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# Climate-Smart Agriculture

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Global warming, driven primarily by anthropogenic greenhouse gas (GHG) emissions, has intensified climate change, resulting in extreme weather events, heat waves, and droughts that adversely affect agricultural productivity, farmers' income, and food security. Agriculture contributes significantly to global GHG emissions through soil organic matter decomposition, crop residue burning, methane emissions from rice fields and livestock, and nitrous oxide emissions from agricultural soils and fertilizers. **Climate-Smart Agriculture (CSA)** has emerged as an integrated approach to address climate change through three major objectives: (i) sustainably increasing agricultural productivity and farmers' income, (ii) enhancing climate resilience and adaptation, and (iii) reducing GHG emissions. Major CSA practices include climate-resilient crop varieties, efficient water management, conservation agriculture, crop diversification, integrated nutrient management, and advanced technologies such as remote sensing, IoT, and artificial intelligence. Despite its potential to improve productivity, resource-use efficiency, and environmental sustainability, CSA faces several technological, economic, and institutional challenges. Therefore, understanding its recent advancements, adoption constraints, and future prospects is essential for promoting climate-resilient agriculture, ensuring food security, and achieving sustainable agricultural development.

## Definition and Development Goals of CSA

The Food and Agriculture Organization (FAO) formally introduced the concept of Climate-Smart Agriculture (CSA) at the Hague Conference in 2010 as an approach to addressing climate change and ensuring food security. CSA integrates economic, social, and environmental dimensions to promote sustainable agricultural development and climate resilience. Its three major objectives are: (i) sustainably increasing agricultural productivity and farmers' income, (ii) enhancing adaptation and resilience to climate change, and (iii) reducing GHG emissions and enhancing carbon sequestration. The implementation and prioritization of these objectives depend on local agro-climatic conditions, socio-economic circumstances, and regional agricultural priorities.

## Recent Advancements of CSA in Different Countries

### CSA in Developing Countries

In developing countries, agriculture plays a vital role in economic growth and food security but is increasingly threatened by climate change. Therefore, CSA prioritizes improving agricultural productivity, ensuring food security, and strengthening farmers' livelihoods, while progressively reducing GHG emissions through sustainable practices. Several countries have adopted region-specific CSA strategies to address these challenges. In Maharashtra, India, water conservation practices such as rainwater harvesting, drip irrigation, sprinkler irrigation, and integrated nutrient management improve water-use efficiency, crop

productivity, and reduce input requirements. In Vietnam's Mekong Delta, improved rice varieties, optimized sowing and harvesting schedules, balanced fertilizer application, and efficient irrigation enhance crop yields and reduce production costs. In Nepal, conservation practices such as zero tillage, crop rotation, and crop residue incorporation improve soil health, water-use efficiency, and wheat productivity while reducing soil erosion [33]. Similarly, in Pakistan, laser land levelling, improved sowing methods, efficient water management, and climate-resilient cotton varieties enhance crop quality and contribute to reducing environmental impacts.

**CSA in Developed Countries**

In developed countries, CSA primarily focuses on reducing GHG emissions, enhancing climate resilience, and improving agricultural resource-use efficiency through advanced technologies, effective policies, and sustainable management practices [39]. In California, USA, strategies such as methane emission reduction, improved water management, drip irrigation, and efficient irrigation systems contribute to sustainable agricultural production. European countries emphasize precision agriculture, ecosystem services, and renewable energy technologies to minimize environmental impacts. For instance, France integrates satellite data and agricultural models for precision farming, Switzerland promotes farm waste recycling through biogas production, the Netherlands adopts energy-efficient LED technology in horticulture, and Cyprus uses agricultural robots for precise pesticide application. These initiatives demonstrate the potential of region-specific CSA practices to reduce GHG emissions, improve resource-use efficiency, strengthen climate resilience, and promote sustainable agricultural development.

## Challenges in CSA

Shortage of Agricultural Water Resources

**Water Security and Agricultural Sustainability**

Water security is essential for food security and sustainable agriculture. Increasing water scarcity, driven by climate variability, droughts and heat waves, poses a major challenge to agricultural productivity and Climate-Smart Agriculture (CSA), with global water demand projected to rise by 55%. Water deficits negatively affect crop yield, nutritional quality and water use efficiency, as reported in sweet corn in Turkey and dryland regions of China. Integrated water and nutrient management can help improve crop performance and ecological restoration under water-scarce conditions. Therefore, assessing agricultural water availability and future supply-demand patterns under climate change is crucial for sustainable water management and strengthening CSA.

**Climate Variability and Climate Change**

Human-induced climate change threatens global food security and the sustainable development of Climate-Smart Agriculture (CSA). Rising temperatures, irregular rainfall, extreme weather events, and increased $CO_2$ concentrations adversely affect crop productivity, farmers' income, and nutritional security, particularly in developing countries. These impacts vary regionally, causing yield reductions in some areas while benefiting others. Increasing droughts, floods, and climatic uncertainties further threaten agricultural sustainability and alter crop distribution and nutritional quality. Therefore, adopting climate-resilient agricultural practices is essential to enhance productivity, reduce greenhouse gas emissions, and ensure long-term food security.

**Agricultural GHG Emissions**

Agricultural greenhouse gas (GHG) emissions pose a major challenge to the sustainable development of Climate-Smart Agriculture (CSA). Fossil fuel consumption, land-use changes, deforestation, and intensive farming practices contribute significantly to global GHG emissions, causing climate change and ecosystem imbalance. Agriculture is a major source of non-$CO_2$ emissions, particularly methane and nitrous oxide. However, it also offers considerable potential for emission reduction through sustainable practices. Climate-smart technologies, such as renewable energy, clean energy alternatives, carbon sequestration,

improved crop varieties, and climate-adaptive farming systems, can help reduce emissions, enhance agricultural productivity, and ensure long-term food security.

**Information Resource Integration**

The effective production, management, transportation, and marketing of Climate-Smart Agriculture (CSA) depend heavily on reliable agricultural information and data. Ensuring data accuracy, accessibility, and security is therefore essential for its sustainable development. However, CSA faces several information-related challenges, including inadequate standardization, incomplete data collection and management, and limited accuracy and reliability of agricultural data. Furthermore, real-time information sharing remains difficult, while concerns regarding data security continue to increase. The growing volume of agricultural information also creates challenges in identifying and filtering misleading or inaccurate data, which may hinder the effective implementation and long-term development of CSA.

## Conclusion

This review examines the recent progress, major challenges, and future prospects of Climate-Smart Agriculture (CSA) across selected developed and developing countries. Although significant advancements have been achieved, CSA continues to face several constraints, including limited availability of agricultural water resources, increasing climate variability, climate change impacts, greenhouse gas emissions, and inadequate integration of agricultural information systems. Future development should focus on strengthening agricultural information security through advanced internet technologies, adopting improved cropping systems and farm management practices, expanding Internet-based weather services, enhancing agricultural advisory services, and promoting weather index-based insurance to improve agricultural resilience and sustainability.

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