E-ISSN: 2618-0618
P-ISSN: 2618-060X

NAAS Rating (2025): 5.20
www.agronomyjournals.com
2025; SP-8(11): 114-121
Received: 24-08-2025
Accepted: 27-09-2025

Akash
University Institute of Agricultural Sciences, Chandigarh University, Gharuan, Punjab, India

Dr. Asma Fayaz Lone
University Institute of Agricultural Sciences, Chandigarh University, Gharuan, Punjab, India

Corresponding Author:
Akash
University Institute of Agricultural Sciences, Chandigarh University, Gharuan, Punjab, India

Climate smart agriculture: Food bridging, adaptation, and mitigation

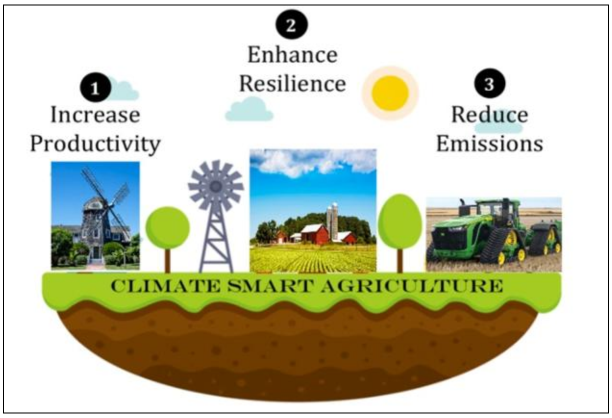
Akash and Asma Fayaz Lone

DOI: https://www.doi.org/10.33545/2618060X.2025.v8.i11Sb.4194

Abstract
Climate-smart agriculture (CSA) is a conceptual framework that is aimed at transforming and re-oriented agricultural systems towards the new realities of climate change by providing their food security. Change of rain patterns and temperature increase is being observed all over the world and this poses a threat to agricultural production thereby subjecting people reliant on agriculture to greater exposure, particularly the world's poor. These weather changes also affect food markets, and this has had a universal threat to food supply. CSA is linked with the measure of containing these risks through the development of the adaptive abilities of the farmers and resiliency and enhancing resource-use efficiency of the agricultural production mechanisms. It promotes administration of efforts that comprise various stakeholders in it such as the farmers, researchers, the private, civil, the policymakers to develop climate resilient means. This strategy has four key areas of action, creating a more pressing evidence foundation to make decisions. Increasing the workability of local institutions. Enhancing climate-similarity with agricultural policy. Linking agriculture finance and climate. Contrary to conventional farming practice, CSA lays both stress on context and the specific solutions to be flexible that is mentioned with the help of new policy and finance mechanisms. This guarantees the contribution of agricultural development towards food security and climate resilience as opposed to the agricultural development taking the role of increasing climate change impacts.

Keywords: Climate-Smart Agriculture (CSA), food security, climate change adaptation, mitigation, resilience

Introduction
One of the critical solutions to changing and reorganizing agricultural systems to provide security against the challenges of climate change is introduced [1, 2] as climate-smart agriculture (CSA). The proposed systematic review protocol is expected to combine evidence-based findings on the interventions which can foster CSA specifically empowerment and resilience of women farmers in low and middle-income nations (LMICs) [2]. The effects of climate change are enormous to agricultural production and the negative impacts exceed the positive impacts eminently as compared to the developing nations [3]. There are extreme weather phenomena, the existence of drought effects, extreme rainfalls, extreme temperatures, and so on increasing and the end result is threatening the entire population with the lack of food because of population-based risks [3]. CSA is important since it tries to minimize these hazards through enhanced adaptive capacity of farmers and higher level of resilience and efficiency in the utilization of resources in agricultural production structures [1]. Unless there is change in attitude toward the agricultural planning and investment, there is a danger to misuse resources thereby providing agricultural systems that cannot support food security and lead to further climate change [4].



Sustainability The idea of CSA is described as one that will raise productivity, strengthen, drop greenhouse gases (GHG), and accelerate the accomplishment of national food security and growth targets [1, 5]. It incorporates the issue of global warming into the design and execution of sustainable agricultural policies [4]. This goal is to facilitate equitable growth in agricultural productivity and release with a view to bolstering equitable growth in food security and developments, on a sustainable basis [6]. Resilience to and adaptation to climate change deals with measures taken at the farm down to national levels as one of the ways to adapt to the impact of climate changes [6]. This goal is seriously oriented towards the reduction of greenhouse gas (GHG) emissions by enabling opportunities to lower the GHG emissions of agriculture in comparison with the past trend [6]. Since CSA has the purpose to fulfill all three goals, it does not mean that all practices in every single place will be associated with triple wins. Nevertheless, alternative synergies and trade-offs vary with regard to the relative priority of each objective, different locations, and circumstances [7].

Rationale for Food Bridging (Linking Production, Supply Chains, and Consumption to Resilience and Sustainability)

The concept of CSA inherently links production, supply chains, and consumption to resilience and sustainability by addressing food security, adaptation, and mitigation simultaneously [4]. It promotes coordinated actions among various stakeholders, Encompassing farmers, researchers, the private sector, the civil society and policymakers, to come up with climate-resilient pathways [1]. This integrative strategy will ensure that even the practices to increase productivity generates the resiliency and emission elimination, yet contribute to the overall sustainability of food system [4, 6]. The synergistic nature of these is a necessity because climatic change influences the food supply of rural and urban populations by compromising the agricultural production and income, increasing the risks, and merging markets [8].

Research Gaps and Purpose of the Review

There is an inadequate evidence base to support effective decision-making, with much of the existing information being inaccessible to decision-makers at national and local levels [9]. The significant gaps in research are the identification of adoption barriers. We have to comprehend the obstacles to the adoption of climate responsive agricultural practices with particular reference to vulnerable populations such as small holders, women, the poor, “marginalized population among others [10]. The extent of adoption of potentially useful practices is frequently low [10]. Learning context-specific efficacy, power-driven research will be required to enhance notions of what is agro-ecologically and farming system-specifically engaging and deficient in disclosing what surpasses agro-ecological and socio-economic contexts of being climate smart [10]. To work around uncertainties in climate models, spatial and temporal scales of current climate impact studies may fail to fit the national and local-level planning requirements because of uncertainties in climate model outputs and less information regarding future changes in climate variability [9].

This systematic review protocol aims to synthesize the available evidence regarding interventions that can be used to promote CSA. To be more specific, it will seek to know how such interventions can empower women farmers and can make them resilient and will increase their agricultural performance in LMICs [2]. CSA represents an important platform of controlling the dynamics of the climate change and food insecurity. It is a major to the building of reliable food systems through the combined thought to the emphasis on productivity, adjustment, and mitigation. The systematic reviews on addressing the existing research gaps will furnish the missing evidence to upscale effective CSA interventions around the world.

Climate-Smart Agriculture: Pillars, Food Security, and Global Integration

Climate-smart agriculture (CSA) is expounded as a very urgent way of transforming and reinventing agricultural systems to sustain food security in the environment of climatic change issues [11]. It attempts to increase productivity sustainably, increase their resilience, lower the green house gases (GHG) and augment the national food security, and development targets [12, 13]. The Three Pillars of Climate-Smart Agriculture: Sustainably Increasing Agricultural Productivity and Incomes. This pillar aims at delivery of equitable growth on food security outcomes and development outcomes. It entails embracing policies which increase the output and economic gains to the farmer in order to ensure there is a stable and adequate food supply to the ever-increasing global population [14, 15]. Preparing and Strengthening against Climate Change. This objective reacts to the need of the agricultural systems to operate with the impact of climate change that have been outlined under the frequency and intensity of extreme weather circumstances, drought, heavy rains, and high temperatures [16, 17]. It entails activity both in smaller-scale operations, such as in single farms, and in global measures, aimed at increasing the adaptability of farmers and making wheat use more efficient [14, 17]. It is likely that the pillar of Reducing Greenhouse Gas (GHG) Emissions would establish opportunities of crushing the rates of GHG emissions in farming of the agriculture in comparison to the trends in previously”. Agriculture alone contributes a significant portion of GHG i.e. about 11 percent of all anthropogenic GHG emission (only land use change) [18]. The CSA practices are directed at reducing its emissions, which are industrial to the global climate aspirations [14, 19].

Food Bridging: Linking Agricultural Practices to Food Security and Nutrition Outcomes

CSA intrinsically introduces production, supply chains, and consumption to the resilience and sustainability through focusing on the food security adaptation and mitigation in tandem [20]. It encourages co-ordinated efforts between the various stakeholders which include the farmers, the researchers, the private industry, the civil society, and the policymakers to come up with climate resilient ways [20]. Large cultivation of CSA would yield output in the agro-based sector, which would lead to lowering of world prices of staple food, including wheat, maize, and rice in case of unfavorable weather later [21]. This will reduce the cost of goods hence food products will be more affordable thus reducing the population of hungry people and underniourished children [21]. Creation of CSA is also considered type of adaptation to the new climatic conditions and thus CSA practices render crop production more resilient [22]. The acquired benefits of practices of CSA have the potential to compensate the adverse effects of climate change on production of maize and rice and prevent the emergence of subsequent price upsurge [23]. While not explicitly detailed in the provided text, the focus on increasing food security and reducing undernourishment implies a direct positive impact on nutrition outcomes. The bigger picture encapsulated by climate change influencing food availability to the people in the rural areas, and the urban areas, includes the decreasing agricultural productivity and agricultural revenues, and destabilizing markets; all this worth the applicability of CSA, as the potentials of sustainability agricultural practices toward enhancing nutritional performance [20]. It encompasses agricultural systems that result into sustainable and equitable agricultural productivity upgrade and food system earnings, enhanced adaptation in food system as well as food system resilience and minimization of GHG emissions [24]. Such a holistic view also guarantees that the success or result of trying to boost productivity can provide resilience and lower the amount of emissions which may be a part of the sustainability of the entire food system [20].

Position within Global Frameworks

United Nations Framework Convention on Climate Change (UNFCCC) and Paris Agreement. Weights on the stimulators to decrease GHG emissions have done a resurgence in need following the recent developments in the negotiations concerning UNFCCC, such as the Paris Agreement (2015) and the Koronivia joint work on agriculture [25]. CSA directly aligns with the mitigation goals of these agreements by focusing on reducing agricultural GHG emissions [14, 19]. Intergovernmental Panel on Climate Change (IPCC)The IPCC's special reports also emphasize the need for agricultural changes to address climate change [15]. CSA's objectives are consistent with IPCC recommendations for climate action within the agricultural sector. CSA of Food and Agriculture Organization (FAO). According to the FAO, CSA is a strategy that gains a reliable boost of productivity, resilience, alleviates greenhouse gas emission, and elevates the attainment of the national objectives of food security and developments [12, 13]. This definition is directly adopted and referenced, positioning the concept within a globally recognized framework for sustainable agriculture. Sustainable Development Goals (SDGs). Although it is unnamed, the triple goals set by CSA have a direct impact on a number of SDGs, especially SDG 2 (Zero Hunger) with its enhanced productivity and food security, SDG 13 (Climate Action) through adaptation and mitigation, and SDG 5 (Gender Equality) by paying more attention to the empowerment of women farmers. CSA also offers an integrated solution process to the challenge of the complexity of interlinked problems of climate change and food insecurity. Its multi-dimensional aspect, which entails the productivity, adaptation, and mitigation, makes it an important plan in the building of robust and viable food systems in the world in accordance with high standards of international climate and development.

CSA Practices and Their Role In Adaptation & Mitigation

The concept of climate-smart agriculture (CSA) involves a broad assortment of approaches of reinforcing agricultural production, resistance and lessening of greenhouse gas (ghg) emissions in a sustainable manner, which makes its role in the food security and development procedures on the national scale [26, 27]. The reason is that such practices are twofold as they would facilitate it easier to respond to the impacts of climate change, but then again, they diminish the impacts of agriculture in global warming.

Crop Management

The CSA crop management activities aim at ensuring that crop grows and yields optimal growth as well as production in addition to maintaining resilience and reducing adverse consequences of plant manufacture on environment. The implementation of enhanced crop varieties modified to the environmental strains like the use of drought-resistant bean and maize, can help immensely in improving the yield, income level of farmers as well as food security [28]. These varieties enhance adaptation by maintaining productivity under adverse climatic conditions. While the provided text does not explicitly detail their mitigation benefits, stress-tolerant varieties can indirectly contribute to mitigation by stabilizing yields, reducing the need for expanding agricultural land (which can lead to deforestation and GHG emissions), and potentially improving nutrient use efficiency. Given that agricultural systems may be diversified, crop yields, stability, profitability, and other livelihood benefits increase [29]. Menus such as rice-maize and rice-sunflower double cropping have been referred to as an example which has recorded high yields [29]. The rice rotation with wheat and rice-potato-sesame rotation can be used, which may bring more political impact to agricultural farms, and the GHG emissions decrease [30]. This practice enhances adaptation by creating more resilient and stable food systems, less susceptible to single crop failures. For mitigation, crop diversification and optimized patterns can lead to increased carbon sequestration in soils and reduced GHG emissions through improved nutrient cycling and reduced reliance on synthetic inputs. Precision Farming, although not explicitly detailed for crop management in terms of dual benefits, precision agriculture, often enabled by technological interventions, allows for optimized resource use. This can lead to increased productivity and reduced waste, indirectly supporting both adaptation by making systems more efficient and mitigation by reducing input-related emissions.

Soil & Water Management

Effective management of soil and water resources is fundamental to CSA, providing direct benefits for both adaptation and mitigation.

It can enhance the biological activity of the soil, water use efficiency, and physical properties of soils through the application of practices like no-tillage, crop rotation, and straw returning to the field [31]. These practices enhance adaptation by improving soil health, making it more resilient to drought and erosion, and increasing water retention. For mitigation, conservation agriculture is highly effective in reducing GHG emissions, particularly CO_2, by increasing soil organic carbon and improving nitrogen utilization efficiency [32, 33]. Irrigation water management technologies, including well digging, pipe wells, rainwater collection, and drip irrigation, are crucial for solving drought issues and improving water utilization efficiency [34]. These methods are key for adaptation, ensuring water availability in regions prone to water scarcity. While primarily an adaptation strategy, efficient water use can indirectly contribute to mitigation and by limiting the amount of energy used in pumping and distributing water, so as to limit GHG emissions. The ongoing agro forestry intercropping of primary fertility species and systematic agro forestry fallow, where there is rapid leguminous tree or shrubs, enhances soil fixation of nitrogen and improves the soil nutrient status [35]. This practice enhances adaptation by diversifying farm income, improving soil fertility, and providing shade, which can reduce heat stress for crops and livestock. For mitigation, agroforestry significantly slows down the emission of GHGs like CO2 and N2O by increasing carbon sequestration in biomass and soils [35].

Livestock & Fisheries

While the provided text focuses primarily on crop-based agriculture, the principles of CSA extend to livestock and fisheries, aiming for sustainable production with reduced environmental impact. Although not explicitly detailed in the provided text, improving livestock breeds for higher productivity and enhancing feed efficiency are common CSA strategies. These practices contribute to adaptation by making livestock systems more resilient and productive under changing conditions. For mitigation, improved feed efficiency can reduce methane emissions per unit of product, as animals require less feed for the same output. Better manure management practices (e.g., biogas digesters) can also capture methane, further contributing to mitigation. The text mentions hydroponic cultivation and mushroom planting as part of adaptation measures in Namibia [36]. While not directly related to livestock or fisheries, these are alternative food production methods that can be more resilient to climate variability. In a broader CSA context, climate-resilient aquaculture involves practices that can withstand climate shocks (adaptation) and reduce environmental impacts, such as minimizing water pollution and GHG emissions from feed production or energy use (mitigation).

Technological Interventions

The use of modern technologies plays an important role in facilitating and empowering CSA practices that provide monitoring tools, decision-making instruments, and resource optimization. The use of Internet of Things (IoT) is aimed at obtaining the data of the environment and crops parameters through a series of sensors to make remote sensing and monitoring possible [37]. Artificial intelligence (AI) has the ability to process and combine data to achieve recognition of the plant, prediction of weeds, prediction of crop yields, forecasting of GHG emissions, and pest control [38]. These technologies also make them more adaptive as they offer real-time information and predictive authority to enable farmers make informed decisions in a timely manner to address the variability of the climate. Through mitigation, AI will enable themost resource utilization (e.g. fertilizers, pesticide, irrigation), therefore, resulting in the decrease in input-based GHG emissions, and, arguably, forecasting. GHG emission in agriculture [38]. The real time, macro, fast and wide view aiming at crop development, planting area and yield, and data on agricultural disasters can be produced using remote sensing technology of using the satellites or unmanned aerial vehicles [39, 40]. This is vital in to adaptation that may allow greater planning and control of agricultural production in specific spheres of climate change [40]. To alleviate it, should land usage change, remote sensing may be employed in order to monitor the carbon sequestration potential change, and find out how mitigation exercise was influenced on a broad basal base. These will be precision agriculture and superior decision making in the ever changing weather, aspects brought by the combination of agricultural models and satellite data as well as remote sensing [40]. Such systems play a crucial role in adjustment as they make a farmer allocate his time purposes and save money in investments and adapt to climate change [40]. They are mitigation agents as a way of rationalizing their resources that might result in a lower GHG emission rate. CSA is practiced as a compound act that presents a synergistic strategy to solve climate change and food insecurity. Sustainable crop, soil, water, livestock and technological management by itself accomplish resiliency and food security (adaptation) as well as actively reduce the carbon footprint of agriculture (mitigation), a more sustainable and climate-resilient agenda is set.

Food Bridging Dimension

The climate smart grid includes agriculture (CSA) which is a planning plan to modify the components of agricultural systems in order to guarantee food security amidst worst climatic conditions [11]. It seeks to record sustainable growth in food output, boost resilience, minimize greenhouse gas, GHG emissions, and support food security and growth targets of nations [11, 12].

CSA's Role in Ensuring Food Security and Nutrition

The core idea of CSA is that it reduces food insecurity and climate change through encouraging agriculture, livelihoods without damaging natural resources and important ecosystems [13]. The technique promotes corporate resilience and climate change adaptation and, at the same time, diminishes GHG emission [13]. This large-scale application of CSA can be listed in increased agricultural production, which has been projected to drive the prices and agricultural products of the planet in the form of wheat, maize, and rice crops to decline, specifically in inhospitable climatic conditions in the future [14]. This discounting of prices brings the food products closer to the hands of its citizens, hence reducing the population of those who can be susceptible to hunger, obese children [14]. The destination of CSA towards sustainability in terms of increasing agricultural production and incomes engaged directly in estimating equitable gains on food security [12]. CSA practices can be seen as a type of adjusting to new weather conditions, which make crop production stronger [15]. The CSA would result in the payment of the adverse climate change production effects on the staple crops production like maize and rice and counter the resultant rise in prices [15]. The resiliency brings a more stable supply of food quantity which is key to food security. Although, the given text does not directly describe the nutrition consequences, emphasis on enhancing food security and decreasing the portion of the undernourished populace suggests that nutrition will have a direct, positive effect. Climate change also affects the access to food by rural and urban communities by negatively affecting agricultural output, earnings, and markets and the relevance of CSA to protect dietary health in this regard.

Bridging Gaps: Production, Markets, and Consumer Access

CSA inherently links production, supply chains, and consumption to resilience and sustainability by simultaneously addressing food security, adaptation, and mitigation [16]. It emphasizes coordinated actions among various stakeholders, including farmers, researchers, the private sector, civil society, and policymakers, to establish climate-resilient pathways [17]. By focusing on sustainably increasing agricultural productivity, CSA ensures a more consistent and higher volume of produce available for markets [12]. Practices like improved crop varieties and efficient resource management contribute to stable yields, even under climate stress, thus securing the supply side.CSA also includes 'institutional/market-smart' approaches, which involve financial services, market information, and off-farm risk management [18]. These interventions help farmers connect to markets more effectively, ensuring that increased production translates into available food for consumers. The projected lower world prices for staple crops due to CSA adoption would make food more affordable and accessible to a wider population, thereby improving consumer access [14].

These include water harvesting and water management techniques, community management of water resources, and solar pumps [19]. They play a vital role in addressing drought issues and enhancing the efficiency of water utilization that directly affects the availability of food due to regular growth of crops. The initiation of high yield varieties and seed load that is stress tolerant is one of the factors [19]. In one of the examples, the output of crops such as drought resistant beans and maize which is classified as a better strain has been reported to yield higher crop quality, the income of the farmers, and food security [20]. Clean technologies in such areas as composting, cover, conservation agriculture, optimal application of fertilizers, no-till and minimum tillage, livestock and fisheries management practices fall under this category [19]. Such practices improve the health and fertility of the soil which results to improved yields and production of food in a sustainable manner. As an example, the topic of conservation agriculture becomes more biological, efficient in the use of water and soil physical properties to reach a more stable and high production [21]. These are the financial services, market information and off-farm risk management [18]. These types of interventions help farmers to address the risks, and access to the resources, which are instrumental in the further production and involvement in markets, which, at a certain point, will lead to food with regards to its affordability and availability.

Trade-offs: Balancing Productivity Gains with Climate and Environmental Goals

CSA is aiming to strike equilibrium between the achievement of its three macro ramifications: economically and agriculturally, to raise were well as to usher into the realm of greater system adaptations and reactive and to reduce GHG emissions [12]. This implies that it will need management trade-offs and exploitative synergies [12]. Numerous practices of CSA have two advantages. An illustrative example of conservation agriculture, that although such strategies help to boost productive capacity and soil health (adaption), diminish GHG emissions by enhancing soil organic carbon content as well as the efficiency of the nitrogen utilizing system (mitigation) [21]. On the same note, agro forestry improves soil fertility and diversification of income (adaptation) and capturing carbon (mitigation). According to the reading, CSA is a framework which completely takes into consideration trade-offs and synergies [12]. Although they do not outline particular negative trade-offs, the requirement of the balanced approach means that sometimes having one pillar as a priority (e.g., productivity) may force a person to pay close attention to another pillar (e.g., environmental goals) to avoid causing any harm to a third one (e.g., innovation). By way of example, the yield of some varieties could be high, meaning that it needed more inputs which could cause emissions when not under the sustainable management approach. Nevertheless, the higher priority of CSA is to seek measures that will optimize the three pillars in a unison. CSA is a holistic approach through which diverse agricultural practices and technologies are combined to promote food security and nutrition by improving production, enhancing resiliency and adaptation to climate change. With production-to-consumer access improved practice and market-sensitive solutions, CSA focuses on building sustainable and equitable food systems but by treading the handling of the inherent trade-offs to arrive at the desired climate and environmental objective.

Challenges and Limitations in Climate-Smart Agriculture Adoption

There are multiple challenges involved with the implementation of Climate-Smart Agriculture (CSA), which are socio-economic, institutional and policy gaps, data and knowledge and issues of farmers perception and access. They are some of the limitations that need to be addressed in order to ensure the successful incorporation of CSA in national agricultural plans.

Socio-economic Factors: Cost, Awareness, and Adoption Constraints

Although the advantages of such practices are promising, the rate at which agricultural practices like CSA get adopted are also poor [1]. The above implies that there are massive obstacles that entrepreneurs cannot use to effect such practices. As an example, adoption of better facilities of livestock feeding is rarely more than 1 percent annually, although it can greatly boost its productivity and income [2]. However, although particular CSA practices may provide mitigation co- benefits, the process to achieve it may become additional costly [3]. These are the costs that are to be identified particularly to the low-emission development strategies equivalence to the traditional high-emission trajectories to associate agricultural development endeavors with climate finance [3]. One of these barriers is the absence of strong research that enhances knowledge of the issue of what works, where, and why in various agro-ecologies and production systems [1]. This is a weakness of lacking context-specific evidence to create wisdom and informed decisions among farmers and policymakers.

Institutional and Policy Gaps

The major impediments to sustainable land management practices that can help in increasing resilience are institutional gaps and institutional weaknesses [2]. The attempt at contracting the private sector in the risk management effectively, e.g. requires it to be good and practical regulation [4]. Formulation of enabling policy and regulatory environments would presuppose stronger interrelation of policy on agriculture/climate change/environmental and food systems [5]. These include harmonising policies in various fields, and creating discussions among pertinent ministries, to tackle tradeoffs, gaps, and overlaps [5]. The international assistance to national activities must also have coordinated strategies in climate change, agricultural, and food security policy sectors [6]. Although agricultural development strategies have put great emphasis on institutional development, this has been associated only with mixed-success because of poor design or funding [7]. The extension and information dissemination processing needs popularization, the positive spillovers should be coordinated, the whole process of risk management strategy must be developed, and access to inputs must be ensured [7].

Data and Knowledge Limitations

The existing evidence base does not ensure successful decision-making and even at the national and local levels is mostly inaccessible [8]. It is especially necessary to have serious studies that will explain what is meant by climate smartness in different contexts [1]. A great part of the climate change impact on agriculture is not suited to national and local-level planning because of uncertainty in climate models, technical complications in downscaling, and lack of information on future climate variability and its effects [8]. "Evaluation of the ability of various policies and technology to adapt or mitigate the impact of climate change, how to enhance resilience, and alternatives and expenses of reducing the growth of the emissions would require tools [8].

Farmers' Perceptions and Access to Resources

Climate change is more disastrous to poor producers, the landless, and marginalized ethnic groups which are the most vulnerable categories [9]. These are the groups which are usually the most hit by the effects of climate change yet have had the least contribution to the climate change [3]. Some of the inputs required by the use of CSA include tree seedlings, seeds or fertilizers, and this limitation on availing an input in time can limit their use on large scale basis [10]. The access to fertilizer, in a good time, in particular, can determine the productivity and stressed higher resource use, yet they are often not available [10]. This variability already exists among farmers but climate change introduces even greater uncertainty and requires greater flexibility and response ability. The resilience to be established through construction of resilience entails minimizing vulnerability of falling into the food-insecure category and enhance capacity of adapting to the risks.

Future Directions and Research Agenda for Climate-Smart Agriculture

The prospect of Climate-Smart Agriculture (CSA) will be to capitalize on new technologies, develop concentrate policy, and consolidate collaboration in worldwide issues; that is, food security and climatic changes problem. These directions are directed at the expansion of productive drills, including the application of digital tools, investing in climate, and disciplinary collaboration.

Scaling CSA through Policies and Incentives

Data formation of enabling regulatory and policy mechanisms is the greatest factor in accomplishing high levels of CSA adoption. This will imply increased coordination of the agricultural, climate change/ environmental and food system policies. Policies in these areas need to be streamlined and dialogue between concerned ministries encouraged to resolve the trade-offs, gaps, and overlaps [26]. International support is also needed for national efforts, coordinating approaches across climate change, agricultural, and food security policy areas [26]. Public support is necessary for extension services, information dissemination, and comprehensive risk management strategies. This includes ensuring reliable access to inputs for farmers [27]. Effective engagement of the private sector in risk management also requires transparent, efficient, and enforceable regulations [28].

While the document does not explicitly detail carbon markets, it notes that realizing mitigation co-benefits from CSA practices may involve additional costs. Identifying these costs, especially for low-emission growth strategies, is important to link agricultural development efforts with climate finance [29]. This implies a need for financial mechanisms to support the transition to more sustainable, low-emission agricultural practices.

Role of Digital Agriculture (AI, IoT, Remote Sensing)

Advanced internet technology is considered a main direction for the future development of CSA, particularly for ensuring agricultural information security and improving agricultural services [30]. Remote sensing technology is widely used due to its fast, macro, real-time, dynamic, and large-area observation capabilities [31]. Continuous improvements in temporal, spatial, and spectral resolutions, along with enhanced inversion algorithms, make remote feeling that it is a key instrument in regional scale CSA [31]. It is applicable in the exact management of crops, tracking of the growth of crops, planting land, crop yield, as well as agricultural calamity details [32, 33]. The next step will be the combination of multi-source remote sensing to achieve more accurate and precise dynamic variations in crop development [31]. IoT refers to inter-linked computing devices, sensors and machines that measure data on environmental and crop factors such as temperature, humidity and pH [34]. In the case of CSA, the development of the IoT in the future must enhance its high flexibility and customization to the local conditions., ensure efficient deployment, reliable network connections, and implement robust security strategies for valuable agricultural data [40]. AI applications in agriculture are expanding, capable of analyzing and integrating data from various areas to achieve plant recognition, weed prediction, crop yield prediction, GHG emissions forecasting, climate prediction, and pest control [41]. AI will be able to enhance crop productivity by predicting the best sowing/harvesting date and crop status, as well as reducing the input expenses [41]. Future directions include strengthening data collection and analysis from diverse sources (soil, climate, diseases, pests) and extending deep learning methods to improve accuracy in plant identification and yield prediction [41].CSA requires coordinated actions among various stakeholders, including farmers, researchers, the private sector, civil society, and policymakers, to establish climate-resilient pathways [42]. This interdisciplinary approach is essential for addressing the complex challenges of food security and climate change comprehensively.

Pathways to Integrate Adaptation, Mitigation, and Food Systems Resilience

CSA is a process of transforming agricultural systems to become food security in new climatic conditions [43]. Some of its local objectives are to improve agricultural productivity and incomes in a sustainable way, to enable agricultural systems to provide and meet climate change demands, and to reduce or even eliminate GHG emissions [44]. The aim of this is to reap a triple win-win of production, gain in stress resistance and reduction in GHG emissions [44]. The future development of CSA will drive sustainable agricultural development to a higher level through the enhancement of the cropping patterns and management methods [45]. It comprises of multiple cropping", crop diversification, zero till farming, application of organic improvers and biochar in order to improve the quality of soil and minimize GHG emissions [46]. Insuring agricultural weather index is regarded a promising direction of CSA in the future [47]. It applies agrometeorological indicators to lead to the compensation in order to reduce or remove the adverse impact of natural risks on agricultural production and it offers a novel method of risk transfer to agricultural producers [48]. Evaluation methods and indicator systems of this insurance are undergone to need more investigations [47].

Conclusion

Climate-Smart Agriculture (CSA) acts as pivotal stratum between ensure that food security, adjusting the transformations of climate, and preventing its changes and reactions. It is an integrated methodology that aims at transforming the agricultural systems in such a way that abates the 21 st century challenges by increasing productivity in a sustainable way, developing elasticity and reducing green lives [43, 44].

A combination of strong policies, science, and action by the farmers are the ingredients of a successful implementation of CSA. These involve the creation of enabling policy and regulatory systems, the exploitation of the latest digital agricultural technologies, such as the AI, the Internet of Things, and the remote sensing, and the attainment of climate capital funding. Also, interdisciplinary cooperation between various stakeholders is the most important in order to promote holistic solutions. Increasingly adopting CSA is not just a wish but a must to design resilient and sustainable food systems that would fulfill security of and climate goals in the world confronting constant change in climate.

Acknowledgement
Not Applicable

Conflict of Interest
The authors declare that there is no conflict of interest regarding the publication of this paper.

Funding Agency
This research received no external funding

References

1. Wheeler T, von Braun J. Climate change impacts on global food security. Science. 2013;341:508-513.
2. International Fund for Agricultural Development (IFAD). Rural Poverty Report 2011. Rome: IFAD; 2011.
3. Alexandratos N, Bruinsma J. World agriculture towards 2030/2050: the 2012 revision. ESA Working Paper No. 12-03. Rome: FAO; 2012.
4. Intergovernmental Panel on Climate Change (IPCC). Summary for policymakers. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Cambridge (UK): Cambridge Univ. Press; 2014.
5. Porter JR, *et al*. Food security and food production systems. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Cambridge (UK): Cambridge Univ. Press; 2014. p. 485-534.
6. Lobell DB, Schlenker W, Costa-Roberts J. Climate trends and global crop production since 1980. Science. 2011;333:616-620.
7. Battisti DS, Naylor RL. Historical warnings of future food insecurity with unprecedented seasonal heat. Science. 2009;323:240-244.
8. Wheeler T, Craufurd PQ, Ellis RH, Porter JR, Prasad PVV. Temperature variability and the yield of annual crops. Agric Ecosyst Environ. 2000;82:159-167.
9. Thornton PK, Gerber P. Livestock production: recent trends and prospects. Mitig Adapt Strateg Glob Chang. 2010;15:169-184.
10. Olsson L, *et al*. Livelihoods and poverty. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Cambridge (UK): Cambridge Univ. Press; 2014. p. 793-832.
11. Nelson GC, Rosegrant MW, Palazzo A, Gray I, Ingersoll C, Robertson R, *et al*. Food security, farming, and climate change to 2050: scenarios, results, policy options. Washington (DC): IFPRI; 2010. http://doi.wiley.com/10.1111/an.1995.36.5.41
12. Lobell DB, Schlenker W, Costa-Roberts J. Climate trends and global crop production since 1980. Science. 2011;333(6042):616-620.
13. Lobell DB, Gourdji SM. The influence of climate change on global crop productivity. Plant Physiol. 2012;160:1686-1697.
14. Wiebe KD, Lotze-Campen H, Sands RD, Tabeau A, van der Mensbrugghe D, Biewald A, *et al*. Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. Environ Res Lett. 2015;10(8):085010.
15. Pugh TAM, Müller C, Elliott J, Deryng D, Folberth C, Olin S, *et al*. Climate analogues suggest limited potential for intensification of production on current croplands under climate change. Nat Commun. 2016;7:12608.
16. Mora C, Caldwell IR, Caldwell JM, Fisher MR, Genco BM, Running SW. Suitable days for plant growth disappear under projected climate change: potential human and biotic vulnerability. PLoS Biol. 2015;13(6):e1002167.
17. Morton JF. The impact of climate change on smallholder and subsistence agriculture. Proc Natl Acad Sci U S A. 2007;104(50):19680-19685.
18. World Bank. World Development Report 2010: Development and Climate Change. Washington (DC): World Bank; 2009.
19. Rosegrant MW, Koo J, Cenacchi N, Ringler C, Robertson R, Fisher M, *et al*. Food Security in a World of Natural Resources: The Role of Agricultural Technologies. Washington (DC): IFPRI; 2014.
20. Smith P, Bustamante M, Ahammad H, Clark H, Dong H, Elsiddig EA, *et al*. Agriculture, forestry, and other land use (AFOLU). In: Mitigation of Climate Change: Contribution of Working Group III to the Fifth Assessment Report of the IPCC. Cambridge (UK): Cambridge Univ. Press; 2014. p. 811-922.
21. United Nations Framework Convention on Climate Change (UNFCCC). Paris Agreement. United Nations Treaty Collection; 2015. https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d
22. UNFCCC. Decision 4/CP.23. Report of the Conference of the Parties on its twenty-third session, held in Bonn from 6 to 18 November 2017. Bonn: UNFCCC; 2018.
23. IPCC. Global Warming of 1.5°C: Summary for Policymakers. Geneva: World Meteorological Organization; 2018. p. 1-32.
24. Frank S, Havlík P, Soussana JF, Levesque A, Valin H, Wollenberg E, *et al*. Reducing greenhouse gas emissions in agriculture without compromising food security? Environ Res Lett. 2017;12:105001.
25. Hasegawa T, Fujimori S, Havlik P, Valin H, Bodirsky BL, Doelman JC, *et al*. Risk of increased food insecurity under stringent global climate change mitigation policy. Nat Clim Chang. 2018;8(8):699-703.
26. IPCC. Climate Change: Synthesis Report. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the IPCC. Geneva: IPCC; 2014.
27. IPCC. Summary for Policymakers of IPCC Special Report on Global Warming of 1.5 °C. Cambridge (UK): Cambridge Univ. Press; 2018.
28. Lipper L, Thornton P, Campbell BM, Baedeker T, Braimoh A, Bwalya M, *et al*. Climate-smart agriculture for food security. Nat Clim Chang. 2014;4:1068-1072.
29. Leisner CP. Review: Climate change impacts on food security—focus on perennial cropping systems and nutritional value. Plant Sci. 2020;7:110412.

30. Hossain MS, Lu Q, Arshad M, Shahid S, Fahad S, Akhter J. Climate change and crop farming in Bangladesh: an analysis of economic impacts. Int J Clim Chang Strateg Manag. 2019;7:424-440.
31. Arshad M, Kächele H, Krupnik TJ, Amjath-Babu TS, Aravindakshan S, Abbas A, *et al*. Climate variability, farmland value, and farmers' perceptions of climate change: implications for adaptation in rural Pakistan. Int J Sustain Dev World Ecol. 2016;11:532-544.
32. Jat ML, Chakraborty D, Ladha JK, Parihar CM, Datta A, Mandal B, *et al*. Carbon sequestration potential, challenges, and strategies towards climate action in smallholder agricultural systems of South Asia. Crop Environ. 2022;1:86-101.
33. Amundson R, Beaudeau L. Soil carbon sequestration is an elusive climate mitigation tool. Proc Natl Acad Sci U S A. 2018;115:11652-11656.
34. Food and Agriculture Organization of the United Nations. Climate-Smart Agriculture: Sourcebook. Rome: FAO; 2013.
35. Adger WN, Arnell NW, Tompkins EL. Successful adaptation to climate change across scales. Glob Environ Change. 2005;15:77-86.
36. Thornton PK, Whitbread A, Baedeker T, Cairns J, Claessens L, Baethgen W, Keating B. A framework for priority-setting in climate-smart agriculture research. Agric Syst. 2018;167:161-175.
37. Makate C. Effective scaling of climate-smart agriculture innovations in African smallholder agriculture: a review of approaches, policy, and institutional strategy. Environ Sci Policy. 2019;96:37-51.
38. Buruchara R, Chirwa R, Sperling L, Mukankusi C, Rubyogo JC, Mutonhi R, *et al*. Development and delivery of bean varieties in Africa: the Pan-Africa bean research alliance (PABRA) model. Afr Crop Sci J. 2011;19:227-245.
39. Fisher M, Carr ER. The influence of gendered roles and responsibilities on the adoption of technologies that mitigate drought risk: the case of drought-tolerant maize seed in eastern Uganda. Glob Environ Change. 2015;35:82-92.
40. Khumairoh U, Lantinga EA, Schulte RPO, Suprayogo D, Groot JCJ. Complex rice systems to improve yield and stability under variable weather conditions. Sci Rep. 2018;8:14746.
41. Assefa Y, Yadav S, Mondal MK, Bhattacharya J, Parvin R, Sarker SR, *et al*. Crop diversification in rice-based systems in the polders of Bangladesh: yield stability, profitability, and risk. Agric Syst. 2021;187:102986.
42. Mhlanga B, Pellegrino E, Thierfelder C, Ercoli L. Conservation agriculture practices drive maize yield by regulating soil nutrient availability, arbuscular mycorrhizas, and plant nutrient uptake. Field Crops Res. 2022;277:108403.
43. Zhao J, Chen J, Beillouin D, Lambers H, Yang YD, Smith P, *et al*. Global systematic review with meta-analysis reveals yield advantage of legume-based rotations and its drivers. Nat Commun. 2022;13:4926.
44. Astor T, Dayananda S, Nautiyal S, Wachendorf M. Vegetable crop biomass estimation using hyperspectral and RGB 3D UAV data. Agronomy. 2020;10:1600.
45. Jurado JM, Ortega L, Cubillas JJ, Feito FR. Multispectral mapping on 3D models and multi-temporal monitoring for individual characterization of olive trees. Remote Sens. 2020;12:1106.
46. Huang YB, Chen ZX, Yu T, Huang XZ, Gu XF. Agricultural remote sensing big data: management and applications. J Integr Agric. 2016;17:1915-1931.
47. Rejeb A, Rejeb K, Abdollahi A, Al-Turjman F, Treiblmaier H. The interplay between the Internet of Things and agriculture: a bibliometric analysis and research agenda. Internet Things. 2022;19:100580.
48. Wolfert S, Isakhanyan G. Sustainable agriculture by the Internet of Things: a practitioner's approach to monitor sustainability progress. Comput Electron Agric. 2022;200:107226.