



Climate-smart agronomic practices for sustainable crop production: A comprehensive review

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Abstract

Climate change poses significant threats to global agriculture through increased temperatures, erratic rainfall patterns, frequent droughts, floods, and declining soil fertility. Climate-smart agronomic practices have emerged as an effective approach to enhance agricultural productivity while improving resilience and reducing greenhouse gas emissions. This review comprehensively examines major climate-smart agronomic interventions, including conservation tillage, crop rotation, cover cropping, integrated nutrient management, precision agriculture, water-efficient irrigation, agroforestry, and the use of climate-resilient crop varieties. These practices contribute to improved soil health, enhanced water-use efficiency, increased carbon sequestration, reduced input costs, and greater adaptation to climatic variability. Despite their demonstrated benefits, adoption remains constrained by limited awareness, high initial investment requirements, inadequate policy support, and technical knowledge gaps. Future research should focus on location-specific technologies, digital agriculture, carbon farming, and integrated farming systems to accelerate the transition toward sustainable crop production. The review highlights that climate-smart agronomy is essential for achieving food security, environmental sustainability, and long-term agricultural resilience under changing climatic conditions.

Keywords: Climate-smart agriculture, sustainable crop production, conservation tillage, precision agriculture, integrated nutrient management

Introduction

Agriculture is one of the most climate-sensitive sectors of the global economy, and its productivity is closely linked to variations in temperature, rainfall, atmospheric carbon dioxide concentration, and the frequency of extreme weather events. In recent decades, climate change has emerged as a major threat to agricultural sustainability, food security, and rural livelihoods across the world ^[1]. Rising temperatures, prolonged droughts, erratic precipitation patterns, heat waves, floods, and increasing incidence of pests and diseases are adversely affecting crop growth and yield stability ^[2]. These challenges are particularly severe in developing countries, where agriculture forms the backbone of the economy and where farmers often have limited access to modern technologies, irrigation infrastructure, and climate adaptation resources. As the global population continues to increase, the demand for food is expected to rise substantially, placing additional pressure on already stressed agricultural systems.

Conventional agricultural practices have contributed significantly to environmental degradation and climate vulnerability. Intensive tillage, monocropping, excessive use of chemical fertilizers and pesticides, overexploitation of groundwater resources, and poor residue management have resulted in declining soil fertility, loss of soil organic carbon, reduced biodiversity, and increased greenhouse gas emissions. Such practices may provide short-term yield gains but often compromise the long-term productivity and resilience of farming systems ^[3]. The degradation of natural resources, combined with increasing climatic uncertainty, highlights the urgent need for agricultural strategies that can sustain crop production while minimizing environmental impacts ^[4-7]. In response to these challenges, the concept of

Climate-Smart Agriculture (CSA) has gained global attention as an integrated approach to agricultural development. CSA aims to achieve three interrelated objectives: increasing agricultural productivity and farm incomes, strengthening resilience and adaptation to climate change, and reducing or removing greenhouse gas emissions wherever possible. Unlike traditional production-oriented approaches, CSA emphasizes the efficient use of natural resources, ecosystem conservation, and long-term sustainability. Agronomic management practices constitute a central component of CSA because they directly influence soil health, water dynamics, nutrient cycling, crop performance, and carbon sequestration processes.

A wide range of climate-smart agronomic practices has been developed and adopted in different agroecological regions. These include conservation tillage, crop rotation, cover cropping, integrated nutrient management, precision agriculture, water-efficient irrigation systems, agroforestry, and the cultivation of climate-resilient crop varieties. Conservation tillage helps maintain soil structure and reduce erosion, while crop diversification improves nutrient cycling and reduces the risk of crop failure under variable climatic conditions. Cover crops enhance soil organic matter and moisture retention, and integrated nutrient management promotes balanced fertilization while reducing nutrient losses to the environment ^[8-11]. Similarly, precision agriculture technologies enable site-specific management of inputs, thereby improving resource-use efficiency and reducing production costs.

Water management has become increasingly important in climate-smart farming due to the growing scarcity of freshwater resources. Techniques such as drip irrigation, sprinkler irrigation, deficit irrigation, and rainwater

harvesting can substantially improve water-use efficiency and help crops withstand drought stress. Agroforestry systems further contribute to climate resilience by integrating trees with crops, enhancing carbon sequestration, regulating microclimates, and diversifying farm income sources. In addition, advances in plant breeding have led to the development of drought-tolerant, heat-tolerant, flood-tolerant, and salt-tolerant crop varieties that are better adapted to changing environmental conditions ^[12-14]. Despite the demonstrated benefits of climate-smart agronomic practices, their adoption remains uneven across regions. Farmers often face constraints such as high initial investment costs, limited technical knowledge, inadequate extension services, fragmented landholdings, and insufficient policy support. Furthermore, the effectiveness of specific practices can vary depending on local soil characteristics, climate conditions, cropping systems, and socio-economic factors. Therefore, there is a need for comprehensive evaluation of climate-smart agronomic interventions to identify the most suitable strategies for different production environments.

The present review aims to provide a comprehensive assessment of major climate-smart agronomic practices and their role in sustainable crop production. The paper examines the principles and applications of conservation tillage, crop diversification, cover cropping, integrated nutrient management, precision agriculture, water-smart irrigation, agroforestry, and climate-resilient crop varieties. It also discusses their contributions to productivity enhancement, climate adaptation, greenhouse gas mitigation, and resource conservation, while highlighting existing challenges and future research priorities. By synthesizing current knowledge on climate-smart agronomy, this review seeks to support researchers, policymakers, extension personnel, and farmers in developing resilient and sustainable agricultural systems capable of meeting future food security demands under changing climatic conditions.

Concept of Climate-Smart Agriculture

Climate-smart agriculture (CSA) is an integrated approach designed to address the interconnected challenges of food security, climate change adaptation, and environmental sustainability. The concept was developed to promote agricultural systems that can maintain or increase productivity while simultaneously enhancing resilience to climate-related stresses and reducing greenhouse gas emissions. Unlike conventional agricultural approaches that focus primarily on maximizing yield, CSA emphasizes the long-term sustainability of production systems and the conservation of natural resources ^[15]. The core objective of climate-smart agriculture is to achieve a balance among

three major goals. The first goal is to sustainably increase agricultural productivity and farm income so that growing food demands can be met without expanding agricultural land. The second goal is to strengthen the adaptive capacity of farming systems by improving their resilience to drought, heat stress, flooding, salinity, and other climate-induced disturbances. The third goal is to contribute to climate change mitigation by reducing emissions of greenhouse gases such as carbon dioxide, methane, and nitrous oxide, and by enhancing carbon sequestration in soils and vegetation ^[16]. Climate-smart agriculture recognizes that there is no single universal technology suitable for all farming environments. Instead, it promotes a combination of locally appropriate practices, technologies, and management strategies that are adapted to specific agroecological and socio-economic conditions. These practices may include conservation tillage, diversified cropping systems, efficient irrigation, integrated nutrient management, agroforestry, and the use of climate-resilient crop varieties. Through the integration of these interventions, CSA seeks to improve resource-use efficiency, protect ecosystem services, and ensure the long-term viability of agricultural production systems under changing climatic conditions.

Conservation Tillage

Conservation tillage is one of the most important climate-smart agronomic practices because it minimizes soil disturbance and preserves crop residues on the soil surface. The practice includes reduced tillage, strip tillage, and no-till systems, all of which aim to maintain soil structure and protect the soil from erosion. By reducing mechanical disturbance, conservation tillage helps conserve soil moisture and promotes the accumulation of organic matter. One of the major benefits of conservation tillage is its contribution to soil carbon sequestration. Crop residues left on the soil surface gradually decompose and increase soil organic carbon levels, thereby improving soil fertility and biological activity. Enhanced organic matter also improves water infiltration and water-holding capacity, which is particularly valuable in drought-prone regions. Furthermore, conservation tillage reduces runoff and erosion, helping to prevent the loss of fertile topsoil and nutrients ^[17]. From a climate mitigation perspective, conservation tillage can reduce fuel consumption because fewer field operations are required compared with conventional plowing. Lower fuel use results in reduced carbon dioxide emissions from farm machinery. The practice also improves the resilience of cropping systems by maintaining better soil moisture during dry periods and reducing the negative impacts of extreme rainfall events. Consequently, conservation tillage has become a key component of sustainable and climate-resilient agricultural systems worldwide.

Table 1: Major Climate-Smart Agronomic Practices and Their Functions

Practice	Primary Function	Climate-Smart Benefit
Conservation tillage	Minimize soil disturbance	Soil carbon sequestration and moisture conservation
Crop rotation	Diversify cropping sequence	Improved nutrient cycling and pest management
Cover cropping	Protect soil surface	Reduced erosion and enhanced soil organic matter
Integrated nutrient management	Balanced nutrient supply	Higher nutrient-use efficiency and lower emissions
Precision agriculture	Site-specific input management	Reduced input wastage and improved efficiency
Water-smart irrigation	Efficient water application	Improved drought resilience and water savings
Agroforestry	Integrate trees with crops	Carbon sequestration and microclimate regulation
Climate-resilient varieties	Tolerance to climatic stress	Stable yields under adverse conditions

Table 2: Environmental and Agronomic Benefits of Climate-Smart Practices

Benefit Category	Examples
Soil health	Higher organic matter, improved structure, enhanced microbial activity
Water management	Better infiltration, reduced runoff, increased water retention
Nutrient efficiency	Reduced fertilizer losses and improved nutrient uptake
Climate adaptation	Greater tolerance to drought, heat, and flooding
Climate mitigation	Lower greenhouse gas emissions and increased carbon storage
Biodiversity	Enhanced habitat for beneficial organisms and pollinators
Economic benefits	Reduced input costs and improved farm profitability

Table 3: Major Constraints to Adoption of Climate-Smart Agriculture

Constraint	Impact on Adoption
High initial investment	Limits adoption of advanced technologies
Limited awareness	Reduces farmer participation
Inadequate training	Poor implementation of recommended practices
Small landholdings	Restricts mechanization and precision farming
Weak policy support	Insufficient incentives for sustainable farming
Limited access to inputs	Reduces effectiveness of climate-smart interventions
Climatic variability	Causes inconsistent performance of practices

Table 4: Future Research Priorities in Climate-Smart Agronomy

Research Area	Expected Outcome
Location-specific CSA packages	Improved regional adaptability
AI and digital agriculture	Real-time decision support
Low-cost precision tools	Greater adoption by smallholders
Carbon farming	Enhanced carbon sequestration
Integrated farming systems	Improved resilience and profitability
Long-term soil carbon studies	Better assessment of mitigation potential
Climate-resilient breeding	Stress-tolerant high-yielding varieties

Crop Rotation and Diversification

Crop rotation and diversification are essential strategies for enhancing the resilience and sustainability of agricultural systems. Crop rotation involves growing different crops in a planned sequence on the same field over successive seasons, while diversification includes practices such as intercropping, mixed cropping, and the cultivation of multiple crop species within a farming system. These approaches reduce dependence on a single crop and help stabilize production under variable climatic conditions ^[17]. Rotating crops with different rooting patterns and nutrient requirements improves soil structure and nutrient cycling. Leguminous crops are particularly valuable in rotations because they fix atmospheric nitrogen through symbiotic relationships with rhizobia, thereby reducing the need for synthetic nitrogen fertilizers. Diversified cropping systems also interrupt pest and disease cycles, leading to lower pesticide requirements and reduced production costs ^[19]. In the context of climate change, crop diversification provides an important risk-management strategy. When one crop performs poorly due to drought, heat, flooding, or pest outbreaks, other crops in the system may still produce acceptable yields, thereby reducing the likelihood of complete crop failure. Diversification also enhances biodiversity, improves ecosystem stability, and supports beneficial organisms such as pollinators and natural enemies of pests. As a result, crop rotation and diversification contribute significantly to both climate adaptation and the long-term sustainability of agricultural production systems.

Cover Cropping

Cover cropping is an important climate-smart agronomic practice in which crops are grown primarily to protect and

improve the soil rather than for direct harvest. Common cover crops include legumes such as clover and vetch, as well as grasses such as rye and oats. These crops are typically cultivated during fallow periods or between main cropping seasons to maintain continuous soil cover and reduce the exposure of soil to erosive forces ^[20]. One of the major advantages of cover crops is their ability to reduce soil erosion caused by wind and water. The plant canopy protects the soil surface, while the root system helps bind soil particles together. Cover crops also contribute to the accumulation of soil organic matter through the addition of plant residues, which improves soil structure, increases microbial activity, and enhances nutrient cycling. Leguminous cover crops further enrich the soil by fixing atmospheric nitrogen, thereby reducing dependence on synthetic fertilizers ^[21]. Cover cropping also improves water management by increasing infiltration and reducing evaporation losses. Soils with higher organic matter content retain more moisture, which can help crops withstand periods of drought or irregular rainfall. In addition, cover crops suppress weed growth through competition for light, water, and nutrients, reducing the need for herbicide applications. These combined benefits make cover cropping a valuable strategy for improving soil health, enhancing resilience to climate variability, and supporting sustainable crop production.

Integrated Nutrient Management

Integrated Nutrient Management (INM) involves the balanced and combined use of organic manures, crop residues, biofertilizers, and inorganic fertilizers to meet crop nutrient requirements. The objective of INM is to optimize nutrient availability while maintaining soil fertility and

minimizing environmental losses. By integrating multiple nutrient sources, INM provides a more sustainable alternative to excessive reliance on chemical fertilizers.

Organic inputs such as farmyard manure, compost, green manure, and crop residues improve soil physical properties and increase soil organic carbon content. These materials enhance microbial activity and support long-term nutrient release. Biofertilizers containing beneficial microorganisms further contribute to nutrient availability by promoting nitrogen fixation, phosphorus solubilization, and improved root growth. Inorganic fertilizers, when applied in appropriate amounts and at the correct time, ensure that crops receive sufficient nutrients for optimal growth and yield [22]. From a climate-smart perspective, INM improves nutrient-use efficiency and reduces nutrient losses through leaching, volatilization, and runoff. Better nutrient management can lower emissions of nitrous oxide, a potent greenhouse gas associated with excessive nitrogen fertilization. The practice also enhances soil carbon sequestration and helps maintain productivity under changing climatic conditions. Consequently, integrated nutrient management plays a critical role in sustainable intensification and climate-resilient agriculture.

Precision Agriculture

Precision agriculture is a modern climate-smart approach that uses advanced technologies such as Global Positioning Systems (GPS), remote sensing, drones, soil sensors, and variable-rate application equipment to manage crops and inputs with high spatial accuracy. The primary goal is to apply the right input, at the right place, at the right time, and in the right amount.

Through the use of digital technologies, precision agriculture enables site-specific management of fertilizers, irrigation water, pesticides, and other inputs. Yield maps, satellite imagery, and sensor data help identify variations in soil fertility, moisture status, and crop health across a field. Farmers can then make informed decisions regarding input application, thereby improving resource-use efficiency and reducing wastage. [23]. Precision agriculture offers significant climate-smart benefits. Reduced over-application of fertilizers and pesticides lowers production costs and minimizes environmental contamination. Efficient irrigation scheduling helps conserve water resources and improves crop performance under drought conditions. Early detection of nutrient deficiencies, pest infestations, and water stress allows timely intervention, reducing yield losses. By increasing input efficiency and reducing unnecessary emissions associated with agricultural operations, precision agriculture contributes to both climate adaptation and climate change mitigation while supporting sustainable crop production.

Water-Smart Irrigation

Water-smart irrigation has become an essential component of climate-smart agriculture because freshwater resources are increasingly limited in many agricultural regions. Climate change has intensified water scarcity through irregular rainfall, prolonged droughts, and higher evapotranspiration rates. Efficient irrigation practices aim to maximize crop productivity while minimizing water use, thereby improving the sustainability and resilience of farming systems.

Modern water-smart irrigation techniques include drip irrigation, sprinkler irrigation, deficit irrigation, alternate

wetting and drying in rice cultivation, and rainwater harvesting systems. Drip irrigation delivers water directly to the root zone, reducing evaporation and runoff losses. Sprinkler systems provide more uniform water distribution than traditional flood irrigation, while deficit irrigation strategically applies less water than full crop requirements during certain growth stages to conserve resources without causing significant yield reductions [24]. These irrigation approaches improve water-use efficiency and help crops maintain productivity under drought conditions. Reduced water application also lowers energy consumption associated with pumping and irrigation operations. In rice systems, alternate wetting and drying can substantially reduce methane emissions compared with continuously flooded fields. Consequently, water-smart irrigation contributes to climate adaptation by enhancing drought resilience and to climate mitigation by reducing greenhouse gas emissions and energy use.

Agroforestry Systems

Agroforestry is the deliberate integration of trees with crops and/or livestock within the same land management system. This practice combines agricultural production with forestry components to create more diversified, productive, and environmentally sustainable farming systems. Agroforestry is widely recognized as a climate-smart strategy because it provides both adaptation and mitigation benefits [25]. Trees in agroforestry systems improve the microclimate by reducing wind speed, moderating temperature extremes, and increasing soil moisture retention. Their deep root systems help stabilize soil, reduce erosion, and access nutrients and water from deeper soil layers. Fallen leaves and organic residues contribute to soil organic matter accumulation and enhance nutrient cycling. In addition, agroforestry systems support greater biodiversity by providing habitats for beneficial insects, birds, and other organisms [26]. One of the most significant advantages of agroforestry is its capacity for carbon sequestration. Trees capture atmospheric carbon dioxide and store carbon in biomass and soil, thereby helping mitigate climate change. Farmers also benefit economically through diversified income sources such as timber, fuelwood, fruits, fodder, and medicinal products. By improving ecological stability and reducing dependence on a single enterprise, agroforestry enhances the overall resilience of agricultural landscapes.

Climate-Resilient Crop Varieties

The development and adoption of climate-resilient crop varieties represent a crucial strategy for sustaining agricultural productivity under changing environmental conditions. Plant breeding programs have produced varieties that can tolerate drought, heat, flooding, salinity, and other abiotic stresses associated with climate change. These varieties are designed to maintain growth and yield performance even under unfavorable conditions.

Drought-tolerant maize, heat-tolerant wheat, submergence-tolerant rice, and salt-tolerant rice and barley are examples of crops developed for climate-stressed environments. Such varieties often possess physiological and morphological traits that improve water-use efficiency, maintain photosynthetic activity under heat stress, or survive temporary flooding. The use of climate-resilient varieties reduces the risk of crop failure and provides greater yield stability across variable seasons [27]. Climate-resilient crop

varieties complement other climate-smart agronomic practices such as conservation tillage, efficient irrigation, and integrated nutrient management. When combined within an integrated farming system, these varieties can significantly enhance adaptation capacity and food security. Continued investment in breeding programs, biotechnology, and germplasm conservation will be essential for developing future crop varieties capable of coping with increasingly complex climate challenges.

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Conclusion

Climate-smart agronomic practices represent a transformative approach for achieving sustainable crop production in the face of increasing climate variability and environmental degradation. The integration of conservation tillage, crop rotation, cover cropping, integrated nutrient management, precision agriculture, water-smart irrigation, agroforestry, and climate-resilient crop varieties offers substantial opportunities to enhance agricultural productivity while conserving natural resources and reducing greenhouse gas emissions. These practices improve soil health, increase water-use efficiency, strengthen nutrient cycling, enhance biodiversity, and promote carbon sequestration, thereby contributing to both climate adaptation and mitigation.

The review highlights that climate-smart agriculture is not a single technology but a holistic management framework that combines agronomic, ecological, and technological innovations to build resilient farming systems. By reducing the vulnerability of crops to drought, heat, flooding, and other climate-related stresses, climate-smart practices help stabilize yields and improve the long-term profitability of agricultural enterprises. Moreover, the adoption of these practices can support broader goals related to food security, environmental sustainability, and rural livelihood improvement.

Despite their significant benefits, several barriers continue to limit widespread adoption, including high initial investment costs, limited technical knowledge, inadequate extension services, fragmented landholdings, and insufficient policy support. Addressing these constraints will require coordinated efforts among researchers,

polymakers, extension agencies, financial institutions, and farming communities. Investment in capacity building, digital agriculture, climate-resilient breeding programs, and location-specific climate-smart technologies will be essential for scaling up adoption.

Future agricultural development strategies must prioritize climate-smart agronomy as a central component of sustainable intensification. Continued research on integrated farming systems, carbon farming, precision resource management, and region-specific adaptation measures will further strengthen the effectiveness of climate-smart interventions. Overall, the successful implementation of climate-smart agronomic practices can play a critical role in ensuring food security, enhancing farmer resilience, and protecting ecosystem health under the rapidly changing climatic conditions of the twenty-first century.

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