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CLIMATE-SMART AGRONOMY, INNOVATIONS SHAPING RESILIENT AND PRODUCTIVE FARMING SYSTEMS

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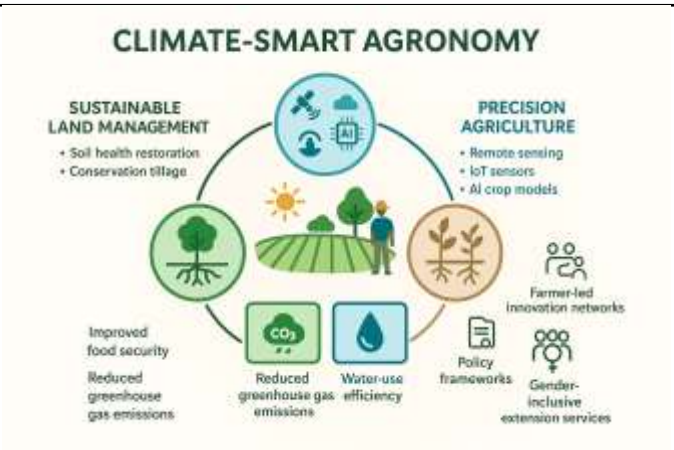
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Abstract
Climate-smart agronomy has emerged as a critical paradigm in addressing the intertwined challenges of food insecurity, climate change, and land degradation. This review article explores the latest innovations driving resilient and productive farming systems through climate-smart approaches that integrate sustainable land management, precision agriculture, and adaptive crop strategies. Emphasizing the synergistic role of soil health restoration, water-use efficiency, and nutrient-smart interventions, the review presents a comprehensive analysis of how data-driven decision-making tools—such as remote sensing, IoT-enabled sensors, and AI-powered crop models—are transforming agronomic practices to withstand environmental stresses. Special attention is given to climate-resilient crop varieties, conservation tillage, agroforestry, and diversified cropping systems that reduce greenhouse gas emissions while enhancing farm productivity and livelihood resilience. The article also examines the role of policy frameworks, farmer-led innovation networks, and gender-inclusive extension services in scaling up climate-smart practices globally. By synthesizing findings from recent field trials, meta-analyses, and case studies across different agroecological zones, the review identifies knowledge gaps and future directions for research and implementation. Ultimately, this work underscores that climate-smart agronomy is not only a toolkit of adaptive practices but a transformative framework for building sustainable agricultural systems that thrive amid climatic uncertainties.
Graphical Abstract:



INTRODUCTION

The need for climate-smart agronomy in the Anthropocene era, an epoch defined by significant human impact on Earth's climate and ecosystems, has become more urgent than ever before (Chhabra et al., 2025). Traditional agricultural practices are increasingly unable to cope with the rapidly changing climate, manifesting in erratic weather patterns, prolonged droughts, floods, soil degradation, pest outbreaks, and declining yields. These shifts threaten global food security, especially for vulnerable populations in climate-sensitive regions (Chin-Yee et al., 2019). Climate-smart agronomy emerges as a pivotal solution, integrating sustainable land management, precision agriculture, advanced biotechnology, and data-driven decision-making to optimize crop productivity while minimizing environmental impact. It emphasizes the use of climate-resilient crop varieties, efficient water and nutrient use, carbon sequestration practices, and diversified farming systems that enhance ecological resilience (Banga et al., 2014). In the context of the Anthropocene, where anthropogenic greenhouse gas emissions and land use changes have altered the planet's natural feedback loops, agronomic strategies must not only ensure immediate productivity but also contribute to long-term sustainability and climate mitigation. Moreover, climate-smart agronomy supports adaptive capacity among farmers by promoting inclusive technologies, policy interventions, and knowledge-sharing networks that align with both local contexts and global climate goals (Ogunyiola et al., 2022). As agriculture remains both a contributor to and victim of climate change, embedding climate-smart principles into agronomic science and practice is no longer optional; it is essential for cultivating a resilient and food-secure future (Traore et al., 2022).

Climate-smart agronomy (CSA) and conventional sustainable agriculture both aim to improve agricultural productivity and environmental stewardship, but they diverge significantly in approach, objectives, and adaptability to contemporary climate challenges (Kabato et al., 2025). While sustainable agriculture traditionally emphasizes conserving natural resources, minimizing chemical inputs, and maintaining soil and water health over time, climate-smart agronomy takes a more dynamic, systems-oriented approach tailored specifically to the complexities of a changing climate. CSA is explicitly designed to address three interlinked goals: sustainably increasing productivity, enhancing resilience (adaptation), and reducing or removing greenhouse gas emissions (mitigation) wherever possible (Matteoli et al., 2025). This tri-fold agenda distinguishes it from conventional practices, which often focus primarily on long-term ecological balance without necessarily factoring in the evolving risks posed by climate variability. CSA practices incorporate advanced tools such as climate forecasting models, precision farming technologies, and real-time data analytics to optimize planting dates, irrigation, nutrient use, and crop selection based on projected weather extremes (Raihan et al., 2024). In contrast, traditional sustainable agriculture may not always

integrate such predictive, high-tech interventions. Moreover, CSA emphasizes context-specific, localized solutions informed by climate projections, vulnerability assessments, and socio-economic dynamics, making it inherently more responsive and anticipatory than static sustainability models (Matteoli et al., 2020). Thus, while both frameworks share core values of environmental care and resource efficiency, climate-smart agronomy represents an evolved, proactive strategy explicitly aligned with the urgent realities of global climate change (Steenwerth et al., 2014).

The primary objective of this review is to critically evaluate the core principles and components of climate-smart agronomy (CSA) in the context of enhancing agricultural productivity, resilience to climate variability, and mitigation of greenhouse gas emissions. It aims to identify and analyze recent technological and biotechnological innovations, such as precision farming tools, AI-integrated decision support systems, and climate-resilient crop varieties, that are shaping the future of sustainable agriculture. A key focus is placed on exploring the role of efficient soil and water management practices in promoting resource conservation and improving the adaptability of farming systems under changing climatic conditions. The review also seeks to examine region-specific adaptation strategies that integrate indigenous knowledge with modern agronomic practices to ensure climate-smart outcomes. Furthermore, it assesses the socio-economic and policy frameworks that facilitate or hinder the widespread adoption of CSA innovations across different agroecological zones. In doing so, it highlights current knowledge gaps and proposes future research directions in areas such as digital agriculture, agroecological intensification, and carbon farming. Lastly, the review presents a synthesis of real-world case studies and success stories that demonstrate the practical impacts of CSA on food security, farmer livelihoods, and environmental sustainability.

Next-Gen Soil Intelligence and Carbon Farming

Next-generation soil intelligence and carbon farming represent a transformative leap in sustainable agriculture, integrating artificial intelligence, advanced soil sensing technologies, and ecological engineering to optimize both productivity and environmental stewardship (SS et al., 2024). AI-integrated soil sensors now enable real-time, hyperlocal monitoring of dynamic nutrient and moisture profiles, allowing farmers to make data-driven decisions about irrigation, fertilization, and planting schedules with unprecedented precision. These sensors, embedded with machine learning algorithms, can learn from historical and seasonal data to provide predictive analytics that minimize resource use while maximizing crop health. In parallel, breakthroughs in soil microbiome diagnostics, powered by genomics and real-time biosensing, offer an intricate understanding of microbial communities, enabling early detection of imbalances that affect soil fertility, disease resistance, and crop resilience. This microbiome intelligence serves as a biological early warning system, forecasting soil health deterioration before visible symptoms appear. Moreover, carbon farming strategies are being redefined through the deployment of cropping patterns that maximize photosynthetic capture and carbon sequestration, supported by innovative interventions like biochar-fungal synergy (Pai et al., 2024). Biochar acts as a stable carbon sink while simultaneously enhancing microbial habitats; when paired with beneficial mycorrhizal fungi, it fosters a symbiotic relationship that boosts nutrient cycling and root development. Altogether, this fusion of AI, soil biology, and carbon-smart agronomy creates a resilient agricultural ecosystem that not only combats climate change but also reimagines farming as a regenerative force (Kim et al., 2018).

Genetic Resilience through Epigenetic Engineering

Genetic resilience through epigenetic engineering represents a transformative frontier in agricultural biotechnology, where the adaptive potential of crops is enhanced not by altering their DNA sequence but by reprogramming the expression of stress-responsive genes (KhokharVoytas et al., 2023). Epigenome editing tools, particularly those based on CRISPR-dCas9 fused with epigenetic modifiers, enable precise and reversible modifications to histone acetylation or DNA methylation, thereby activating or silencing genes associated with climate-adaptive traits. This approach allows researchers to induce beneficial phenotypes such as enhanced drought, salinity, or heat tolerance without introducing permanent

genetic changes, making it a more flexible and potentially socially acceptable method compared to traditional transgenic approaches. A key aspect of this strategy is the induction of stress memory in plants, wherein prior exposure to environmental stress primes specific signaling and transcriptional networks, leading to a faster or stronger response upon subsequent stress events (Hilker et al., 2019). These priming mechanisms, often governed by chromatin remodeling and small RNAs, can be harnessed and amplified through epigenetic interventions to build long-term resilience. Furthermore, CRISPR-based modulation of key regulators like *DREB*, *Hsf*, or *NAC* transcription factors involved in abiotic stress responses enables tailored tuning of physiological pathways such as stomatal regulation, osmolyte production, and antioxidant defense. Together, these innovations converge into a powerful strategy for developing climate-resilient crops capable of withstanding fluctuating environmental conditions, ensuring food security in the face of global climate change (Sarma et al., 2024).

Nano-Agronomy for Microclimate Management

Nano-Agronomy for Microclimate Management is an emerging frontier in sustainable agriculture, offering highly targeted tools to modulate the plant environment and mitigate the impacts of climate variability (Ogwu et al., 2025). One of the most promising innovations is the use of *smart nano-coatings for reflective mulching*, which are engineered with light-responsive nanomaterials to reflect specific wavelengths of solar radiation. These nano-mulches help regulate soil temperature by reducing heat absorption during hot periods while maintaining warmth during cooler nights, thereby stabilizing the root zone microclimate and enhancing plant resilience. Complementing this, *nano-fertilizers* are designed for precision nutrient delivery that adapts to extreme weather conditions such as drought or flooding. These fertilizers are encapsulated within nanocarriers that respond to moisture, temperature, or pH, allowing for controlled and timely release of nutrients only when the crop needs them most, minimizing leaching and maximizing uptake efficiency (Yadav et al., 2023). Furthermore, *nanobiosensors* integrated into soil or plant tissues offer real-time, in situ monitoring of microclimatic stressors like heat, salinity, or drought. These nanosensors use biorecognition elements to detect physiological changes or environmental stress signals at the molecular level, enabling early warning systems for farmers and automated responses through smart irrigation or nutrient systems. Together, these nano-agronomic interventions create a fine-tuned, adaptive microclimate around crops, boosting productivity, reducing resource use, and making farming systems more resilient to climate extremes (Aldhahri et al., 2025).

Technology	Functional Role	Mechanism of Action	Nanomaterials Used	Application Method	Impact on Crop and Soil Microclimate	Current Research/Development Status
Smart Nano-Coatings for Reflective Mulching	Modulate soil temperature and reduce heat stress	Reflective nanoparticles modify light absorption by increasing albedo; thermally	TiO_2, SiO_2 nanoparticles; polymeric nano-laminates	Surface application as mulch films or sheets	Lowers soil surface temperature, reduces evaporation, minimizes thermal stress on roots, and	Demonstrated in controlled field trials; scalable for high-value crops and arid zones

		responsive coatings regulate insulation properties dynamically			enhances photosynthetic efficiency	
Nano-Fertilizers for Precision Nutrient Release	Controlled nutrient delivery under variable weather conditions	Encapsulation or surface modification enables release in response to soil pH, temperature, and moisture levels	Hydroxyapatite NPs, zeolite NPs, nano-clays, chitosan-based carriers	Soil or foliar application; drip irrigation integration	Enhances nutrient use efficiency (NUE), reduces losses during drought/flood, and prevents nutrient leaching	Widely studied in lab and pilot-scale field trials; commercialization is expanding
Nanobiosensors for In Situ Climate Stress Detection	Real-time monitoring of plant or soil responses to environmental stress	Biosensing elements detect changes in ionic content, redox potential, temperature, or biomarkers of stress; signals transmitted wirelessly or visually	Quantum dots, carbon nanotubes (CNTs), gold nanoparticles, graphene oxide	Embedded in soil, plant tissues, or leaf surfaces	Enables early detection of drought, salinity, or thermal stress; supports automated irrigation and input decisions	Active research area with proof-of-concept devices; requires integration with IoT
Nano-Hydrogels for Moisture Regulation	Maintain soil moisture during	Nano-scale crosslinked hydrophilic polymers absorb water and	Cellulose nanofibers, polyacrylamide-silica	Mixed into root zone or coated	Improves water retention, reduces irrigation frequency,	Field validation in arid regions underway; eco-toxicology under evaluation

	extreme dry periods	release it slowly over time	nanocomposites	around seeds	and enhances root-zone humidity	
Nanophotonic Films for Light Management	Optimize light spectrum reaching plant canopy	Filters or enhances specific wavelengths (e.g., red/blue) to improve photosynthesis and reduce heat buildup	Photonic crystal films, doped TiO_2/SiO_2 layers	Canopy or greenhouse covers	Increases photosynthetic efficiency, mitigates excess solar radiation, reduces temperature-induced stress	Prototypes tested in greenhouses and high-intensity horticulture
Thermo-Responsive Nanomaterials	Dynamic heat shielding or insulation of plants	Materials change conformation or optical properties with temperature variations, providing active insulation or reflection	VO_2 nanoparticles, phase-change nanocomposites	Coatings on greenhouse panels, plant covers	Protects crops from heat spikes or cold snaps, stabilizes microclimate fluctuations	Research emerging; applications in precision greenhouse farming

Table 1: Nano-Agronomic Innovations for Microclimate Management in Crops

Regenerative Agronomy and Synthetic Ecology

Regenerative agronomy, when integrated with the principles of synthetic ecology, offers a transformative approach to reimagining agricultural systems that are not only productive but also ecologically resilient (Pretty et al., 2023). Central to this paradigm is the re-design of polyculture systems through synthetic ecological modeling, which leverages computational tools and systems biology to optimize plant diversity and functional complementarity. By simulating ecological interactions among multiple crops, synthetic models can predict synergistic plant pairings that enhance nutrient cycling, pest resistance, and resource use efficiency. This enables the strategic development of dynamic intercropping systems tailored to specific agroecological zones, improving carbon sequestration in soils, maximizing nitrogen fixation through leguminous integration, and

optimizing water retention through diversified root architectures. Moreover, microbial consortia engineering plays a critical role in advancing regenerative farming by designing soil microbiomes that support plant health, boost stress tolerance, and mediate nutrient availability. Through synthetic biology, beneficial microbes such as nitrogen-fixing bacteria, phosphate-solubilizing fungi, and stress-resilient endophytes can be co-assembled into synthetic microbial communities that act as bio-enhancers for soil fertility and crop productivity (Pathak et al., 2013). This systems-level integration of plant-soil-microbe interactions under regenerative frameworks redefines the future of sustainable agriculture—moving beyond input-dependence toward self-regenerating, biodiverse, and climate-resilient farming ecosystems (Heider et al., 2023).

Weather-Adaptive Agronomic Decision Systems

Weather-Adaptive Agronomic Decision Systems represent a cutting-edge convergence of climate science, data analytics, and digital agriculture, empowering farmers to make real-time, site-specific choices that enhance resilience and productivity (Balyan et al., 2024). At the core of these systems is **hyperlocal climate modeling**, which uses high-resolution geospatial data, satellite imagery, and IoT-enabled weather sensors to generate field-level forecasts and microclimatic trends. This granular insight enables **precision agronomic scheduling**—from sowing and irrigation to pest control and harvesting—tailored to specific crop needs and environmental conditions. Enhancing this ecosystem are **blockchain-linked crop advisory platforms** that integrate verified agronomic data, localized climate alerts, and farmer-reported outcomes to create transparent, secure, and decentralized channels for agricultural decision-making (Mssassi et al., 2023). These platforms ensure that advisory services are both accountable and traceable, reducing misinformation and aligning stakeholders—from input suppliers to policy planners—on a unified data ledger. Furthermore, the emergence of **agro-digital twins**—virtual replicas of entire farm systems—allows farmers and agronomists to simulate different climate scenarios, input strategies, and management interventions, helping them forecast the impact of decisions before implementation. These twins not only facilitate adaptive planning under unpredictable weather patterns but also optimize resource allocation, reduce risks, and boost sustainability outcomes. Collectively, these innovations mark a transformative leap toward climate-smart agriculture, enabling proactive, data-driven, and climate-resilient farming systems (Vishnoiet al., 2024).

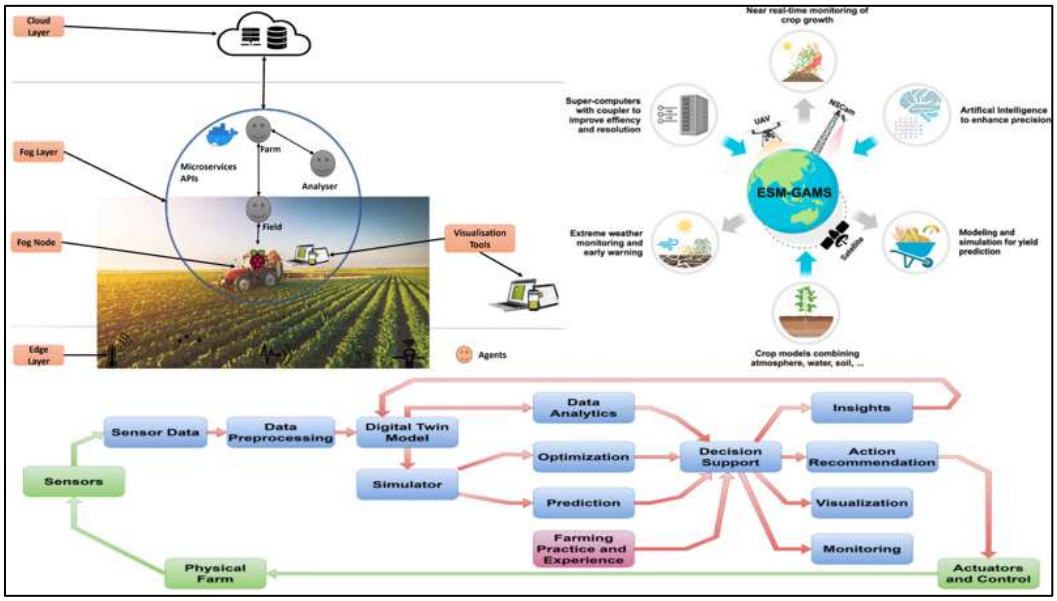


Fig 1: Weather-Adaptive Agronomic Decision Systems

Climate-Smart Seed Banks and Germplasm Innovation

Climate-Smart Seed Banks and Germplasm Innovation are rapidly emerging as critical tools in the battle against climate-induced agricultural instability (Ahmad et al., 2023). At the core of this transformation lies the development of cloud-based genomic banks, which digitally catalog and store the genetic blueprints of climate-resilient cultivars, enabling global researchers and breeders to access, share, and collaboratively improve plant genetics in real time. These genomic repositories not only preserve biodiversity but also accelerate breeding programs by offering detailed insights into gene-trait associations for heat, drought, salinity, and pest resistance. Equally important is the practice of participatory climate breeding, where scientists co-create solutions with farmers by integrating indigenous knowledge, traditional varietal preferences, and real-time field observations. This bottom-up approach ensures that the developed cultivars are both socially acceptable and ecologically adapted to local agroecosystems (Altieri et al., 1993). Alongside digital innovations, cryopreservation techniques offer ultra-long-term storage of germplasms—ensuring the conservation of rare or wild alleles that may hold the key to future resilience. Complementing this, rapid phenotyping platforms using drones, AI-powered sensors, and multispectral imaging are being employed to swiftly evaluate stress tolerance in germplasm collections, drastically reducing the breeding cycle. Collectively, these integrated approaches position climate-smart seed banks not merely as static repositories but as dynamic, decentralized hubs for innovation, collaboration, and future-proof food security (Pol et al., 2025).

Space-Guided Agronomy and Geo-AI

Space-guided agronomy, bolstered by the convergence of satellite hyperspectral imaging, drones, and GeoAI (Geospatial Artificial Intelligence), is revolutionizing climate-resilient agriculture (Vaiyapuri et al., 2025). By leveraging hyperspectral sensors aboard satellites and UAVs (drones), researchers and farmers can now perform highly granular crop-climate response analysis, capturing key physiological traits such as chlorophyll content, water stress, disease incidence, and photosynthetic efficiency across large-scale fields in near real time. These rich spectral datasets enable early detection of biotic and abiotic stressors, offering unprecedented insight into plant health, microclimate variability, and phenological shifts triggered by climate anomalies (Dhaliwal et al., 2024). In parallel, GeoAI enhances the analytical depth by integrating satellite-derived data with machine learning algorithms to develop adaptive zoning models. These models optimize crop selection and rotation patterns based on spatiotemporal patterns of soil health, water availability, and climate risk profiles, paving the way for dynamic and location-specific cropping systems. Furthermore, the advent of low Earth orbit (LEO) satellite constellations—capable of delivering high-frequency, high-resolution data—facilitates continuous agro-climatic monitoring and rapid decision-making for interventions like precision irrigation, pest control, and nutrient application. Together, this synergy of space-based technologies and AI transforms agronomic planning from a reactive to a predictive science, making farming systems more resilient, efficient, and responsive to the uncertainties of climate change (Bi et al., 2022).

Biointensive Farming and Mycorrhizal Optimization

Biointensive farming, grounded in the principles of ecological intensification, offers a promising avenue to confront the dual challenges of soil degradation and climate variability (Gudadhe et al., 2025). At the heart of this approach lies the optimization of mycorrhizal associations—particularly arbuscular mycorrhizal fungi (AMF)—which form symbiotic relationships with plant roots and significantly enhance plant nutrient uptake, water absorption, and resistance to abiotic stressors. Mycorrhizal fungi improve climate resilience by extending the rhizosphere's functional surface area, enabling plants to access deeper and less mobile water reserves during drought conditions. Furthermore, advances in fungal-root interface engineering, such as selective inoculation with drought-adapted AMF strains and modulation of root exudate profiles to favor beneficial fungal colonization, are paving the way for bio-designed symbioses tailored to extreme environmental conditions. These engineered interactions increase the efficiency of water and nutrient transport under stress, enhance osmotic adjustment, and reduce

oxidative damage in host plants (Singhal et al., 2023). Concurrently, biointensive agronomic practices—such as compost enrichment, green manuring, intercropping with mycorrhiza-friendly species, and minimal tillage—foster microbial habitat complexity, enhance soil organic matter, and build stable carbon pools. This enhances soil structure, water-holding capacity, and microbial synergy, creating a buffering environment against climatic shocks. Together, these integrative strategies present a powerful, systems-based solution for resilient agriculture, merging the biological potential of mycorrhizae with holistic soil stewardship to sustain productivity under changing climatic regimes (Ogwu et al., 2025).

Component	Mechanism	Scientific Insights	Impact on Climate Resilience	Relevant Biointensive Practice(s)
Arbuscular Mycorrhizal Fungi (AMF)	Symbiotic colonization of plant roots	AMF penetrate root cortical cells, forming arbuscules and vesicles, facilitating the exchange of nutrients and water	Enhances plant water uptake, phosphorus acquisition, and systemic resistance under abiotic stress	Inoculation of AMF-rich compost; polyculture systems using AMF-compatible crops
Mycorrhizal Water Channeling	Hyphal extension into micropores	Mycorrhizal hyphae access water in soil micropores inaccessible to roots; aquaporin expression increases in root cells	Increases drought tolerance through improved soil–plant hydraulic conductivity	Use of drought-adapted AMF strains; mycorrhizal seed coatings
Root Exudate Modulation	Biochemical signaling between roots and microbes	Plants modulate exudates (e.g., flavonoids, strigolactones) to attract specific AMF; stress conditions intensify these signals	Facilitates selective recruitment of beneficial microbes under stress conditions	Compost tea application; intercropping with exudate-stimulating companion plants (e.g., legumes)
Fungal-Root Interface Engineering	Directed symbiosis via microbial design	Synthetic consortia and engineered AMF strains designed for climate stress (e.g., desiccation-tolerant genes)	Precision-enhanced mycorrhizal symbiosis tailored to extreme environments	Advanced microbial consortia inoculants; genetic selection of AMF-tolerant crop varieties
Carbon Sequestration via Mycorrhizae	Hyphal carbon transfer and glomalin production	AMF produce glomalin-related soil proteins (GRSP), stabilizing soil aggregates and	Enhances long-term soil carbon storage, reducing atmospheric CO_2	Green manuring; fungal-friendly organic amendments

		contributing to carbon pools		
Soil Aggregation and Structure	Hyphal entanglement and glomalin-mediated stabilization	Mycorrhizal hyphae and exudates bind soil particles into aggregates, reducing erosion and enhancing porosity	Improves infiltration, water retention, and root penetration	No-till practices; permanent raised beds
Nutrient Bioavailability	Enhanced uptake of P, Zn, Cu, N	AMF access immobile nutrients through hyphal exploration; organic acid secretion dissolves bound minerals	Sustains plant nutrition under variable moisture regimes	Composting with rock phosphate; application of mycorrhiza-accessible organic inputs
Mycorrhiza–Microbiome Interactions	Synergistic microbial networks	AMF interact with rhizobacteria, nitrogen-fixers, and phosphate-solubilizers, amplifying functional outcomes	Builds resilient soil microbial networks capable of buffering stress	Use of microbial consortia; vermicompost application
Moisture Buffering via Organic Matter	SOM accumulation and water-holding capacity	High SOM increases field capacity and water retention; supports microbial survival during dry spells	Delays onset of plant water stress, increases yield stability	Double digging, deep compost layers, cover cropping
Biointensive Crop Design	Spatial and temporal diversity	Crop rotations, companion planting, and stacking increase mycorrhizal persistence and reduce soil stress	Minimizes pest/disease cycles, improves root-microbe continuity	Intensive intercropping; seasonal rotation with AMF host plants
Climate-Adaptive Soil Health	Resilient soil biological architecture	Synergistic impact of mycorrhizae, organic matter, and biodiversity creates	Increases system-level adaptation to extreme weather events	Integrated soil fertility management; adaptive nutrient cycling

		stable, responsive soil systems		

Table 2: Integrated Roles of Mycorrhizal Optimization and Biointensive Farming in Enhancing Climate Resilience

Waste-to-Wealth Agronomy in Climate Mitigation

Agro-waste upcycling into bio-inputs for climate-resilient crops

Agro-waste, such as crop residues, fruit peels, and animal manure, contains substantial amounts of organic carbon, nitrogen, phosphorus, and micronutrients (El-Ramady et al., 2020). Through controlled biological and physicochemical transformation (e.g., fermentation, enzymatic hydrolysis, and pyrolysis), these residues can be upcycled into value-added bio-inputs, such as biofertilizers, biostimulants, and biopesticides. These products enhance soil microbial diversity, stimulate plant systemic resistance, and improve nutrient uptake efficiency. In climate-stressed conditions—like drought, salinity, or heat—bio-inputs derived from agro-waste support climate-resilient agriculture by promoting adaptive root architecture, osmolyte production, and antioxidant pathways in crops, thus reducing dependency on synthetic fertilizers and mitigating GHG emissions from conventional inputs (Ansabayeva et al., 2025).

Circular nutrient systems integrating livestock, aquaponics, and crops

Circular nutrient systems close the loop in agricultural waste and input cycles. In integrated systems combining livestock, aquaponics, and crops, animal manure is processed through anaerobic digestion or composting into organic fertilizers for crops. Simultaneously, aquaponic systems use fish waste as a nutrient source for hydroponic plant cultivation, while plants purify water for the fish. These interlinked components reduce resource leakage, optimize nutrient recycling, and minimize external input requirements (Shaviv et al., 1993). Such systems reduce methane (CH_4) and nitrous oxide (N_2O) emissions from livestock waste and limit nitrate leaching from crop fields. This regenerative approach increases productivity per unit of resource and forms a resilient agri-ecosystem capable of adapting to climate variabilities.

Climate-adaptive composting strategies for degraded land reclamation

Degraded lands—often characterized by low organic matter, poor structure, and disrupted microbial activity—are highly susceptible to climate extremes. Climate-adaptive composting involves the thermophilic decomposition of agro-waste under optimized temperature, moisture, and aeration conditions to produce high-quality, pathogen-free compost. Incorporation of biochar, rock phosphate, or microbial consortia (e.g., phosphate-solubilizing or nitrogen-fixing bacteria) further enhances the compost's functional value (Ahmed et al., 2023). When applied to degraded soils, this bio-enhanced compost improves carbon sequestration, cation exchange capacity, and water-holding capacity, restoring soil fertility and structure. These strategies support land reclamation in arid or semi-arid regions and buffer crops against climate-induced stresses like drought and heat waves.

Behavioral Agronomy and Farmer-Centric Innovation

Nudging Behavioral Change for Climate-Resilient Practices

Behavioral agronomy applies principles of behavioral science to influence farmers' decision-making in adopting sustainable agricultural practices (Dessart et al., 2019). "Nudging" refers to subtle policy or environmental changes that steer behavior without restricting choice, as proposed in behavioral economics. In the context of climate-resilient agriculture, nudges can include:

- **Framing information** about climate risks and solutions in locally relevant and emotionally resonant ways.

- **Social norm cues**, such as showcasing peer adoption of drought-resistant seeds or conservation agriculture, influence others' behavior.
- **Choice architecture**, like altering the default options in subsidy schemes to favor climate-smart technologies. Research shows that such interventions can significantly increase the uptake of sustainable farming practices without heavy-handed regulation or financial incentives.

Farmer Innovation Labs and Social Learning Networks

Farmer-centric innovation platforms, such as Farmer Innovation Labs, are participatory ecosystems where farmers co-develop, test, and refine technologies alongside researchers and extension agents. These labs are grounded in experiential learning theory and promote bottom-up solutions tailored to local agro-ecological and socio-economic contexts. Additionally, social learning networks, informal or structured groups where farmers share knowledge and practices, accelerate the diffusion of climate-smart innovations (Adjognon et al., 2022). These networks leverage collective intelligence, enhance trust in new technologies, and reduce perceived risks. Integrating ICT (e.g., mobile apps, WhatsApp groups) into these networks further amplifies reach and impact.

Psychological Resilience and Decision-Making under Climate Stress

Climate change imposes cognitive and emotional stress on farmers, affecting their capacity to make rational, long-term decisions. Behavioral agronomy incorporates **cognitive psychology** and **stress neuroscience** to understand how risk perception, loss aversion, and temporal discounting (preference for short-term gains) shape behavior under uncertainty (Story et al., 2014). Psychological resilience—the ability to maintain mental well-being and decision-making capacity in the face of adversity—is crucial. Strategies to enhance it include:

- **Stress-reduction interventions** (e.g., mindfulness, community support).
- **Improved communication of probabilistic weather information** to reduce anxiety.
- **Building farmers' self-efficacy**, so they feel empowered to adapt rather than helpless against climate variability.

Metrics, Modeling, and Monitoring Climate-Smart Outcomes

Life-cycle agronomic impact models under variable climate scenarios

Life-cycle agronomic impact models are computational frameworks designed to simulate and quantify the environmental, economic, and productivity impacts of agricultural practices across their entire lifespan, from input application (e.g., planting, fertilization) to harvest and post-harvest stages (Vlad et al., 2023). These models incorporate detailed biophysical processes such as crop growth, soil nutrient cycling, water use efficiency, and greenhouse gas emissions. When embedded within variable climate scenarios, generated by global or regional climate models (GCMs/RCMs), these life-cycle models enable researchers to predict how different climate futures (e.g., changes in temperature, precipitation patterns, and extreme weather events) influence the agronomic performance and sustainability of farming systems. This integrative approach supports evaluation of climate-smart agronomic practices by forecasting their long-term impacts on crop productivity, resource use, and environmental footprint under climate variability and change (Bijarniya et al., 2020).

Climate-smart indicators beyond yield: resilience, risk buffering, and equity

While crop yield remains a fundamental metric, climate-smart agriculture requires multidimensional indicators that capture system resilience, risk mitigation, and social equity. Resilience indicators assess the capacity of agroecosystems to absorb shocks (e.g., drought, floods) and maintain function, often quantified via stability metrics such as yield variance or recovery time after stress events. Risk buffering metrics evaluate the effectiveness of practices in reducing exposure or sensitivity to climatic risks, including soil moisture retention, diversification indices, or insurance proxies (Fisher et al., 2019). Equity indicators measure the fair distribution of benefits and burdens among diverse stakeholders, encompassing socio-economic dimensions like access

to resources, gender inclusion, and livelihood security. Together, these indicators provide a holistic framework for assessing the sustainability and inclusiveness of climate-smart interventions beyond mere productivity gains.

AI-driven continuous M&E (Monitoring & Evaluation) for climate-smart interventions

Artificial intelligence (AI) enhances the monitoring and evaluation of climate-smart agricultural interventions by enabling real-time, high-resolution data collection, integration, and analysis. Using remote sensing technologies, Internet of Things (IoT) sensors, and big data analytics, AI systems continuously track agronomic variables (e.g., soil moisture, crop health), weather conditions, and socio-economic parameters. Machine learning algorithms process these heterogeneous datasets to detect patterns, predict outcomes, and identify anomalies, facilitating adaptive management (Diro et al., 2021). This continuous M&E framework supports timely decision-making, optimizing intervention efficacy under dynamic climatic and socio-economic contexts. Moreover, AI-driven approaches enable scalable, cost-effective monitoring that can be tailored to local conditions and stakeholder needs, accelerating the diffusion and impact assessment of climate-smart practices.

Future Directions and Policy Innovations

Anticipatory Governance for Climate-Smart Agronomy

Anticipatory governance refers to proactive, forward-looking policy frameworks that integrate scientific foresight and stakeholder engagement to manage emerging challenges in agronomy under climate change. This approach leverages predictive models, scenario analyses, and early-warning systems to enable timely decision-making and adaptive management of agricultural systems (van Ginkel et al., 2021). By anticipating potential climate risks and opportunities, governance structures can dynamically adjust policies, regulations, and resource allocations to foster resilient and sustainable agronomic practices, minimizing maladaptation and enhancing system robustness.

Next-Generation Subsidies and Carbon Credits Tailored for Adaptive Practices

Traditional agricultural subsidies often fail to incentivize environmentally sustainable practices adequately. Next-generation financial instruments, such as adaptive subsidies and performance-based carbon credit schemes, are designed to reward farmers for adopting climate-smart practices that reduce greenhouse gas emissions, improve soil health, and increase carbon sequestration (Baylis et al., 2022). These mechanisms incorporate real-time monitoring technologies and data-driven metrics to quantify environmental benefits accurately, thus aligning economic incentives with ecological outcomes. Tailored subsidies encourage innovation and enable farmers to transition toward resilient cropping systems that can withstand climatic variability.

Open-Source Climate-Agronomy Data Hubs and Farmer Co-Creation Platforms

The establishment of open-source data hubs democratizes access to high-resolution climate, soil, crop, and management data, fostering transparency and collaboration among researchers, policymakers, extension services, and farmers. Such platforms facilitate real-time data sharing, integrative analytics, and participatory knowledge generation. Farmer co-creation platforms empower local stakeholders to contribute indigenous knowledge and experiential insights into climate-smart solutions, ensuring contextual relevance and social acceptance (van der Horst et al., 2022). Together, these digital infrastructures accelerate innovation diffusion, improve adaptive capacity, and support evidence-based agronomic decisions at scale.

Conclusion

In conclusion, the synthesis of cross-disciplinary momentum is crucial for advancing climate-smart agronomy, where insights from agronomy, environmental science, data analytics, and socioeconomics come together to drive transformative change. Building on this foundation, a clear roadmap toward intelligent, resilient, and decentralized agronomic systems emerges, leveraging cutting-edge technologies such as AI, IoT, and blockchain to enhance productivity while safeguarding ecosystems. Achieving climate-smart scalability demands a

convergence of policy, practice, and innovation, where supportive regulations, farmer-centered approaches, and continuous technological advancement align to foster sustainable agricultural landscapes capable of adapting to the challenges of climate change and global food security. This integrated pathway offers a promising vision for the future of farming systems that are not only productive but also equitable and environmentally sound.

References

Adjognon, G. S., Huy, T. N., Guthoff, J., & van Soest, D. (2022). Incentivizing social
learning for the diffusion of climate-smart agricultural techniques.

Ahmad, U., Hassain, M., Arshad, Z., & Ayub, B. (2023). Harnessing potential of plant breeding strategies for climate smart agriculture. *Theor Appl Plant Sci*, *1*, 72-83.

Ahmed, T., Noman, M., Qi, Y., Shahid, M., Hussain, S., Masood, H. A., ... & Li, B. (2023). Fertilization of microbial composts: a technology for improving stress resilience in plants. *Plants*, *12*(20), 3550.

Aldhahri, E. A., Almazroi, A. A., Alkinani, M. H., Ayub, N., Alghamdi, E. A., & Janbi, N. F. (2025). Smart Farming: Enhancing Urban Agriculture through Predictive Analytics and Resource Optimization. *IEEE Access*

Altieri, M. A., & Masera, O. (1993). Sustainable rural development in Latin America: building from the bottom-up. *Ecological economics*, *7*(2), 93-121.

Ansabayeva, A., Makhambetov, M., Rebouh, N. Y., Abdelkader, M., Saudy, H. S., Hassan, K. M., ... & Ebrahim, M. (2025). Plant growth-promoting microbes for resilient farming systems: mitigating environmental stressors and boosting crops productivity—A review. *Horticulturae*, *11*(3), 260.

Balyan, S., Jangir, H., Tripathi, S. N., Tripathi, A., Jhang, T., & Pandey, P. (2024). Seeding a sustainable future: Navigating the digital horizon of smart agriculture. *Sustainability*, *16*(2), 475.

Banga, S. S., & Kang, M. S. (2014). Developing climate-resilient crops. *Journal of Crop Improvement*, *28*(1), 57-87.

Baylis, K., Coppess, J., Gramig, B. M., & Sachdeva, P. (2022). Agri-environmental programs in the United States and Canada. *Review of Environmental Economics and Policy*, *16*(1), 83-104.

Bi, Z., Yung, K. L., Ip, A. W., Tang, Y. M., Zhang, C. W., & Da Xu, L. (2022). The state of the art of information integration in space applications. *IEEe Access*, *10*, 110110-110135.

Bijarniya, D., Parihar, C. M., Jat, R. K., Kalvania, K., Kakraliya, S. K., & Jat, M. L. (2020). Portfolios of climate smart agriculture practices in smallholder rice-wheat system of Eastern Indo-Gangetic plains—Crop productivity, resource use efficiency and environmental footprints. *Agronomy*, *10*(10), 1561.

Chhabra, V., Kaur, G., Sreethu, S., & Kaur, M. (2025). Journey of Man from Anthropocene Epoch to Climate-Smart Agriculture. In *Climate Change: Conflict and Resilience in the Age of Anthropocene* (pp. 159-174). Cham: Springer Nature Switzerland.

Chin-Yee, S. (2019). Climate change and human security: case studies linking vulnerable populations to increased security risks in the face of the global climate challenge. *King's College London: EUCERS Strategy Paper*, 2-31.

Dessart, F. J., Barreiro-Hurlé, J., & Van Bavel, R. (2019). Behavioural factors affecting the adoption of sustainable farming practices: a policy-oriented review. *European Review of Agricultural Economics*, *46*(3), 417-471.

Dhaliwal, S. S., Sharma, V., Shivay, Y. S., Gupta, R. K., Verma, V., Kaur, M., ... & Hossain, A. (2024). Assessment and detection of biotic and abiotic stresses in field crops through remote and proximal sensing techniques—

evidence from earlier findings. *Arabian Journal of Geosciences*, *17*(6), 188.

Diro, A., Chilamkurti, N., Nguyen, V. D., & Heyne, W. (2021). A comprehensive study of anomaly detection schemes in IoT networks using machine learning algorithms. *Sensors*, *21*(24), 8320.

El-Ramady, H., El-Henawy, A., Amer, M., Omara, A. E. D., Elsakhawy, T., Elbasiouny, H., ... & El-Mahrouk, M. (2020). Agricultural waste and its nano-management: Mini review. *Egyptian Journal of Soil Science*, *60*(4), 349-364.

Fisher, E., Hellin, J., Greatrex, H., & Jensen, N. (2019). Index insurance and climate risk management: Addressing social equity. *Development Policy Review*, *37*(5), 581-602.

Gudadhe, N. N., Babu, S., Singh, R., Ramkrushna, G. I., Pandey, A., Devi, K., ... & Kumar, S. (2025). Agroecological Approaches for Sustainable Intensification. In *Agricultural Diversification for Sustainable Food Production* (pp. 369-387). Singapore: Springer Nature Singapore.

Heider, K., Rodriguez Lopez, J. M., Bischoff, A., Balbo, A. L., & Scheffran, J. (2023). Toward climate-resilient and biodiverse agriculture in the Mediterranean region: experiences and perceptions of farmers engaged in sustainable food production. *Organic Agriculture*, *13*(4), 513-529.

Hilker, M., & Schmülling, T. (2019). Stress priming, memory, and signalling in plants. *Plant, Cell & Environment*, *42*(3), 753-761.

Kabato, W., Getnet, G. T., Sinore, T., Nemeth, A., & Molnár, Z. (2025). Towards climate-smart agriculture: Strategies for sustainable agricultural production, food security, and greenhouse gas reduction. *Agronomy*, *15*(3), 565.

KhokharVoytas, A., Shahbaz, M., Maqsood, M. F., Zulfiqar, U., Naz, N., Iqbal, U. Z., ... & AlShaqhaa, M. A. (2023). Genetic modification strategies for enhancing plant resilience to abiotic stresses in the context of climate change. *Functional & integrative genomics*, *23*(3), 283.

Kim, K. G. (2018). Low-carbon smart cities. *Tools for Climate Resilience Planning, Alemania: Springer*.

Matteoli, F., Schnetzer, J., & Jacobs, H. (2020). Climate-smart agriculture (CSA): an integrated approach for climate change management in the agriculture sector. In *Handbook of climate change management: research, leadership, transformation* (pp. 1-29). Cham: Springer International Publishing.

Matteoli, F., Schnetzer, J., & Jacobs, H. (2020). Climate-smart agriculture (CSA): an integrated approach for climate change management in the agriculture sector. In *Handbook of climate change management: research, leadership, transformation* (pp. 1-29). Cham: Springer International Publishing.

Mssassi, S., & El Kalam, A. A. (2023, October). Leveraging Blockchain for Enhanced Traceability and Transparency in Sustainable Development. In *International Conference on Advanced Intelligent Systems for Sustainable Development* (pp. 162-177). Cham: Springer Nature Switzerland.

Ogunyiola, A., Gardezi, M., & Vij, S. (2022). Smallholder farmers' engagement with climate-smart agriculture in Africa: role of local knowledge and upscaling. *Climate Policy*, *22*(4), 411-426.

Ogwu, M. C., & Kosoe, E. A. (2025). Integrating Green Infrastructure into Sustainable Agriculture to Enhance Soil Health, Biodiversity, and Microclimate Resilience. *Sustainability*, *17*(9), 3838.

Pai, S., Shetty, V., Rajangane, S., & Selvaraj, S. (2024). Synergistic Interactions of Fungi and Biochar for Various Environmental Applications. In *Bioprospecting of Multi-tasking Fungi for a Sustainable Environment: Volume I* (pp. 219-247). Singapore: Springer Nature Singapore.

Pathak, R. K., & Ram, R. A. (2013). Bio-enhancers: A potential tool to improve soil fertility, plant health in organic production of horticultural crops. *Progressive Horticulture*, *45*(2), 237-254.

Pol, I. S. V. (2025). *Food for thought: Rethinking sustainability in urban food with blockchain: Exploring the role of blockchain technology in reshaping urban food systems through degrowth and the pursuit of strong sustainability* (Master's thesis, University of Twente).

Pretty, J. (2023). Regenerative agriculture and redesign for sustainability. In *Biological approaches to regenerative soil systems* (pp. 13-24). CRC press.

Raihan, A. (2024). A review of recent advances, challenges, and potential future directions of climate-smart agriculture. In *Proceedings of the international conference on climate-smart agriculture*.

Sarma, H. H., Borah, S. K., Dutta, N., Sultana, N., Nath, H., & Das, B. C. (2024). Innovative approaches for climate-resilient farming: strategies against environmental shifts and climate change. *International Journal of Environment and Climate Change*, *14*(9), 217-241.

Shaviv, A., & Mikkelsen, R. L. (1993). Controlled-release fertilizers to increase efficiency of nutrient use and minimize environmental degradation-A review. *Fertilizer research*, *35*(1), 1-12.

Singhal, R. K., Fahad, S., Kumar, P., Choyal, P., Javed, T., Jinger, D., ... & Nawaz, T. (2023). Beneficial elements: New Players in improving nutrient use efficiency and abiotic stress tolerance. *Plant Growth Regulation*, *100*(2), 237-265.

SS, V. C., Hareendran, A., & Albaaji, G. F. (2024). Precision farming for sustainability: An agricultural intelligence model. *Computers and Electronics in Agriculture*, *226*, 109386.

Steenwerth, K. L., Hodson, A. K., Bloom, A. J., Carter, M. R., Cattaneo, A., Chartres, C. J., ... & Jackson, L. E. (2014). Climate-smart agriculture global research agenda: scientific basis for action. *Agriculture & Food Security*, *3*(1), 11.

Story, G. W., Vlaev, I., Seymour, B., Darzi, A., & Dolan, R. J. (2014). Does temporal discounting explain unhealthy behavior? A systematic review and reinforcement learning perspective. *Frontiers in behavioral neuroscience*, *8*, 76.

Traore, B., Birhanu, B. Z., Sangaré, S., Gumma, M. K., Tabo, R., & Whitbread, A. M. (2021). Contribution of climate-smart agriculture technologies to food self-sufficiency of smallholder households in Mali. *Sustainability*, *13*(14), 7757.

Vaiyapuri, T., & Julie, G. (2025). AI and Geospatial Technologies for Climate Change Mitigation: Opportunities, Challenges, and Pathways to Sustainability. *Procedia Computer Science*, *259*, 1346-1355.

van der Horst, S., Goosen, H., van Selm, M., Koomen, I., Matsaba, E. O., Wesonga, J., ... & Klein Holkenborg, M. (2022). Co-creation of a scalable climate Service for Kenyan Smallholder Farmers. *Frontiers in Climate*, *4*, 859728.

van Ginkel, M., & Biradar, C. (2021). Drought early warning in agri-food systems. *Climate*, *9*(9), 134.

Vishnoi, S., & Goel, R. K. (2024). Climate smart agriculture for sustainable productivity and healthy landscapes. *Environmental Science & Policy*, *151*, 103600.

Vlad, I. M., Butcaru, A. C., Fîntîneru, G., Bădulescu, L. A., Stănică, F., & Mihai, C. A. (2023). A Life Cycle Cost Analysis—Relevant Method Supporting the Decision to Establish an Apple Orchard in an Organic System. *Horticulturae*, *9*(12), 1263.

Yadav, A., Yadav, K., & Abd-Elsalam, K. A. (2023). Nanofertilizers: types, delivery, and advantages in agricultural sustainability. *Agrochemicals*, *2*(2), 296-336.