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Climate-smart agriculture: Strategies for resilient farming systems

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Abstract
Climate change poses significant threats to global food security and agricultural livelihoods. Climate-Smart Agriculture (CSA) offers a holistic approach to address these challenges by sustainably increasing agricultural productivity, enhancing resilience to climate change, and reducing greenhouse gas emissions. This paper examines key CSA strategies, including conservation agriculture, efficient water management, improved livestock management, climate-resilient crop varieties, and climate information services. We discuss the strengths and weaknesses of each strategy, highlighting their potential impacts on soil health, water resources, biodiversity, and farmer livelihoods. Furthermore, we emphasize the importance of context-specific implementation, considering the unique agro-ecological, socio-economic, and technological contexts of different farming systems. By integrating these strategies and fostering strong partnerships among farmers, researchers, and policymakers, we can build more resilient and sustainable agricultural systems that can withstand the impacts of climate change and ensure food security for future generations.

Keywords: Climate change, food security, resilience, climate smart agriculture (csa), sustainable agriculture

Introduction
Climate-Smart Agriculture (CSA) is an integrated approach to agriculture that aims to sustainably increase agricultural productivity and incomes, adapt to climate change, enhance resilience to climate change, and reduce greenhouse gas emission. It is a multifaceted approach that considers the interconnectedness of environmental, social, and economic factors. Particularly in developing nations, farmers have modified their farming methods to accommodate the shifting climate and other difficulties (Nyasimi *et al*., 2017) [12]. Improved fodder production, the use of novel crop and animal breeds, water conservation technology, and soil and land management techniques are some of the ways that agricultural methods are evolving to target both livestock and crop productions (Sattar *et al*., 2017) [16]. These technologies (also known as CSA technologies) and practices are expected to improve food security, adaptive capability, and climate change mitigation in resource-poor small-scale agricultural systems (Hellin and Fisher, 2019) [7].
The detrimental effects of climatic variability on agriculture can be considerably mitigated by using CSA technology and practices separately or in combination (Ali and Erenstein, 2017) [1]. Another definition of CSA is a contemporary agricultural system that can: i) boost yields, ii) manage climate extremes, and iii) help find answers to climate change. According to Chandra *et al*. (2018) [4], CSA systems are made to maximize input consumption and use efficient management techniques following harvest. The goal of the CSA system is to improve productivity and adaptability while lowering (mitigating) greenhouse gas emissions, with a focus on contemporary agricultural practices (World Bank, 2011) [18]. In addition, CSA is different from "business-as-usual" approaches in that it contributes to the improvement of farmers' adaptive capacity, agricultural production system adaptation, and resource use efficiency by strengthening the coordination of efforts by farmers, researchers, the private sector, civil society, and policymakers (Lipper *et al*., 2014) [10].

According to Rosenstock *et al.* (2016) [15], adaptation and food security are commonly seen as the two most obvious objectives for agricultural development in the context of climate change, out of the three pillars of CSA (Azadi *et al*., 2021) [2]. However, some detractors have questioned the justification for small-scale farmers' CSA mitigation aims, which has led to more thorough discussions regarding the role of mitigation within a larger CSA approach (Lipper *et al*., 2014) [10].

Impact of Climate Change on Agriculture

Global population growth, urbanization, climate change, and environmental stressors have all put enormous strain on the agricultural system's ability to use resources. According to estimates from the United Nations' Food and Agriculture Organization (FAO), in order to feed the world's projected 9 billion people by 2050, food production must rise by at least 60% (FAO, 2014) [5]. Given that one in eight people today experience food insecurity and that climate change and variability have a major impact on agriculture, this presents a serious problem for global agriculture (Ghosh, 2019) [6]. In its Fifth Assessment Report, the Inter-Governmental Panel on Climate Change (IPCC) issued a warning that the world's climate has been changing and would likely continue to do so for some time to come (IPCC, 2014) [9]. By the end of this century, the average global surface temperature is expected to rise by 1.4 to 5.8°C over 1990 levels. Changes in climate variability and the frequency and severity of some extreme climatic events would also occur, resulting in more frequent floods, droughts, cyclones, and glacier retreat over time, as well as uncertain monsoon onsets (IPCC, 2001) [8]. A serious danger to agriculture, climate change has been shown to increase food production instability and negatively impact food security and the livelihoods of millions of people across numerous nations.

The production of crops, fisheries, forestry, and aquaculture would be directly and negatively impacted by rising temperatures and an increase in the frequency of extreme weather events like floods and droughts, according to the IPCC (2014) [9]. According to a number of studies (Brida and Owiyo, 2013; Lobell *et al*., 2012; Prasanna, 2014; Singh *et al*., 2013) [3, 11, 14, 17], rising temperatures, shifting rainfall patterns, and changes in the frequency and severity of extreme weather events could all have a negative impact on agricultural output. According to Porter *et al.* (2014) [13], depending on the region, future temperature scenarios, and anticipated years, the estimated yield loss from climate change can reach up to 35% for rice, 20% for wheat, 50% for sorghum, 13% for barley, and 60% for maize. As a result, climate unpredictability and change are becoming major threats to global food security, especially in developing and impoverished nations. As one of the world's most densely populated regions, South Asia is particularly vulnerable to climate change and unpredictability; without adaptation and mitigation, this could have a significant impact on poverty, food security, and other developmental objectives (IPCC, 2014) [9].

Key Strategies of CSA for Resilient Farming Systems:

There are a few strategies of CSA for resilient farming systems (Chandra *et al*., 2018; Ghosh, 2019; Azadi *et al*., 2021 and Sarma *et al*., 2024) [4, 6, 2, 19] which have been discussed here (fig. 1):

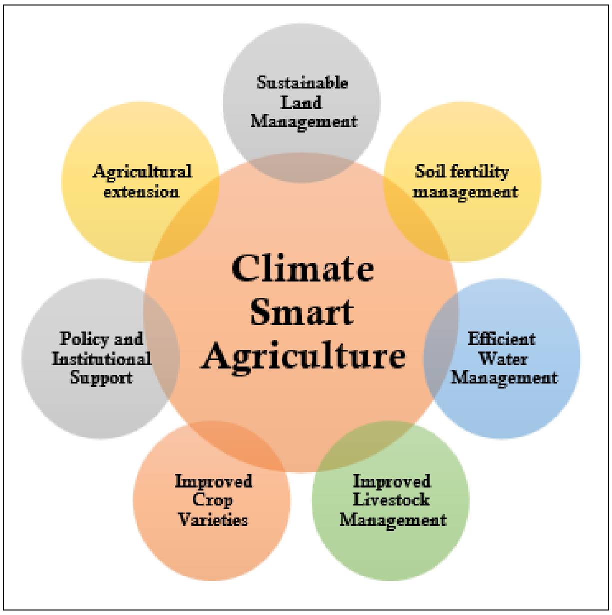

Fig 1: Key Strategies of CSA for Resilient Farming Systems

1. **Sustainable Land Management**

a) **Conservation Agriculture:** Minimizes soil disturbance, maintains permanent soil cover, and promotes crop diversity. This helps to improve soil health, reduce erosion, and enhance water retention. It includes:

- **No-till or Reduced Tillage:** This involves minimizing soil disturbance during cultivation. By leaving crop residues on the surface, it reduces soil erosion (Strong winds and heavy rains can wash away topsoil, leading to nutrient loss and decreased fertility), improves soil structure (Minimizes compaction, allowing for better water infiltration and root growth) and increases organic matter (Crop residues decompose, enriching the soil with nutrients).
- **Crop Rotation:** Instead of planting the same crop year after year, farmers rotate different crops. This breaks disease and pest cycles (Reduces the buildup of pests and diseases specific to one crop), improves soil health (Different crops have varying root structures and nutrient requirements, leading to better soil aeration and nutrient cycling) and increases biodiversity (Supports a wider range of beneficial organisms in the soil).
- **Cover Cropping:** Planting cover crops between main crops

(like legumes, grasses, or brassicas) helps protect soil (Prevents erosion and moisture loss), suppress weeds (Reduces competition for water and nutrients) and improve soil fertility (Some cover crops (legumes) fix nitrogen from the atmosphere, enriching the soil).

b) **Agroforestry:** Integrating trees and shrubs into agricultural landscapes and with crops or livestock. This provides shade, improves soil fertility, and can increase biodiversity.
- **Increases biodiversity:** Provides habitat for pollinators and other beneficial organisms.
- **Improves soil health:** Tree roots improve soil structure and fertility.
- **Mitigates climate change:** Trees absorb carbon dioxide from the atmosphere.

c) **Sustainable Grazing Practices:** Rotational grazing and controlled stocking rates can help to prevent overgrazing and improve pasture quality.

d) **Integrated pest management:** Using a combination of biological, cultural, and chemical methods to control pests while minimizing environmental impact. It reduces reliance on synthetic pesticides, which can harm beneficial insects and pollinate

2. Soil fertility management
CSA places a strong emphasis on sustainable soil management practices. Healthy soils are crucial for increasing agricultural productivity, enhancing resilience to climate change, and reducing greenhouse gas emissions. Here's a detailed list of key soil management strategies for CSA. By implementing these soil management strategies, farmers can enhance soil health, increase agricultural productivity, and build more resilient and sustainable farming systems that can withstand the challenges of climate change.

a. Soil Organic Matter Management
- Composting and Organic Inputs: Incorporating compost, animal manure, and green manure into the soil increases organic matter (Improves soil structure, water-holding capacity, and nutrient availability), enhances microbial activity (Supports a healthy soil ecosystem).
- Cover Cropping for Green Manure: Growing and then tilling cover crops into the soil adds organic matter and nutrients (Enriches the soil with nitrogen, carbon, and other essential elements), improves soil structure (Increases soil porosity and water infiltration).

b. Nutrient Management
Precision Fertilization: Applying fertilizers precisely based on soil tests and crop needs reduces fertilizer waste (Minimizes nutrient runoff and leaching, protecting water quality) and improves fertilizer use efficiency (Ensures crops receive the right amount of nutrients at the right time).Organic Fertilizers: Utilizing organic fertilizers like compost, manure, and green manure improves soil health (Enhances soil structure, water-holding capacity, and nutrient availability), reduces reliance on synthetic fertilizers (Minimizes environmental impact and potential pollution).

c. Soil Health Monitoring
Regular Soil Testing: Assessing soil properties like pH, nutrient levels, and organic matter content provides valuable information (Helps farmers make informed decisions about soil management practices), tracks progress (Monitors the effectiveness of soil health improvement efforts).

3. Efficient Water Management
Use water-saving practices like drip irrigation and rainwater collection to ensure crops receive enough water, even during droughts.

a) **Water Harvesting and Storage:** Collecting and storing rainwater for use during dry periods.

b) **Efficient Irrigation Techniques:** Using drip irrigation or other efficient methods to minimize water loss.

c) **Drought-Tolerant Crops:** Selecting and breeding crops that are more resistant to drought stress.

d) **Precision Irrigation:** This involves using technologies like drip irrigation or sprinklers to deliver water directly to plant roots. This reduces water waste (Minimizes runoff and evaporation, saving water and money), improves water use efficiency (Plants receive the exact amount of water they need), reduces nutrient leaching (Prevents fertilizers from being washed away with excess water) and rainwater Harvesting (Collecting and storing rainwater in tanks or reservoirs: Provides a reliable water source during dry periods, reduces reliance on groundwater, which is often overexploited).

e) **Mulching:** Applying organic or inorganic materials (like straw, plastic, or rocks) around plants reduces evaporation: Prevents soil moisture from escaping into the atmosphere, suppresses weeds: Creates a barrier that prevents weed seeds from germinating, maintains soil temperature: Helps regulate soil temperature, protecting roots from extreme heat or cold.

4. Improved Livestock Management
a) **Improved Feed Efficiency:** Optimizing livestock diets can:
- **Reduce methane emissions:** Some feed additives can decrease the production of methane, a potent greenhouse gas, by ruminant animals (like cows and sheep).
- **Improve animal health and productivity:** A balanced diet leads to healthier animals, which are more efficient at converting feed into meat or milk.

b) **Manure Management:** Proper handling and utilization of manure:
- **Reduces greenhouse gas emissions:** Anaerobic decomposition of manure in open areas releases methane. Proper storage and composting can minimize these emissions.
- **Improves soil fertility:** Manure is a rich source of nutrients for crops.

c) **Silvopasture:** Integrating trees with grazing lands:
- **Provides shade for livestock:** Reduces heat stress during hot weather.
- **Improves soil health:** Tree roots improve soil structure and increase water infiltration.
- **Sequesters carbon:** Trees absorb carbon dioxide from the atmosphere.

5. Improved Crop Varieties
a) **Climate-Resilient Crop Varieties**
- Developing and promoting drought-tolerant, heat-resistant, and pest-resistant crop varieties.
- Early and late planting: Adjusting planting dates to avoid extreme weather events.

b) **Crop diversification:** Growing a variety of crops can help to reduce risk and improve resilience to climate variability. Plant a variety of crops to reduce the risk of adverse weather conditions, pests, and diseases. Diversifying crops can also improve soil health.

6. Policy and Institutional Support

a) Supporting research and development: Investing in research to develop and disseminate climate-smart agricultural technologies and practices.
b) Creating enabling policy environments: Providing incentives for farmers to adopt CSA practices, such as subsidies and tax breaks.
c) Strengthening farmer organizations: Empowering farmers to participate in decision-making processes and access information and resources.

7. Agricultural extension

Provide access to effective agricultural extension services to help farmers adopt climate-resilient crops. Climate Information Services:

a) Providing farmers with access to weather forecasts, climate information, and early warning systems.
b) Developing and disseminating climate-smart agricultural knowledge and practices.
c) Strengthening agricultural extension services to support farmers in adopting CSA practices.

By implementing these strategies, farmers can build more resilient and sustainable agricultural systems that can withstand the challenges of climate change while ensuring food security and livelihoods for future generations.

Critical analysis of different Key Strategies of CSA for Resilient Farming Systems

CSA encompasses a diverse set of strategies, each with unique strengths and weaknesses. Conservation Agriculture focuses on improving soil health through reduced tillage, crop rotation, and cover cropping, offering benefits like reduced erosion and enhanced biodiversity, but may require significant initial investment and careful weed management (Chandra *et al*., 2018) [4]. Efficient Water Management, such as precision irrigation and rainwater harvesting, optimizes water use and reduces waste, but can be costly and require technical expertise. Improved Livestock Management, including optimizing feed and managing manure, reduces greenhouse gas emissions and improves soil fertility, but requires careful planning and may present challenges with odour and pollution (Ghosh, 2019 and Azadi *et al*., 2021) [6, 2]. Climate-Resilient Crop Varieties enhance resilience to climate change by increasing yield stability and ensuring food security, but require long-term research and development. Finally, Climate Information Services empower farmers with weather forecasts and early warning systems, improving decision-making and reducing risk, but may require improved access to information and data interpretation skills. The most effective CSA approach will vary depending on specific conditions and requires careful consideration of synergies and trade-offs between different strategies. (Chandra *et al*., 2018 and Sarma *et al*., 2024) [4, 19].

Conclusion

Comprehensive research on reliable intelligent agriculture tools, like the drones that are now on the market for field spraying, could contribute to the growth of the smart agricultural ecosystem and the fight against climate change. Nevertheless, the environment in which these inventions are used is frequently overlooked in research on them. Certain elements of the intricate, smart agricultural ecosystem—like farm equipment, labor sharing, and organizational choices—are impacted by environmental factors. Smart farming-specific security measures are required due to domain-specific problems such as location, user skill level, insider threats, and generated data. Therefore, before smart farm technology is extensively adopted in the community, more research is required.

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