systematic review. Frontiers in Sustainable Food Systems, 10, Article 1760101. https://doi.org/10.3389/fsufs.2026.1760101

[4]. Becker, A., Wegner, J. D., Dawoe, E., Schindler, K., Thompson, W. J., Bunn, C., Garrett, R. D., Castro, F., Hart, S. P., & Blaser-Hart, W. J. (2024). The unrealized potential of agroforestry for an emissions-intensive agricultural commodity. arXiv.

[5]. Bihar Agricultural University. (2025). BAU scientists develop new climate-resilient rice varieties for flood tolerance, disease resistance, and high yield.

[6]. Bouis, H. E., & Saltzman, A. (2017). Improving nutrition through biofortification: A review of evidence from HarvestPlus, 2003 through 2016. Global Food Security, 12, 49–58. https://doi.org/10.1016/j.gfs.2017.01.009

[7]. Bunny, S. M., Rahman, M. M., Hossain, M. M., & others. (2024). Aflatoxin risk in the era of climatic change: A comprehensive review. CABI Agriculture and Bioscience.

[8]. Cantonjos, N. A., & Biswas, A. (2025). AgroAskAI: A multi-agentic AI framework for supporting smallholder farmers' enquiries globally. arXiv.

[9]. Casu, A., Camardo Leggieri, M., Toscano, P., & Battilani, P. (2024). Changing climate, shifting mycotoxins: A comprehensive review of climate change impact on mycotoxin contamination. Comprehensive Reviews in Food Science and Food Safety, 23, e13323.

[10]. Centers for Disease Control and Prevention. (2025). Micronutrient facts. U.S. Department of Health and Human Services. https://www.cdc.gov/nutrition/features/micronutrient-facts.html

[11]. CGIAR. (2021). Climate-smart maize. CGIAR.

[12]. CGIAR. (2025, May 8). How climate-resilient short-duration cold-tolerant rice is securing farmers' livelihood in Haor region of Bangladesh. CGIAR. https://www.cgiar.org/news-events/news/how-climate-resilient-short-duration-cold-tolerant-rice-is-securing-farmers-livelihood-in-haor-region-of-bangladesh

[13]. Climate Policy Initiative. (2023). The climate finance gap for small-scale agrifood systems. Climate Policy Initiative.

[14]. Collis, S., Kinyua, F., Kumar, V., Lakougna, H., Merz, C., Pandey, K., & Resch, C. (2025). Building AI-based advisory services for smallholder farmers: Technical learnings from the AIEP Initiative. arXiv.

[15]. Enyew, S. (2025). Adoption of climate smart agricultural practices impact on food security of smallholder farmers in North-Western Ethiopia. Discover Sustainability. https://doi.org/10.1007/s43621-025-01793-7

[16]. Fanzo, J., Davis, C., McLaren, R., & Choufani, J. (2025). Climate change, extreme weather events, food security, and nutrition. Annual Review of Nutrition, 45. https://doi.org/10.1146/annurev-nutr-111324-111252

[17]. Food and Agriculture Organization of the United Nations, & World Meteorological Organization. (2026). Extreme heat and agriculture. FAO and WMO.

[18]. Food and Agriculture Organization of the United Nations, International Fund for Agricultural Development, United Nations Children's Fund,

World Food Programme, & World Health Organization. (2025). The state of food security and nutrition in the world 2025: Addressing high food price inflation for food security and nutrition. FAO.

[19]. Food and Agriculture Organization of the United Nations. (2017). Climate-smart agriculture sourcebook (2nd ed.). FAO. https://www.fao.org/climate-smart-agriculture-sourcebook/en/

[20]. Food and Agriculture Organization of the United Nations. (2020). Rice farming: Saving water through alternate wetting and drying (AWD) method. FAO. https://www.fao.org/family-farming/detail/en/c/1618095/

[21]. Food and Agriculture Organization of the United Nations. (2021). Facts and figures: Land and water. FAO.

[22]. Food and Agriculture Organization of the United Nations. (2021). The state of the world's land and water resources for food and agriculture: Systems at breaking point. FAO.

[23]. Food and Agriculture Organization of the United Nations. (2024). Greenhouse gas emissions from agrifood systems: Global, regional and country trends, 2000–2022. FAO.

[24]. Food and Agriculture Organization of the United Nations. (2025). Alternate wetting and drying rice farming: Climate-smart agriculture. FAO.

[25]. Food Security Information Network, & Global Network Against Food Crises. (2025). Global report on food crises 2025. FSIN and GNAFC.

[26]. Garcia-Cela, E., & Marcon Gasperini, A. (2024). Climate change and mycotoxins: A growing food safety concern. Journal of Consumer Protection and Food Safety, 19(4), 373–375.

[27]. Godwin, N., & Johnson, M. (2025). A smart IoT framework for climate-resilient and sustainable maize farming in Uganda. arXiv.

[28]. Gyamfi, E. K., ElSayed, Z., Kropczynski, J., Yakubu, M. A., & Elsayed, N. (2024). Agricultural 4.0 leveraging on technological solutions: Study for smart farming sector. arXiv. https://arxiv.org/abs/2401.00814

[29]. HarvestPlus. (2025). Biofortification: The evidence. HarvestPlus. https://www.harvestplus.org/wp-content/uploads/2025/02/BiofortificationThe-Evidence.pdf

[30]. Hasan, A. R., Kundu, N. K., Hasan, S., Hoque, M. R., & Shatabda, S. (2024). Accurate water level monitoring in AWD rice cultivation using convolutional neural networks. arXiv.

[31]. Hultgren, A., Carleton, T., Delgado, M., Gergel, D., Greenstone, M., Houser, T., Hsiang, S., Jina, A., Kopp, R. E., Malevich, S. B., McCusker, K., Mayer, T., Nath, I., Rising, J., Rode, A., & Yuan, J. (2025). Impacts of climate change on global agriculture accounting for adaptation. Nature.

[32]. Intergovernmental Panel on Climate Change. (2019). Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. IPCC.

[33]. Intergovernmental Panel on Climate Change. (2022). Climate change 2022: Impacts, adaptation and vulnerability. Cambridge University Press.

[34]. Intergovernmental Panel on Climate Change. (2022). Climate change 2022: Mitigation of climate change. Cambridge University Press.

[35]. Kabato, W. (2025). Towards climate-smart agriculture: Strategies for enhancing crop productivity, climate resilience, and greenhouse gas mitigation. Agronomy, 15(3), 565.

[36]. Kulatunga, C., Dhelim, S., & Kechadi, T. (2024). Machine learning for dynamic management zone in smart farming. arXiv.

[37]. Kumar, D., & Doan, M. K. (2025). Adoption of agricultural technologies by smallholder farmers: A synthesis of empirical evidence. World Bank.

[38]. Li, L., Huang, Z., Mu, Y., & Song, S. (2024). Alternate wetting and drying maintains rice yield and reduces global warming potential: A global meta-analysis. Field Crops Research, 318, 109603.

[39]. Li, W., Kafle, K., & Josephson, A. (2025). Gender and agricultural commercialization in Sub-Saharan Africa: Evidence from three panel surveys. arXiv.

[40]. Machefer, M., Ronco, M., Thomas, A.-C., Assouline, M., Rabier, M., Corbane, C., & Rembold, F. (2025). A monthly sub-national Harmonized Food Insecurity Dataset for comprehensive analysis and predictive modeling. arXiv.

[41]. Mishra, T., & others. (2026). Exploring barriers to adoption of climate-smart agriculture among smallholder farmers. Scientific Reports.

[42]. Mnukwa, M. L., Mdoda, L., & Mudhara, M. (2025). Assessing the adoption and impact of climate-smart agricultural practices on smallholder maize farmers' livelihoods in Sub-Saharan Africa: A systematic review. Frontiers in Sustainable Food Systems, 9, Article 1543805. https://doi.org/10.3389/fsufs.2025.1543805

[43]. Mudzielwana, R. V. A. (2025). Climate-smart food systems: Integrating adaptation and mitigation strategies for sustainable agriculture in South Africa. Frontiers in Sustainable Food Systems, 9, Article 1580516.

[44]. Neupane, B. (2024). Integrating climate-smart agriculture for sustainable agricultural development. Archives of Agriculture and Environmental Science.

[45]. Office of Dietary Supplements, National Institutes of Health. (2022). Folate: Fact sheet for health professionals. U.S. Department of Health and Human Services. https://ods.od.nih.gov/factsheets/Folate-HealthProfessional/

[46]. Office of Dietary Supplements, National Institutes of Health. (2024). Iodine: Fact sheet for health professionals. U.S. Department of Health and Human Services. https://ods.od.nih.gov/factsheets/Iodine-HealthProfessional/

[47]. Office of Dietary Supplements, National Institutes of Health. (2025a). Iron: Fact sheet for health professionals. U.S. Department of Health and Human Services. https://ods.od.nih.gov/factsheets/Iron-HealthProfessional/

[48]. Office of Dietary Supplements, National Institutes of Health. (2025b). Vitamin A and carotenoids: Fact sheet for health professionals. U.S. Department of Health and Human Services. https://ods.od.nih.gov/factsheets/VitaminA-HealthProfessional/

[49]. Office of Dietary Supplements, National Institutes of Health. (2025c). Vitamin B12: Fact sheet for health professionals. U.S. Department of Health and Human Services. https://ods.od.nih.gov/factsheets/VitaminB12-HealthProfessional/

[50]. Office of Dietary Supplements, National Institutes of Health. (2025d). Vitamin D: Fact sheet for health professionals. U.S. Department of Health and Human Services. https://ods.od.nih.gov/factsheets/VitaminD-HealthProfessional/

[51]. Office of Dietary Supplements, National Institutes of Health. (2026). Zinc: Fact sheet for health professionals. U.S. Department of Health and Human Services. https://ods.od.nih.gov/factsheets/Zinc-HealthProfessional/

[52]. Olabanji, M. F., Davis, J., & others. (2025). The adoption and scaling of climate-smart agriculture technologies: A comprehensive review of practices, barriers, and policy implications. AgriEngineering, 6(2), 51.

[53]. Omokpariola, D. O. (2025). Climate change, crop yield, and food security in Sub-Saharan Africa. Discover Sustainability.

[54]. Pakistan Council of Research in Water Resources. (2017). Water-use efficiency and economic feasibility of laser land leveling in irrigated areas of Pakistan. PCRWR.

[55]. Pedersen, T. D. S. (2026). CERES: A probabilistic early warning system for acute food insecurity. arXiv.

[56]. Punjab Agricultural University. (2025). PAU-developed wheat variety PBW 826 records high performance in India's 2024–2025 national wheat trials.

[57]. Richards, M. B., & Sander, B. O. (2014). Alternate wetting and drying in irrigated rice. CGIAR Research Program on Climate Change, Agriculture and Food Security.

[58]. Rufin, P., Hammer, P. L., Thomas, L.-F., Lisboa, S. N., Ribeiro, N., Sitoe, A., Hostert, P., & Meyfroidt, P. (2025). National level satellite-based crop field inventories in smallholder landscapes. arXiv.

[59]. Saleem, S., et al. (2023). Gradient-based laser land leveling increases the water productivity of cotton. Pakistan Academy of Sciences.

[60]. Saran, A., White, H., Kuper, H., & others. (2024). Interventions promoting resilience through climate-smart agriculture in low- and middle-income countries: A systematic review. Campbell Systematic Reviews.

[61]. Shah, A., Singh, R., Zaytar, A., Abebe, G. A., Robinson, C., Tafti, N., Wood, S. E., Dodhia, R., & Ferres, J. M. L. (2025). Machine learning for sustainable rice production: Region-scale monitoring of water-saving practices in Punjab, India. arXiv.

[62]. Swarnam, T. P., Velmurugan, A., Kundu, M. S., & others. (2024). Climate smart crop-livestock integrated farming as a sustainable strategy to enhance productivity and food security of smallholder farmers. International Journal of Agricultural Sustainability, 22(1).

[63]. Times of India. (2025, July 27). OUAT launches climate-resilient farming project in Ganjam.

[64]. Traore, B., Sultan, B., Sanogo, D., & others. (2026). On-farm adoption and impacts of climate-smart agricultural practices on food security of smallholder farmers in Mali. Food Security.

[65]. United Nations Environment Programme. (2024). Food Waste Index Report 2024. UNEP.

[66]. Wang, H., Fan, J., Zhang, S., Liao, Z., Zhang, F., & Wang, Y. (2022). Yield and water productivity of crops, vegetables and fruits under subsurface drip irrigation: A global meta-analysis. Agricultural Water Management, 269, 107645.

[67]. World Bank. (2024). Climate-smart agriculture: From knowledge to implementation. World Bank.

[68]. World Bank. (2025). Water for food. World Bank.

[69]. World Bank. (2025a). Can everyone afford to eat healthy? New data show progress, but challenges remain. World Bank Blogs.

[70]. World Bank. (2025b). Climate-smart agriculture. World Bank.

[71]. World Food Programme. (2025). Global hunger declines, but rises in Africa and western Asia. WFP.

[72]. World Health Organization. (2024). Malnutrition. WHO. https://www.who.int/news-room/fact-sheets/detail/malnutrition

[73]. World Meteorological Organization. (2025). State of global water resources 2024. WMO.

[74]. Yiridomoh, G. Y. (2025). Climate-smart agriculture adoption and food security in Sub-Saharan Africa: A systematic review. Climate Resilience and Sustainability. https://doi.org/10.1002/cli2.70017

[75]. Zafar, O., Santa González, R., Morales, A., & Ayday, E. (2025). Digital agriculture sandbox for collaborative research. arXiv.

[76]. Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D. B., Huang, Y., Huang, M., Yao, Y., Bassu, S., Ciais, P., Durand, J.-L., Elliott, J., Ewert, F., Janssens, I. A., Li, T., Lin, E., Liu, Q., Martre, P., Müller, C., Peng, S., Peñuelas, J., Ruane, A. C., Wallach, D., Wang, T., Wu, D., Liu, Z., Zhu, Y., Zhu, Z., & Asseng, S. (2017). Temperature increase reduces global yields of major crops in four independent estimates. Proceedings of the National Academy of Sciences, 114(35), 9326–9331. https://doi.org/10.1073/pnas.1701762114

[77]. Zia, B. (2025). Global agricultural competitiveness index in the context of climate change: A holistic approach. arXiv. https://arxiv.org/abs/2505.05508

[78]. Zubair, M., Salim, M. S., Rahman, M. M., Basher, M. J. I., Imran, S., & Sarker, I. H. (2024). Agricultural recommendation system based on deep learning: A multivariate weather forecasting approach. arXiv.