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AFTEFS

Climate-Smart Agronomy Integrating Resilient Crops, Regenerative Soils and Efficient Water Management

संकलन

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INTRODUCTION

Climate change has emerged as one of the most significant challenges facing global agriculture in the 21st century. Rising temperatures, erratic rainfall patterns, prolonged droughts, floods, and increasing frequency of extreme weather events are directly affecting crop productivity and farm livelihoods. These changes not only reduce yields but also threaten soil health, water availability, and overall ecosystem stability. In this context, the concept of Climate-Smart Agriculture (CSA) has gained prominence as a holistic approach to ensure food security under changing climatic conditions.

Figure 01. Climate-Smart Agriculture

Climate-Smart Agriculture aims to achieve three primary goals: sustainably increasing agricultural productivity, enhancing resilience and adaptive capacity to climate change, and reducing or removing greenhouse gas emissions wherever possible. Rather than focusing on a single intervention, CSA promotes an integrated approach combining improved crop varieties, sustainable soil management, efficient water use, and smart technologies. Climate-smart agronomy specifically emphasizes the integration of resilient crops, regenerative soil practices, and resource-efficient management strategies. The objective is to optimize productivity while conserving natural resources, strengthening farmer adaptability, and ensuring long-term environmental sustainability. By aligning agronomic practices with climate realities, CSA provides a pathway toward stable, profitable, and environmentally responsible agricultural systems.

CLIMATE-RESILIENT CROP DEVELOPMENT

Climate-resilient crop development is a cornerstone of climate-smart agronomy, aimed at sustaining productivity under increasing environmental stress. As temperatures rise and rainfall patterns become unpredictable, breeding crops that can tolerate drought, heat, and salinity has become a top priority. Drought-tolerant varieties maintain yield under water deficit conditions through deeper root systems and improved water-use efficiency. Heat-tolerant genotypes protect reproductive stages from temperature-induced sterility, while salinity-tolerant crops sustain growth in salt-affected soils, which are expanding due to climate change and improper irrigation practices. Short-duration and stress-adaptive varieties offer another practical solution. These crops complete their life cycle before the onset of terminal drought or heat stress, thereby reducing climate risk. Early-maturing cultivars also enable multiple cropping systems and better resource utilization.
Biotechnology and gene editing tools, such as CRISPR-based techniques, are accelerating the development of resilient crops by precisely modifying stress-responsive genes.

These innovations enhance tolerance traits without compromising yield potential. Crop diversification further strengthens resilience by spreading risk across different species and varieties. Additionally, breeding low greenhouse gas-emitting genotypes-such as rice varieties with reduced methane emissions-contributes to climate mitigation while sustaining productivity. Together, these strategies ensure stable food production in a changing climate.
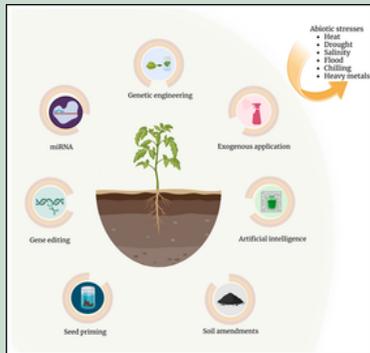

Figure 2. Summary of the possible approaches to create climate resilient crops: These approaches include genetic engineering by overexpressing one or more genes, gene editing technology, use of microRNAs, seed priming, exogenous application of chemicals, use of soil amendments such as biochar, and the use of artificial intelligence.

REGENERATIVE SOIL MANAGEMENT

Regenerative soil management is fundamental to climate-smart agronomy, as healthy soils serve as the foundation for resilient and productive farming systems. Soil health-characterized by good structure, organic matter content, biological activity, and balanced nutrient availability-enhances a farm's capacity to adapt to climate variability. Healthy soils improve water infiltration and retention, reduce erosion, and support beneficial microbial communities, all of which help crops withstand droughts, floods, and temperature extremes. One of the most significant components of regenerative soil management is soil carbon sequestration. By increasing soil organic carbon through sustainable practices, agriculture can remove carbon dioxide from the atmosphere and store it in stable soil forms. This not only mitigates climate change but also improves soil fertility, aggregation, and moisture-holding capacity. Conservation tillage and reduced soil disturbance protect soil structure and minimize carbon losses. These practices preserve microbial habitats and reduce erosion. Similarly, cover cropping and diversified crop rotations enhance soil biodiversity, suppress weeds, and improve nutrient cycling. The application of organic amendments such as farmyard manure (FYM), compost, and green manure further enriches soil organic matter. Integrated nutrient management strategies combine organic and inorganic inputs judiciously, ensuring balanced fertilization, improved nutrient-use efficiency, and long-term soil sustainability.

EFFICIENT WATER MANAGEMENT STRATEGIES

Efficient water management is a critical pillar of climate-smart agronomy, particularly in regions facing increasing water scarcity and erratic rainfall. As climate change intensifies drought frequency and alters precipitation patterns, optimizing water use has become essential for sustaining crop productivity. Modern irrigation strategies focus not only on supplying water but on applying the right amount at the right time to maximize crop response and minimize losses. Precision irrigation techniques such as drip and sprinkler systems significantly improve water-use efficiency compared to traditional flood irrigation. Drip irrigation delivers water directly to the root zone, reducing evaporation and runoff, while sprinkler systems ensure uniform distribution across fields. These methods conserve water, reduce nutrient leaching, and enhance yield stability. Sensor-based irrigation scheduling further refines water management. Soil moisture sensors, weather-based models, and automated systems help farmers determine irrigation timing and quantity based on real-time crop needs. This data-driven approach prevents over-irrigation and conserves scarce water resources. Rainwater harvesting and watershed management strengthen on-farm water security by capturing and storing excess rainfall. In rainfed agriculture, drought mitigation practices such as mulching, contour farming, and selection of drought-tolerant varieties improve moisture conservation and crop resilience under limited water conditions.

INTEGRATION OF DIGITAL AND SMART TECHNOLOGIES

The integration of digital and smart technologies is transforming climate-smart agronomy by enabling data-driven decision-making and precision resource management. As climate variability increases, real-time monitoring and predictive analytics help farmers respond proactively rather than reactively. These technologies enhance productivity, reduce input wastage, and improve resilience against climate risks. Remote sensing and Geographic Information Systems (GIS) play a crucial role in monitoring crop growth, soil variability, and water stress across large areas. Satellite imagery and drone-based observations provide insights into vegetation indices, nutrient deficiencies, and pest incidence. GIS integrates spatial data to create detailed field maps, supporting site-specific nutrient and irrigation management. IoT-based soil moisture monitoring systems further improve precision. Sensors placed in fields continuously measure soil moisture levels and transmit data to mobile or cloud platforms. This allows farmers to apply irrigation only when necessary, optimizing water use and preventing stress conditions. Decision Support Systems (DSS) combine weather data, soil information, and crop models to provide actionable recommendations on sowing time, fertilizer application, and pest management. Climate forecasting tools also assist in seasonal farm planning, enabling better risk management and adaptive strategies under changing climatic conditions.

ENVIRONMENTAL AND ECONOMIC BENEFITS

Climate-smart agronomy delivers significant environmental and economic benefits by aligning productivity goals with ecological sustainability. By integrating resilient crops, regenerative soil practices, efficient water management, and digital technologies, farming systems can reduce their environmental footprint while improving profitability and long-term viability. One major environmental advantage is the reduction of greenhouse gas (GHG) emissions. Practices such as conservation tillage, optimized fertilizer use, precision irrigation, and the cultivation of low-emission crop varieties help lower emissions of carbon dioxide, methane, and nitrous oxide.

Improved nitrogen-use efficiency, for example, reduces nitrous oxide losses, while better water management in rice fields can limit methane emissions. Economically, climate-smart practices enhance farm profitability by improving input efficiency. Precision nutrient and water management reduce wastage, lower production costs, and increase yield stability. Diversified cropping systems and resilient varieties also minimize losses due to climate stress, ensuring more consistent income for farmers. Additionally, regenerative practices improve soil biodiversity and ecosystem services, including nutrient cycling, pest regulation, and improved soil structure. These benefits contribute to long-term sustainability and resilience, enabling agricultural systems to withstand climatic uncertainties while maintaining productivity and environmental health.

CHALLENGES AND FUTURE PROSPECTS

Despite its significant potential, the adoption of climate-smart agronomy faces several practical challenges. One major barrier is limited awareness and technical knowledge among farmers, particularly smallholders. High initial investment costs for technologies such as drip irrigation systems, sensors, and improved seed varieties can discourage adoption. Inadequate access to credit, fragmented landholdings, and risk aversion also slow the transition toward climate-smart practices. Additionally, uncertainty regarding long-term benefits may make farmers hesitant to shift from conventional methods. Strong policy and institutional support are essential to overcome these barriers. Governments must promote incentive-based schemes, subsidies for precision technologies, crop insurance, and carbon credit mechanisms to encourage adoption. Supportive policies that integrate climate adaptation and mitigation goals into agricultural planning can accelerate large-scale implementation. Capacity building and effective extension services play a critical role in bridging the knowledge gap. Farmer training programs, demonstration plots, digital advisory platforms, and participatory research approaches can enhance awareness and confidence in climate-smart technologies. Looking ahead, research priorities include developing stress-resilient crop varieties, improving soil carbon monitoring methods, enhancing water-use efficiency technologies, and integrating artificial intelligence into farm decision-making systems. These advancements will strengthen the future of climate-smart agronomy.

CONCLUSION

Climate-smart agronomy represents a comprehensive and forward-looking approach to addressing the challenges posed by climate change. By promoting the holistic integration of resilient crops, regenerative soil management, and efficient water use, it ensures that agricultural systems remain productive while conserving natural resources. Rather than treating crops, soils, and water as separate components, climate-smart agronomy recognizes their interdependence and manages them as parts of a unified ecosystem. Healthy soils enhance water retention and nutrient availability; resilient crop varieties optimize resource use; and efficient irrigation systems reduce stress and input losses. Together, these interconnected strategies create a balanced and adaptive farming system.

This integrated approach provides a practical pathway toward sustainable and climate-resilient agriculture. It supports stable yields, reduces environmental degradation, lowers greenhouse gas emissions, and strengthens farmers' adaptive capacity. As climate variability intensifies, the need for such integrated solutions becomes increasingly urgent. Through supportive policies, scientific innovation, farmer participation, and technology adoption, climate-smart agronomy can transform agricultural landscapes into resilient, productive, and environmentally responsible systems capable of feeding present and future generations sustainably.