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Original Article

Enhancing Crop Productivity and Reducing Carbon Footprints through Climate-Smart Cropping Approaches

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Abstract: *Addressing the dual challenges of a growing global population and climate change is essential for ensuring food security and sustainable agriculture. By 2050, agricultural output must rise by 60%, yet climate variability continues to disrupt farming systems through erratic weather, degraded soils, and extreme events. Traditional farming practices contribute significantly to greenhouse gas (GHG) emissions, intensifying climate impacts. Climate-Smart Cropping Systems (CSCS) offer a strategic alternative to boost productivity, build resilience, and lower environmental footprints.This review explores key elements of Climate-Smart Agriculture (CSA), including conservation agriculture, precision farming, agroforestry, integrated nutrient management, and water-efficient techniques. These practices improve soil quality, enhance biodiversity, optimize input use, and strengthen climate resilience. Examples from Bangladesh—such as floating gardens, gher farming, and flood-tolerant crops—illustrate localized CSA strategies.Despite proven benefits, large-scale adoption faces obstacles like high initial investments, limited technical know-how, and insufficient policy frameworks. Advancing CSA requires improved climate information services, robust extension support, and cross-sectoral collaboration. Ultimately, CSCS presents a viable pathway for increasing food production while mitigating climate change, contingent on sustained investments in research, innovation, and institutional backing.*

Keywords: *Climate-Smart Agriculture (CSA), Sustainable Agriculture, Food Security, Resilient Cropping Systems, Greenhouse Gas Emissions.*

I. INTRODUCTION

With the global population expected to surpass 9 billion by 2050, the demand for food will increase substantially, requiring a 60% rise in global food production over the coming decades [1]. However, agricultural systems worldwide are increasingly vulnerable to the adverse impacts of climate change [2]. Unpredictable weather patterns, more frequent and severe droughts and floods, and declining soil fertility are already contributing to reduced crop yields. Climate change—manifested through rising temperatures, shifting precipitation regimes, and heightened climate variability—is projected to significantly disrupt crop productivity and alter regional agricultural zones, posing serious threats to global food security [3]. In Bangladesh, agriculture is highly sensitive to climatic conditions such as temperature, rainfall, humidity, and day length. The sector is frequently impacted by natural disasters, including floods, droughts, cyclones, and salinity intrusion, which are anticipated to intensify with continued climate change and sea-level rise. Future projections indicate increasing occurrences of waterlogging and flooding in central regions, flash floods in the northeast, prolonged droughts in the northwest and southwest, and escalating salinity and coastal inundation in the southern coastal areas. These threats demand a profound transformation of agricultural practices, particularly in developing nations, to secure food and nutritional needs amid growing climate uncertainty [4]. Reducing the vulnerability of agricultural systems to climate change necessitates both building resilience among farmers and minimizing greenhouse gas (GHG) emissions. Conventional farming methods, heavily reliant on chemical inputs and water-intensive practices, significantly contribute to GHG emissions and environmental degradation. In contrast, Climate-Smart Cropping Systems (CSCS) offer a more sustainable path forward. These systems integrate climate-resilient strategies—such as soil health management, resource-efficient input use, and innovative agricultural technologies—to enhance productivity while reducing environmental impacts.The broader framework of Climate-Smart Agriculture (CSA) strengthens the adaptive capacity of farmers, extension workers, researchers, and policymakers. By promoting environmentally sound practices, CSA helps safeguard food and nutritional security and

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improve the livelihoods of climate-vulnerable communities. This review explores how CSCS contributes to increasing agricultural productivity, minimizing carbon emissions, and fostering long-term sustainability in food systems.

II. REVIEW AND DISCUSSION

A. Understanding the Concept of Climate-Smart Agriculture

Climate-Smart Agriculture (CSA) is a comprehensive approach that aims to sustainably increase agricultural productivity, strengthen resilience to climate change, and reduce or remove greenhouse gas (GHG) emissions from the farming sector [4]. First introduced in 2009, CSA has emerged as a vital strategy for adapting to the impacts of climate change and aligning agricultural development with environmental sustainability goals [5],[6]. Through the application of innovative technologies, CSA enhances soil fertility, improves water-use efficiency, and promotes sustainable land management, thereby contributing to the long-term viability of food production systems.

Despite its promise, CSA implementation remains hindered by various obstacles, including limited conceptual clarity, insufficient policy frameworks, inadequate prioritization, and a lack of financial support for innovative practices[7]. The CSA framework is structured around three fundamental pillars: (1) increasing agricultural productivity; (2) enhancing adaptation and resilience; and (3) reducing or eliminating GHG emissions.

The adaptation and resilience components focus on empowering farmers, communities, and national systems to cope with the adverse effects of climate variability. Adaptation involves proactive strategies to mitigate anticipated risks, while resilience emphasizes the capacity to recover from unexpected climate-induced disruptions[8]. According to [9] these pillars can be summarized as follows:

- Sustainable Productivity: Enhancing yields and outputs from crops, livestock, fisheries, and related services to ensure food and nutritional security and increase farm incomes.
- Adaptation and Resilience: Strengthening the capacity of farming systems through methods such as conservation agriculture, diversified cropping patterns, integrated pest and nutrient management, and improved water-use practices to buffer both short- and long-term climate shocks.
- GHG Mitigation: Reducing emissions by curbing deforestation, adopting agroforestry, and implementing low-emission agricultural technologies that sequester carbon and contribute to a more stable climate.

Unlike a one-size-fits-all solution, CSA is a flexible, context-specific approach. It builds upon principles of sustainable agriculture, ecosystem stewardship, and integrated land and water resource management. This adaptability is particularly critical in developing countries, where agriculture plays a central role in economic growth and livelihoods.

B. Evolution of the Climate-Smart Agriculture Framework

The development of CSA is rooted in global efforts to reconcile agricultural productivity with climate action. Recognizing the multifaceted goals of economic viability, social equity, and environmental protection, the Food and Agriculture Organization (FAO) proposed CSA as a means to balance short- and long-term objectives in agricultural policy and practice. The concept gained formal recognition at the 2010 Hague Conference on Agriculture, Food Security, and Climate Change, though its foundational ideas were introduced earlier in FAO's 2009 report, Food Security and Agricultural Mitigation in Developing Countries. At the time, agriculture's critical role in climate adaptation and mitigation was underrepresented in international policy discussions, and the divide between adaptation and mitigation negotiations limited synergistic approaches. The early articulation of CSA emphasized agriculture's dual role: its vulnerability to climate impacts and its contribution to GHG emissions. It called for a transformation of agriculture to serve both food security and climate objectives [10]. Following the Hague conference, two parallel global initiatives—focused on policy and science—paved the way for the formation of the Global Alliance for Climate-Smart Agriculture (GACSA), aiming to coordinate international CSA efforts.

Key Components of Climate-Smart Cropping Systems and Their Role in Enhancing Productivity and Reducing Carbon Emissions

C. Conservation Agriculture (CA)

Conservation Agriculture is a central component of CSA that promotes long-term soil health and sustainability through three core principles: minimal soil disturbance, permanent soil cover, and crop diversification. These interrelated practices collectively improve soil organic matter, enhance water retention capacity, and reduce land degradation [11].

- Minimal Soil Disturbance: Reducing tillage helps maintain soil structure, conserves organic carbon, and supports beneficial microbial activity. No-till or reduced-till practices minimize CO_2 emissions from soil and improve overall soil fertility.
- Permanent Soil Cover: The use of cover crops or retention of crop residues shields the soil from erosion, enhances moisture conservation, and contributes to the buildup of soil organic carbon.

- Crop Diversification: Implementing crop rotations and intercropping disrupts pest and disease cycles, improves nutrient cycling, and reduces dependence on synthetic fertilizers and pesticides.

Through these practices, CA not only improves soil structure and fertility but also reduces GHG emissions by decreasing reliance on chemical inputs and fostering carbon sequestration. Studies have shown that conservation agriculture enhances resilience to climate variability while contributing to environmental sustainability [12].

D. Precision Agriculture

Precision Agriculture (PA) leverages advanced technologies such as remote sensing, GPS-guided equipment, and variable rate technologies (VRT) to optimize the use of agricultural inputs, thus minimizing waste and reducing environmental impact. These technologies enable farmers to apply water, fertilizers, and pesticides in precise amounts at specific times and locations, improving both efficiency and sustainability.

- Remote Sensing and GIS: These tools enable continuous monitoring of soil health and crop conditions, aiding in more informed and accurate decision-making.
- Variable Rate Application: By applying inputs only where and when needed, this technique prevents overuse and reduces emissions associated with excessive input application.
- Automated Irrigation Systems: These systems help conserve water and energy, contributing to more sustainable farming practices.

By utilizing technologies such as GPS, remote sensing, and Internet of Things (IoT)-based sensors, PA ensures that resources like water, fertilizers, and pesticides are applied optimally. This reduces environmental degradation, increases input efficiency, and lowers emissions, thereby contributing to climate-smart agriculture [13].

E. Agroforestry

Agroforestry is an integrated approach that incorporates trees and shrubs into cropping systems, enhancing biodiversity, improving soil fertility, and promoting carbon sequestration. This practice offers a holistic solution to sustainable farming by delivering key ecosystem services, such as improved water retention, windbreaks, and erosion control [14].

- Carbon Sequestration: Trees absorb carbon dioxide (CO_2) from the atmosphere, reducing the carbon footprint of farming.
- Biodiversity Enhancement: Agroforestry systems support a diverse range of organisms, helping to maintain ecological balance.
- Soil Fertility Improvement: The roots of trees help structure the soil and enhance nutrient cycling, boosting crop yields.

Agroforestry systems, by combining crops with trees, also provide additional income streams and help mitigate the effects of climate change. The presence of trees on farmland captures carbon, reduces soil erosion, and creates a favorable microclimate for crop growth [15].

F. Integrated Nutrient Management (INM)

Integrated Nutrient Management (INM) focuses on balancing organic and inorganic fertilizers to maintain soil fertility while minimizing the environmental impacts of agricultural practices. By integrating biofertilizers, compost, and green manure, INM enhances microbial activity in the soil and reduces dependency on synthetic fertilizers, which are significant contributors to greenhouse gas emissions [16].

G. Water-Smart Practices

Water-smart practices such as drip irrigation, rainwater harvesting, and deficit irrigation techniques enhance water-use efficiency while maintaining crop yields. These methods help reduce energy consumption associated with irrigation systems and facilitate adaptation to water-scarce conditions.

- Planting Pits: Techniques like zai and half-moon pits, used for water retention, have proven effective in Sahelian regions of West Africa for the production of drought-resistant crops like sorghum and millet [7].

By improving water conservation, these practices mitigate the risks associated with water scarcity, support drought resilience, and reduce the environmental footprint of irrigation systems.

H. Cover Cropping and Green Manuring

Cover cropping involves planting crops during off-seasons to maintain soil health, improve moisture retention, and reduce erosion. Green manuring refers to growing nitrogen-fixing plants and incorporating them into the soil to enhance organic matter content, improving soil fertility.

- Soil Protection: Cover crops reduce erosion and help retain soil moisture.

- Nitrogen Fixation: Leguminous cover crops naturally enrich the soil, reducing the need for synthetic fertilizers.
- Weed and Pest Control: These crops help smother weeds and attract beneficial insects, reducing the need for herbicides and pesticides.

By implementing cover crops and green manuring, farmers can boost soil fertility, decrease environmental degradation, and enhance ecosystem health [17].

I. System of Rice Intensification (SRI)

The System of Rice Intensification (SRI) is an innovative rice farming method that improves productivity while reducing water and chemical inputs. It involves transplanting younger seedlings at wider spacing and using intermittent irrigation instead of continuous flooding.

- Water Conservation: Intermittent wetting and drying reduces methane emissions, which are typically associated with traditional rice farming methods.
- Improved Root Systems: Wider spacing allows rice roots to grow deeper, enhancing nutrient uptake.
- Higher Yields: Studies demonstrate that SRI can increase rice production by 20-50%, while also lowering input costs.

This method promotes water conservation, reduces methane emissions, and improves the overall efficiency and sustainability of rice production [18].

J. Diversified Cropping Systems

Diversification through intercropping, crop rotation, and polyculture enhances agricultural resilience to climate variability. These practices improve soil fertility and increase production while mitigating risks associated with extreme weather events.

- Pest and Disease Control: Crop diversification disrupts pest cycles and reduces the reliance on chemical controls.
- Nutrient Cycling: Different crops contribute unique nutrients to the soil, enhancing its overall health and productivity.
- Climate Resilience: By diversifying crops, farmers can better withstand the shocks of unpredictable weather patterns.

Diverse cropping systems also improve the sustainability of agricultural landscapes and contribute to long-term food security [19].

K. Cash Transfers for Building Resilience

In regions where financial markets are underdeveloped, cash transfer programs can help smallholder farmers enhance their resilience. By providing predictable financial support, these programs enable farmers to invest in climate-resilient practices, such as improved irrigation or crop diversification, thereby increasing both productivity and income [6].

L. Technological Innovations

Climate-resilient crop varieties and improved livestock breeds are crucial components of CSA. These innovations focus on increasing productivity and improving tolerance to climate stresses such as temperature fluctuations, drought, and floods. By selecting for climate-resistant traits, these improved varieties help secure food systems against the evolving challenges posed by climate change.

M. Climate Technologies for Mitigating Water Risks

Technologies that address water-related risks are critical in regions vulnerable to flooding. Flood hazard mapping plays a pivotal role in identifying at-risk zones, enabling the implementation of preventative and adaptive measures tailored to local contexts. Complementing this, early flood warning systems offer advanced alerts to communities, allowing timely actions that can significantly reduce potential damage. These tools are particularly effective in flood-prone regions, where proactive planning is essential to agricultural sustainability and disaster resilience.

N. Climate-Smart Cropping Approaches in Bangladesh

In Bangladesh, Climate-Smart Agriculture (CSA) technologies present promising solutions for simultaneously addressing climate change and advancing agricultural development. Within the national context, CSA practices are those that not only contribute to food security but also enhance climate resilience and/or mitigate environmental impacts.

Many of these CSA strategies are rooted in traditional knowledge, particularly in the southern coastal plains, where communities have adapted to recurring climate hazards such as flooding and cyclones. Gher farming, originally designed for shrimp aquaculture, has evolved into a multifunctional system integrating fish, prawns, and vegetable cultivation. Raised dikes around ponds now support trellised vine crops, while floating vegetable gardens, constructed from water hyacinth layered with soil, have been revived and scaled to manage tidal flooding. Crops like kangkong (water spinach), once grown near ponds, are now cultivated more extensively using improved varieties.

In persistently waterlogged areas, farmers have adopted techniques such as the Sorjan system—raised planting beds alternated with water-filled furrows used for fish or submergence-tolerant crops. Rice field fish rings, small concrete structures placed in rice paddies, protect fish during dry spells and are becoming more widespread. The cultivation of small indigenous fish species in irrigation canals and ponds provides both nutritional benefits and supplementary income, especially for resource-constrained farmers.

Although some of these practices have existed for decades, their uptake remains limited in northern and southern Bangladesh. Variants like the 'hari' system—where freshwater fish are cultivated during the rainy season and excess water is drained to enable boro rice cultivation—demonstrate locally adapted solutions [20].Scaling these practices will require institutional support, particularly in identifying appropriate crop varieties, improving access to technology and credit, and disseminating best practices.

Salinity intrusion, exacerbated by sea-level rise, has emerged as a major challenge, especially in coastal zones. The use of salt- and flood-tolerant crop varieties has proven effective, but adoption remains slow due to a delayed seed distribution pipeline and poor market dissemination. Despite this, there have been notable improvements in the adoption of submergence-tolerant rice varieties in flash flood-prone areas over the past decade. In saline winter conditions, innovative practices such as vegetable towers—stacked containers of soil-supported by bamboo and polythene—offer a means of continuing food production when land becomes unsuitable.

O. Challenges to CSA Adoption in Bangladesh

Small-scale farmers face several systemic barriers to adopting CSA practices. These include limited access to affordable credit, an insufficient number of extension workers to deliver knowledge and technologies at scale, and underdeveloped financing and insurance mechanisms. For instance, while index-based crop insurance was piloted through a partnership between Oxfam and a private insurer, the absence of a viable business model has hindered national expansion.

P. Impact of Climate-Smart Cropping Systems (CSCS)

Climate-Smart Cropping Systems (CSCS) have been shown to improve agricultural outcomes across multiple dimensions:

a) Improvements in Crop Production:

- Enhanced soil structure and fertility
- Greater resilience to climate variability [21].
- Higher crop yields and improved quality [22].
- More efficient utilization of inputs and resources [23].
- Reduced input costs and minimized environmental degradation .

b) Reduction of Carbon Footprints:

- Increased soil organic carbon storage [24].
- Lower reliance on synthetic fertilizers and pesticides
- Greater energy efficiency through low-emission technologies [25].
- Adoption of carbon-neutral farming methods [26].

Q. Policy Implications and Institutional Support

Despite their proven benefits, the widespread adoption of CSCS is impeded by structural and policy-related challenges. These include high initial investment requirements, inadequate technical training, and fragmented or non-supportive agricultural policies. To address these barriers, both national governments and international agencies must develop enabling policy frameworks, provide financial incentives for sustainable practices, and invest in research, innovation, and extension services that facilitate CSA scaling [27], [28].

R. Future Research Direction

Ongoing research is essential to unlock the full potential of CSCS. Key areas for future exploration include:

- Development of climate-resilient crop varieties and livestock breeds
- Expansion of digital agriculture technologies and decision-support tools
- Longitudinal studies on the socio-economic and environmental impacts of CSCS
- Cross-disciplinary, participatory approaches that engage farmers and stakeholders in co-creation of solutions

III. CONCLUSION

Addressing climate change within agriculture requires the advancement of both adaptation and mitigation strategies. The effective implementation of Climate-Smart Agriculture (CSA), particularly through Climate-Smart Cropping Systems (CSCS), is essential to meeting the dual objectives of enhancing food production and reducing environmental impacts. By integrating practices such as conservation agriculture, precision farming, agroforestry, and efficient resource management, CSCS not only improves agricultural productivity but also minimizes greenhouse gas emissions and environmental degradation.

To facilitate the broader adoption and operational success of CSA, the following strategic recommendations are proposed:

- Enhance Climate Information Services: Strengthen the generation, accessibility, and dissemination of climate-related information to support timely and informed decision-making by farmers, researchers, and policymakers.
- Strengthen Technical Advisory Services**:** Equip extension agents with robust technical knowledge of CSA practices to support widespread implementation and contribute to emission reductions.
- Promote Institutional Coordination: Foster greater collaboration and coordination among governmental and non-governmental institutions involved in CSA initiatives to ensure cohesive and sustainable agricultural development.
- Encourage Multi-Stakeholder Engagement: Establish and support platforms that bring together stakeholders from research, policy, extension, and farming communities to share experiences, build capacity, and coordinate actions.
- Leverage Local Information Hubs: Utilize existing infrastructure, such as the Agricultural Information Service (AIS) at Union Parishad complexes, to develop village-level knowledge hubs under the Department of Agricultural Extension (DAE) for more effective grassroots outreach and CSA knowledge dissemination.

In conclusion, realizing the full potential of climate-smart cropping systems will depend on sustained investments in research, capacity building, infrastructure development, and inclusive policymaking that bridges the gap between innovation and on-the-ground implementation.

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