



Climate-Smart Agriculture and Sustainable Agronomic Practices for Enhancing Crop Productivity and Food Security

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Abstract

Background Climate change intensifies temperature extremes, droughts, floods, and soil degradation, reducing crop yields and threatening global food security, particularly for smallholder farmers in vulnerable regions. Conventional agriculture often exacerbates resource depletion and greenhouse-gas emissions.

Objective This review examines climate-smart agriculture (CSA) principles and sustainable agronomic practices that simultaneously enhance productivity, build resilience, and mitigate emissions to strengthen food security.

Methods A synthesis of peer-reviewed literature (primarily 2018–2025) and authoritative reports from FAO, IPCC, and related bodies was conducted. Focus areas included climate impacts, CSA components, conservation agriculture, nutrient and water management, crop diversification, agroforestry, climate-resilient genetics, and digital technologies.

Results CSA practices such as conservation agriculture, integrated nutrient management, water-smart irrigation, and crop diversification improve soil health, water-use efficiency, and yield stability under stress. Meta-analyses indicate yield gains of 10–38% under climate stress, enhanced soil carbon sequestration, and reduced nitrous oxide emissions. Precision tools—remote sensing, IoT sensors, AI/ML models, and decision-support systems—optimize inputs and enable early risk detection. These interventions support all four dimensions of food security while delivering adaptation and mitigation co-benefits.

Conclusion Integrating sustainable agronomy with digital technologies and resilient cultivars offers a pathway to productive, resilient, and lower-emission agriculture. Persistent barriers include high upfront costs, limited extension services, digital divides, and policy gaps. Scaling requires site-specific approaches, multidisciplinary collaboration, supportive finance, and participatory design to achieve long-term food security and environmental sustainability.

Keywords: Climate-smart agriculture, sustainable agriculture, climate change, crop productivity, food security, soil health, precision agriculture, resource-use efficiency

1. Introduction

Agriculture depends heavily on climate-sensitive resources—rainfall, temperature regimes, and soil fertility. Rising global temperatures, more frequent droughts and floods, irregular rainfall, and extreme weather events are already reducing yields of major staples in many regions ^[1, 2]. Observed climate change has negatively affected maize and wheat productivity in lower-latitude areas while producing mixed effects at higher latitudes ^[3]. Soil degradation, organic-matter decline, and nutrient losses further constrain production ^[4].

These pressures undermine the four dimensions of food security: availability, access, utilization, and stability. Smallholder farmers in developing regions are especially vulnerable because of limited adaptive capacity and high dependence on rain-fed systems ^[5].

Climate-smart agriculture (CSA), introduced by the FAO around 2010, addresses these challenges through three interlinked objectives: (1) sustainably increasing agricultural productivity and incomes; (2) adapting and building resilience to climate change; and (3) reducing or removing greenhouse-gas (GHG) emissions where possible [6, 7]. CSA builds on existing sustainable practices but explicitly integrates climate considerations and evaluates trade-offs among the three pillars.

Conventional high-input systems often achieve short-term yield gains at the expense of soil health, water resources, and emissions intensity. Sustainable agronomic practices—conservation agriculture, integrated nutrient management, diversified rotations, and efficient water use—offer pathways to reverse these trends while maintaining or increasing productivity [8, 9].

Despite growing evidence, gaps remain in the systematic integration of CSA principles with modern genetic and digital technologies under diverse agro-ecological conditions. This review synthesizes current knowledge on climate impacts, CSA components, key agronomic practices, climate-resilient crops, precision and digital tools, food-security outcomes, environmental and socioeconomic benefits, adoption barriers, and future research priorities. The objective is to provide a scientifically grounded overview suitable for researchers, practitioners, and policymakers seeking to enhance crop productivity and food security under climate change.

2. Climate Change and Its Impacts on Agricultural Production

2.1. Temperature and Heat Stress

Elevated temperatures accelerate crop development, shorten grain-filling periods, and reduce yields of heat-sensitive crops such as wheat, maize, and rice. Heat stress during flowering and pollination can cause sterility and lower grain quality [1, 3]. Phenological shifts alter the timing of critical growth stages relative to rainfall and pest cycles.

2.2. Drought and Water Scarcity

Increasing frequency and severity of agricultural droughts

raise irrigation demand while reducing water-use efficiency. Rain-fed systems experience yield instability, and groundwater depletion intensifies in irrigated regions [4].

2.3. Flooding and Extreme Weather Events

Floods cause soil erosion, nutrient leaching, waterlogging, and heightened disease pressure. Extreme rainfall events damage crops and infrastructure, disrupting supply chains [2].

2.4. Soil Degradation and Nutrient Decline

Higher temperatures and intense rainfall accelerate organic-matter decomposition, erosion, salinization, and compaction. Declining soil fertility reduces the buffering capacity of agroecosystems against climate shocks [4, 9].

2.5. Implications for Global Food Security

Climate-driven yield reductions threaten food availability and price stability. Low-income consumers and smallholders face reduced access and utilization; nutritional quality of crops may also decline under elevated CO₂ [3, 5]. Developing regions with limited adaptive capacity are disproportionately affected.

3. Principles and Components of Climate-Smart Agriculture

CSA is a context-specific approach that seeks triple wins of productivity, adaptation, and mitigation [6, 7]. Core components include climate-resilient crop production, sustainable intensification, soil and water conservation, efficient nutrient management, crop diversification, agroforestry, integrated crop–livestock systems, conservation agriculture, and climate information services. Farmer-centered, location-specific design is essential because optimal practices vary by agro-ecology and socioeconomic conditions.

Adaptation (building resilience), productivity (sustainable intensification), and mitigation (emission reduction or carbon sequestration) interact dynamically. Practices that improve soil organic carbon, for example, simultaneously enhance water retention (adaptation), nutrient supply (productivity), and carbon storage (mitigation) [8, 9].

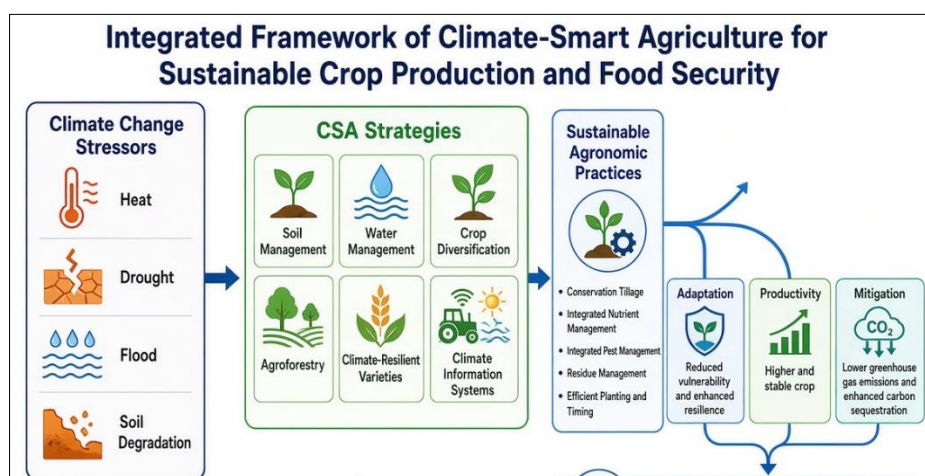


Fig 1: Integrated Framework of Climate-Smart Agriculture for Sustainable Crop Production and Food Security

The framework illustrates how coordinated interventions convert climate risks into opportunities for resilient and productive systems.

4. Sustainable Agronomic Practices for Climate Resilience

4.1. Conservation Agriculture

Minimum or zero tillage, permanent soil cover, and diversified crop rotations improve soil structure, reduce erosion, enhance moisture retention, and promote carbon sequestration [10,11]. Long-term studies show conservation agriculture can maintain yields under warming while improving soil-health indicators [10].

4.2. Crop Diversification and Rotation

Cereal–legume rotations, intercropping, and polycultures enhance biodiversity, nutrient cycling, pest suppression, and yield stability [9,12]. Diversification buffers production against climate extremes.

4.3. Integrated Nutrient Management

Combining organic amendments (compost, manure, biofertilizers) with mineral fertilizers improves nitrogen-use efficiency and reduces nitrous oxide emissions [8,13]. Precision application further limits losses.

4.4. Soil Health Management

Practices that increase soil organic carbon—cover crops, mulching, biochar—enhance microbial diversity, water-holding capacity, and nutrient cycling [9,14]. Healthy soils provide greater resilience to drought and extreme rainfall.

4.5. Water-Smart Agriculture

Drip and sprinkler irrigation, rainwater harvesting, deficit irrigation, and alternate wetting and drying in rice improve water productivity [13,15]. Soil-moisture sensors enable timely application.

4.6. Agroforestry

Integrating trees with crops moderates microclimates, sequesters carbon, supports biodiversity, and diversifies livelihoods [8,16].

Table 1: Major Climate-Smart Agricultural Practices, Mechanisms, Benefits, and Climate-Resilience Outcomes

Practice	Mechanism	Productivity Benefit	Adaptation Benefit	Mitigation Potential
Conservation agriculture	Reduced tillage, residue cover, rotation	Yield stability, lower costs	Improved moisture retention, erosion control	Soil C sequestration
Crop diversification	Legume rotations, intercropping	Yield stability, N fixation	Pest suppression, risk spreading	Reduced fertilizer demand
Integrated nutrient management	Organic–inorganic combination	Higher N-use efficiency	Sustained fertility	Lower N ₂ O emissions
Water-smart practices	Efficient irrigation, AWD	Higher water productivity	Drought resilience	Reduced CH ₄ (rice), energy use
Agroforestry	Tree–crop integration	Diversified income	Microclimate regulation	Biomass & soil C sequestration
Soil-health practices	Cover crops, biochar, mulching	Improved nutrient cycling	Enhanced water holding	Increased SOC stocks

These practices demonstrate clear synergies among productivity, adaptation, and mitigation when adapted to local conditions [8–11].

5. Climate-Resilient Crops and Genetic Approaches

Drought-, heat-, flood-, and salinity-tolerant varieties, together with short-duration cultivars, enable production under stress [17]. Conventional breeding, marker-assisted selection, genomic selection, and CRISPR-based editing accelerate development of climate-adapted germplasm [18]. Genetic diversity remains a critical resource for future adaptation. Improved varieties complement agronomic management by providing intrinsic tolerance that reduces the magnitude of yield losses under extreme conditions.

6. Precision Agriculture and Digital Technologies in Climate-Smart Farming

6.1. Remote Sensing and Satellite Monitoring

Vegetation indices (e.g., NDVI), drought assessment, and

yield estimation support timely interventions [19,20].

6.2. Internet of Things and Smart Sensors

Soil-moisture, weather, and nutrient sensors enable automated irrigation and precise input application [21].

6.3. Artificial Intelligence and Machine Learning

Models predict yields, detect diseases, forecast pests, optimize irrigation, and assess climate risk [20,22].

6.4. Geographic Information Systems

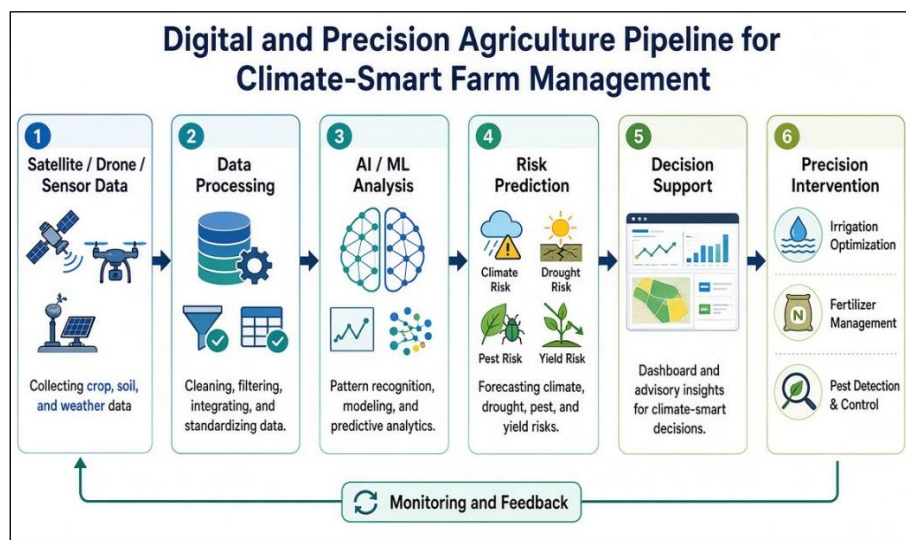
Spatial soil mapping, crop-suitability analysis, and climate-risk zoning guide site-specific recommendations [19].

6.5. Digital Decision-Support Systems

Weather-based advisories and early-warning systems improve farm-level decisions [23].

Table 2: Digital Technologies Supporting Climate-Smart Agriculture and Their Agricultural Applications

Technology	Application	Major Benefit	Key Limitation	Potential Contribution to CSA
Remote sensing/satellites	Crop health, drought, yield estimation	Large-area monitoring	Cloud cover, resolution trade-offs	Early risk detection, adaptation
IoT sensors	Soil moisture, weather, nutrients	Real-time data	Cost, connectivity, maintenance	Efficient water/nutrient use
AI/ML	Yield prediction, disease/pest detection	Predictive accuracy	Data quality, model transferability	Optimized interventions, mitigation
GIS	Suitability mapping, risk zoning	Spatial decision support	Data availability	Targeted resilience planning
Decision-support systems	Advisories, early warning	Actionable recommendations	Digital literacy, access	Farmer resilience, productivity

**Fig 2:** Digital and Precision Agriculture Pipeline for Climate-Smart Farm Management

Benefits include higher resource-use efficiency and reduced emissions intensity. Limitations encompass high costs, connectivity gaps, data quality issues, digital literacy barriers, and equity concerns that can exclude smallholders [21,22].

7. Role of Climate-Smart Agriculture in Food Security

CSA enhances food availability through higher and more stable yields under stress [8,24]. Improved productivity and reduced production risks raise farm incomes, supporting food access. Better nutritional quality of diverse systems and reduced post-harvest losses improve utilization. Yield stability and diversified income streams strengthen food-system stability. Overall, CSA reduces vulnerability of agricultural supply chains and contributes to nutritional security, especially when combined with climate information services [5,7].

8. Environmental and Socioeconomic Benefits

CSA practices sequester soil carbon, reduce N₂O and CH₄ emissions, conserve water, enhance biodiversity, and lower chemical inputs [8,11,14]. Ecosystem services such as erosion control and pollination support are strengthened. Socioeconomically, higher profitability, rural employment opportunities, and greater resilience benefit smallholders. Gender and social inclusion improve when technologies and extension services are designed inclusively [16,24]. Many practices deliver both adaptation and mitigation benefits; others primarily support one pillar, requiring careful prioritization according to local needs.

9. Challenges and Barriers to CSA Adoption

High initial investment costs, limited access to technology and finance, small and fragmented landholdings, weak extension services, inadequate climate information, poor rural infrastructure, policy gaps, digital divides, and uncertainty about long-term returns constrain adoption [25,26]. Knowledge and skill gaps further hinder uptake. Overcoming these barriers requires blended finance, targeted subsidies, strengthened extension and digital literacy programs, participatory technology development, supportive policies, and improved market linkages that reward sustainable practices.

10. Future Perspectives and Research Priorities

Promising directions include AI-driven decision systems, autonomous machinery, digital twins of farming systems, advanced remote sensing, accelerated climate-resilient breeding, carbon farming, regenerative approaches, nature-based solutions, integrated crop–livestock–forestry systems, climate-risk insurance, and digital agricultural extension [20,22,27]. Multidisciplinary collaboration among agronomists, soil scientists, climatologists, economists, data scientists, policymakers, and farmers is essential. Participatory, farmer-centered development will ensure relevance and equitable scaling.

11. Conclusion

Climate-smart agriculture provides a coherent framework for simultaneously raising productivity, building resilience, and reducing emissions. Sustainable agronomic practices

centered on soil health, efficient water and nutrient management, crop diversification, and agroforestry form the foundation of resilient production systems. Climate-resilient cultivars and digital technologies amplify these gains through precise, timely interventions. Together they strengthen all dimensions of food security while delivering environmental co-benefits. Realization of this potential depends on overcoming cost, knowledge, infrastructure, and policy barriers through targeted investment, inclusive extension, and enabling institutions. Future research and policy should prioritize site-specific integration of genetic, agronomic, and digital innovations within participatory frameworks to secure long-term food security and environmental sustainability under a changing climate.

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