

## NANOTECHNOLOGY FOR CLIMATE SMART AGRICULTURE

### CHAPTER 5

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**ABSTRACT:** Climate change poses unprecedented challenges to global agricultural systems, threatening food security through altered precipitation patterns, increased temperatures, and enhanced pest pressures. Nanotechnology has emerged as a transformative approach to develop climate-smart agricultural practices that enhance productivity while minimizing environmental impacts. This chapter explores the application of nanomaterials in precision agriculture, including nano-fertilizers, nano-pesticides, nanosensors, and nano-enabled water management systems. The integration of nanotechnology in agriculture offers solutions for improving nutrient use efficiency, reducing chemical inputs, enhancing stress tolerance in crops, and enabling real-time monitoring of soil and plant health. Despite promising advances, the widespread adoption of agricultural nanotechnology faces challenges related to potential environmental and health risks, regulatory frameworks, and economic feasibility. This chapter synthesizes current research on nano-enabled agricultural innovations, examines their role in climate change adaptation and mitigation, and discusses future directions for sustainable implementation of nanotechnology in farming systems worldwide.

**Keywords:** Nanotechnology, climate-smart agriculture, nano-fertilizers, precision farming, sustainable agriculture, climate change adaptation.

### INTRODUCTION

The global agricultural sector stands at a critical juncture where traditional farming practices are increasingly inadequate to meet the dual challenges of feeding a growing population and mitigating climate change impacts (Kah *et al.*, 2018). By 2050, agricultural production must increase by approximately 70% to feed an estimated 9.7 billion people, while simultaneously reducing greenhouse gas emissions and adapting to changing climatic conditions (Parisi *et al.*, 2015). Climate change manifests in agriculture through multiple stressors including rising temperatures, erratic rainfall patterns, increased frequency of extreme weather events, soil degradation, and enhanced pest and disease pressures. These challenges necessitate innovative technological interventions that can optimize resource use efficiency while maintaining or enhancing crop productivity.

Nanotechnology, defined as the manipulation of matter at the atomic and molecular scale (1-100 nanometers), has emerged as a promising frontier in agricultural innovation (Fraceto *et al.*, 2016). At the nanoscale, materials exhibit unique physical, chemical, and biological properties that differ fundamentally from their bulk counterparts, offering unprecedented opportunities for agricultural applications. The high surface-area-to-volume ratio of nanomaterials enables enhanced reactivity, improved solubility, and controlled release mechanisms that are particularly valuable in agricultural contexts (Prasad *et al.*, 2017).

Climate-smart agriculture (CSA) represents an integrated approach that aims to increase agricultural productivity and incomes, build resilience to climate change, and reduce greenhouse gas emissions where possible (Lipper *et al.*, 2014). Nanotechnology aligns remarkably well with CSA principles by enabling precision delivery of agricultural inputs,

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reducing waste, enhancing resource use efficiency, and providing tools for real-time environmental monitoring. The convergence of nanotechnology and agriculture offers pathways to develop farming systems that are simultaneously productive, resilient, and environmentally sustainable.

This chapter examines the multifaceted applications of nanotechnology in climate-smart agriculture, exploring how nano-enabled innovations address specific climate-related challenges in crop production. We discuss the mechanisms by which nanomaterials enhance agricultural productivity, their role in climate change adaptation and mitigation, and the critical considerations for their safe and sustainable implementation. Through comprehensive analysis of current research and emerging trends, this chapter provides insights into how nanotechnology can contribute to transforming agriculture into a climate-resilient and sustainable enterprise.

### Nano-Fertilizers and Nutrient Management

One of the most promising applications of nanotechnology in climate-smart agriculture lies in the development of nano-fertilizers that address the inefficiency of conventional fertilization practices. Traditional fertilizers suffer from low nutrient use efficiency, with plants typically absorbing only 30-35% of applied nitrogen, 18-20% of phosphorus, and 35-40% of potassium (Dimkpa & Bindraban 2016). The remainder is lost through leaching, volatilization, runoff, and fixation, leading to environmental pollution, greenhouse gas emissions, and economic losses. This inefficiency is exacerbated under climate change conditions, where altered precipitation patterns and increased temperatures further reduce nutrient availability and uptake.

Nano-fertilizers represent a paradigm shift in nutrient delivery systems, utilizing nanomaterials as nutrient carriers or as nutrients themselves. These include nano-sized nutrients, nutrient-loaded nanoparticles, and nanoscale coating materials that enable controlled and targeted release (Liu & Lal 2015). The enhanced surface area and reactivity of nano-fertilizers facilitate greater interaction with plant roots and improved penetration through leaf stomata, resulting in superior nutrient uptake compared to conventional fertilizers. Research has demonstrated that nano-fertilizers can increase nutrient use efficiency by 20-30% while reducing application rates by 25-50% (Elemike *et al.*, 2019).

Several types of nano-fertilizers have been developed for different nutrients. Nano-nitrogen fertilizers, such as nano-urea and nitrogen-loaded chitosan nanoparticles, provide slow-release nitrogen that matches plant uptake patterns more precisely than conventional urea (Raliya *et al.*, 2018). Nano-phosphorus formulations, including hydroxyapatite nanoparticles and phosphorus-loaded polymeric nanocarriers, enhance phosphorus availability in soils where it would otherwise be immobilized by calcium, iron, or aluminum (Marchiol *et al.*, 2020). Nano-potassium fertilizers and micronutrient-containing nanoparticles address deficiencies in essential elements like zinc, iron, and manganese that are increasingly problematic under climate stress conditions.

The controlled-release mechanism of nano-fertilizers is particularly valuable for climate adaptation. By synchronizing nutrient release with plant demand throughout the growing season, these systems reduce nutrient losses during heavy rainfall events and minimize the need for multiple applications (Kottegoda *et al.*, 2017). This controlled delivery also reduces nitrogen oxide emissions, a potent greenhouse gas with approximately 300 times the global warming potential of carbon dioxide. Studies have shown that nano-urea can reduce nitrous oxide emissions by 40-50% compared to conventional urea while maintaining or improving crop yields (Subramanian *et al.*, 2015).

The encapsulation of fertilizers in nanomaterials also protects nutrients from rapid degradation and enhances their stability under variable climatic conditions. For instance, polymer-coated nano-fertilizers maintain nutrient integrity during storage and after application, even under high temperatures and moisture stress that would rapidly degrade conventional fertilizers (Vejan *et al.*, 2021). This stability is crucial in regions experiencing increased climate variability where unpredictable weather patterns make timing of fertilizer applications challenging.

Despite these advantages, several challenges must be addressed for widespread adoption of nano-fertilizers. The production costs currently exceed those of conventional fertilizers, though economies of scale and improved manufacturing processes are expected to reduce this gap (Grillo *et al.*, 2021). Additionally, the long-term fate of nanoparticles in soil ecosystems and their potential accumulation in food chains require thorough investigation to ensure environmental safety and sustainability.

### Nano-Enabled Pest and Disease Management

Climate change significantly alters pest and disease dynamics in agricultural systems, with warmer temperatures enabling pest survival in previously inhospitable regions, altered phenology affecting pest-plant synchrony, and increased stress making crops more susceptible to pathogen attacks (Sharma *et al.*, 2019). Conventional pesticides, while effective, pose environmental and health concerns through non-target toxicity, pesticide resistance development, and groundwater contamination. Nanotechnology offers innovative solutions for more targeted, efficient, and environmentally benign pest and disease management.

Nano-pesticides represent a diverse class of pest control agents that include nano-encapsulated active ingredients, nano-emulsions, and pesticidal nanomaterials with inherent antimicrobial or insecticidal properties (Kah *et al.*, 2018). The nanoscale formulation of pesticides enhances their solubility, stability, and bioavailability while enabling controlled release and targeted delivery to specific sites of action. This precision reduces the quantity of active ingredients required, minimizes off-target effects, and decreases environmental contamination. Research indicates that

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nano-encapsulated pesticides can reduce application rates by 60-80% while maintaining or improving pest control efficacy compared to conventional formulations (Kumar *et al.*, 2019).

Metallic and metal oxide nanoparticles, including silver, copper, zinc oxide, and titanium dioxide nanoparticles, exhibit broad-spectrum antimicrobial activity against bacterial, fungal, and viral plant pathogens (Chhipa, 2017). These nanomaterials disrupt microbial cell membranes, generate reactive oxygen species, and interfere with cellular metabolism, providing multiple modes of action that reduce the likelihood of resistance development. Silver nanoparticles have demonstrated effectiveness against various phytopathogens including *Xanthomonas* species, *Fusarium* species, and *Alternaria* species at concentrations significantly lower than conventional fungicides (Ocsoy *et al.*, 2017).

Nano-encapsulation technologies protect pesticide active ingredients from premature degradation by environmental factors such as UV radiation, high temperatures, and microbial decomposition. This protection extends pesticide efficacy under the variable and often extreme conditions associated with climate change, reducing the need for frequent reapplications (Nuruzzaman *et al.*, 2016). Polymer-based nanocapsules, lipid nanoparticles, and mesoporous silica nanoparticles serve as effective carriers that respond to environmental triggers such as pH, temperature, or enzymatic activity to release pesticides precisely when and where needed.

Nanotechnology also enables the development of intelligent delivery systems that respond to pest presence or plant stress signals. For example, pH-responsive nanocarriers can release pesticides in the alkaline gut environment of insect pests or in response to pathogen-induced pH changes in plant tissues (de Oliveira *et al.*, 2018). Similarly, nanoformulations incorporating plant defense elicitors such as chitosan or salicylic acid can enhance plant immunity against pests and diseases while simultaneously serving as carriers for conventional pesticides when needed.

The reduced environmental footprint of nano-pesticides contributes to climate change mitigation by decreasing the energy and resources required for pesticide production, application, and management of environmental contamination. Lower application rates translate to reduced fuel consumption for spraying operations and decreased pesticide manufacturing, both of which contribute to greenhouse gas emission reductions (Kah *et al.*, 2018). Furthermore, enhanced pest control efficacy protects crop yields from climate-exacerbated pest pressures, maintaining agricultural productivity without expanding cultivated land area.

However, the potential ecotoxicological effects of nano-pesticides require careful evaluation. While targeted delivery reduces exposure to non-target organisms, the novel properties of nanomaterials may introduce new risks to beneficial insects, soil microorganisms, and aquatic ecosystems (Grillo *et al.*, 2021). Comprehensive risk assessments considering nanoparticle fate, transformation, and bioaccumulation in agricultural environments are essential for developing safe and sustainable nano-enabled pest management strategies.

### Nanosensors and Precision Agriculture

The successful implementation of climate-smart agriculture requires real-time monitoring of environmental conditions, soil health, plant physiological status, and pest pressures to enable timely and precise management decisions. Nanotechnology has revolutionized agricultural sensing through the development of highly sensitive, selective, and miniaturized sensors capable of detecting minute changes in agricultural systems (Giraldo *et al.*, 2019). These nanosensors facilitate the transition from reactive to proactive agricultural management, allowing farmers to respond to stress conditions before visible damage occurs, thereby complementing conventional disease screening and crop protection strategies (Makwana *et al.*, 2023; Kulkarni & Sabeena 2023).

Nanosensors operate using a variety of detection principles, including optical, electrochemical, and mechanical transduction mechanisms, to identify target analytes such as nutrients, pesticides, pathogens, hormones, and environmental parameters (Husen & Siddiqi 2014). Their nanoscale dimensions offer multiple advantages, including ultra-low detection limits, rapid response times, minimal sample requirements, and compatibility with wireless sensor networks for continuous monitoring. Nanomaterials such as carbon nanotubes, quantum dots, gold nanoparticles, and graphene derivatives form the basis of many agricultural nanosensors due to their exceptional electrical, optical, and chemical properties. These technological advancements align with recent agri-bio innovations aimed at modernizing Indian and global agriculture (Lal *et al.*, 2024).

Soil health monitoring represents one of the most critical applications of nanosensors in climate-smart agriculture. Electrochemical nanosensors can accurately quantify soil nutrients such as nitrogen, phosphorus, and potassium, enabling site-specific fertilizer management that improves nutrient use efficiency. Such precision supports integrated nutrient management approaches that enhance crop productivity while reducing environmental losses (Kumar *et al.*, 2024). Additionally, nanosensor platforms can assess soil pH, salinity, organic matter content, and heavy metal contamination, providing comprehensive soil health diagnostics essential for sustainable crop production under climate variability.

Plant-based nanosensors provide unprecedented insights into crop physiological status and stress responses. These sensors may be applied externally to plant surfaces or embedded within plant tissues to monitor water status, nutrient deficiencies, hormone levels, and early pathogen invasion (Giraldo *et al.*, 2019). For instance, carbon nanotube-based sensors integrated into plant leaves can detect water stress prior to visible wilting, enabling timely irrigation

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interventions that conserve water and sustain yield. Such early warning capabilities are increasingly valuable in regions experiencing frequent droughts and erratic rainfall patterns due to climate change.

Fluorescent nanosensors utilizing quantum dots or fluorescent nanoparticles facilitate early-stage detection of plant pathogens and pests, often before the appearance of visual symptoms (Khater *et al.*, 2017). These sensors identify specific pathogen biomarkers, including proteins, nucleic acids, and metabolites, allowing rapid and accurate diagnosis. Early detection enhances the effectiveness of disease management strategies such as resistant cultivar deployment and targeted interventions, thereby reducing pesticide dependency (Makwana *et al.*, 2023; Kulkarni & Sabeena 2023).

The integration of nanosensors with digital agriculture technologies has led to the development of intelligent farming systems that support data-driven decision-making. Wireless nanosensor networks deployed across fields continuously collect data on soil, plant, and environmental parameters and transmit them to cloud-based platforms for analysis using artificial intelligence and predictive modeling tools (Raliya *et al.*, 2018). These systems enable precision agriculture practices such as variable-rate input application, automated irrigation scheduling, and early prediction of pest and disease outbreaks, enhancing overall farm efficiency.

Climate monitoring through nanosensor networks provides localized, real-time data on temperature, humidity, solar radiation, and precipitation trends. This high-resolution climate information improves the prediction of crop growth stages, pest emergence, and disease risk, facilitating proactive farm management strategies (Rai *et al.*, 2021). Such localized monitoring is particularly important as climate change increases spatial and temporal variability in weather patterns, reducing the reliability of generalized regional forecasts.

The miniaturized design and low energy requirements of nanosensors allow deployment in resource-limited and remote agricultural settings where conventional monitoring infrastructure is often unavailable. Solar-powered nanosensor systems can operate autonomously for extended periods, making them especially suitable for smallholder farmers who are disproportionately affected by climate change (Husen & Siddiqi 2014). However, successful adoption requires addressing challenges related to sensor calibration, data interpretation, infrastructure development, and farmer capacity building to fully realize the benefits of nanosensor technologies in diverse agro-ecological contexts.

### Nano-Enabled Water Management

Water scarcity represents one of the most severe consequences of climate change for agriculture, with altered precipitation patterns, increased evapotranspiration rates, and depleted groundwater resources threatening crop production globally (Dimkpa *et al.*, 2019). Agriculture accounts for approximately 70% of global freshwater withdrawals, creating urgent need for technologies that enhance water use efficiency. Nanotechnology offers multiple approaches to optimize agricultural water management through improved irrigation systems, soil water retention enhancement, and development of drought-tolerant crops.

Nanomaterials can significantly improve soil water retention capacity, a critical factor for maintaining crop productivity under drought conditions. Hydrogel nanocomposites incorporating clay nanoparticles or carbon nanotubes exhibit superior water absorption and retention properties compared to conventional soil amendments (Elsawy *et al.*, 2017). These nano-enhanced hydrogels can absorb water quantities hundreds of times their own weight and release it gradually to plant roots as soil dries, effectively buffering crops against short-term drought stress. Application of such nanomaterials in sandy or degraded soils can increase water holding capacity by 40-60%, substantially reducing irrigation requirements.

Zeolite nanoparticles and nano clays serve as effective soil conditioners that improve soil structure, reduce water evaporation, and enhance nutrient retention alongside water conservation benefits (Mahmoodi *et al.*, 2018). These nanomaterials create microporous structures in soil that facilitate water infiltration during rainfall or irrigation while reducing surface runoff and deep percolation losses. The improved soil structure also enhances root development, enabling plants to access water from greater soil depths during drought periods.

Nanotechnology enables development of intelligent irrigation systems through integration with nanosensors and nano-enabled actuators. Real-time soil moisture monitoring using nanosensor networks, coupled with weather forecasting and evapotranspiration modeling, enables precision irrigation that delivers water only when and where needed (Raliya *et al.*, 2018). This approach can reduce irrigation water use by 30-50% compared to conventional scheduling methods while maintaining or improving crop yields. Nano-coated drip irrigation systems exhibit reduced fouling and extended operational life, decreasing maintenance costs and improving system reliability.

Foliar application of certain nanoparticles can enhance plant drought tolerance through multiple mechanisms. Silicon dioxide nanoparticles have been shown to reduce transpiration rates, enhance photosynthetic efficiency under water stress, and improve root hydraulic conductivity (Rastogi *et al.*, 2019). Titanium dioxide and zinc oxide nanoparticles act as anti-transpirants by inducing partial stomatal closure while maintaining adequate carbon dioxide uptake for photosynthesis. These effects enable crops to maintain productivity with reduced water consumption, a critical adaptation strategy for drought-prone regions.

Nanoparticles also serve as carriers for plant hormones and osmoprotectants that enhance drought stress tolerance. Nano-encapsulated abscisic acid, proline, or glycine betaine can be delivered to plants through foliar spray or seed treatment, triggering physiological and biochemical responses that improve water stress resilience (Dimkpa *et al.*,

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2019). The controlled release provided by nanocarriers ensures sustained availability of these protective compounds throughout stress periods, offering more consistent protection than single applications of non-encapsulated compounds.

Development of nano-enabled desalination and water purification technologies contributes to agricultural water security by expanding the availability of usable water sources. Graphene oxide membranes, carbon nanotube filters, and photocatalytic titanium dioxide nanoparticles enable efficient removal of salts, pathogens, and contaminants from brackish water or wastewater, rendering them suitable for irrigation (Qu *et al.*, 2013). These technologies are particularly relevant for coastal agricultural regions facing seawater intrusion into aquifers due to sea-level rise and regions where water scarcity forces reliance on marginal quality water sources.

The cumulative water-saving effects of nano-enabled technologies contribute significantly to climate change mitigation by reducing the energy required for water pumping, treatment, and distribution. Agriculture-related water pumping accounts for substantial greenhouse gas emissions globally, and reducing irrigation water demand by 30-50% through nanotechnology applications would yield proportional reductions in energy consumption and emissions (Kah *et al.*, 2018). These benefits are particularly pronounced in regions relying on groundwater irrigation where pumping depths and energy requirements are substantial.

### Nanotechnology for Soil Health and Carbon Sequestration

Soil degradation accelerated by climate change threatens agricultural sustainability through reduced fertility, increased erosion susceptibility, and diminished carbon storage capacity. Nanotechnology offers innovative solutions for soil remediation, fertility enhancement, and carbon sequestration that contribute to both climate change adaptation and mitigation (Usman *et al.*, 2020). Healthy, carbon-rich soils not only support productive agriculture but also serve as significant carbon sinks, potentially offsetting agricultural greenhouse gas emissions.

Nanomaterials can remediate contaminated and degraded soils through various mechanisms including adsorption, catalytic degradation, and immobilization of pollutants. Zero-valent iron nanoparticles effectively remove heavy metals, pesticides, and organic contaminants from agricultural soils through reduction and precipitation reactions (Yan *et al.*, 2013). Carbon-based nanomaterials such as biochar nanoparticles and graphene oxide exhibit high adsorption capacity for organic pollutants and excess nutrients, preventing their leaching into groundwater while improving soil quality. These remediation approaches restore soil functionality and enable continued agricultural use of degraded lands without requiring land expansion.

Nano-enabled biochar represents a particularly promising material for enhancing soil health and carbon sequestration. Conventional biochar improves soil properties, but its effects can be enhanced through nanotechnology modifications such as activation with metal nanoparticles or integration with nanoclays (Sohi, 2012). Nano-biochar composites exhibit superior cation exchange capacity, water retention, and nutrient holding capacity compared to unmodified biochar. Additionally, the recalcitrant carbon in biochar provides long-term carbon storage in soils, with residence times of hundreds to thousands of years, making it an effective tool for climate change mitigation.

Application of certain nanoparticles directly stimulates soil microbial communities that drive nutrient cycling and organic matter decomposition. Iron oxide nanoparticles, for example, can enhance activities of beneficial soil bacteria and fungi that solubilize nutrients and form symbiotic relationships with plant roots (Vishwakarma *et al.*, 2020). Nanomaterials also serve as carriers for beneficial microorganisms such as nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and mycorrhizal fungi, protecting them during application and enhancing their establishment in soil. These biological approaches reduce dependence on synthetic fertilizers while improving soil biological health.

Nanoparticles can modify soil aggregation and structure in ways that reduce erosion and enhance carbon storage. Polymer nanoparticles and nanoclays stabilize soil aggregates through binding mechanisms that increase aggregate strength and reduce vulnerability to water and wind erosion (Usman *et al.*, 2020). Improved aggregation creates protected microsites where organic matter accumulates and resists microbial decomposition, effectively sequestering carbon for extended periods. This aggregate-level carbon protection is particularly important under climate change scenarios where increased temperature and altered moisture regimes typically accelerate organic matter decomposition.

Nanotechnology enables development of slow-release soil amendments that provide sustained improvement in soil properties over time. Nano-encapsulated organic acids, humic substances, and microbial metabolites can be formulated to release gradually, providing continuous support for soil biological activity and nutrient availability (Mahmoodi *et al.*, 2018). This approach is more efficient than conventional organic amendments that often decompose rapidly or volatilize before plants can fully utilize them.

Monitoring soil carbon dynamics and microbial activity is enhanced through nanosensor technologies that provide real-time data on soil respiration, enzyme activities, and microbial population dynamics. These measurements enable verification of carbon sequestration and assessment of management practice effectiveness, supporting carbon credit programs and climate-smart agriculture initiatives (Raliya *et al.*, 2018). Accurate, cost-effective monitoring is essential for scaling up soil-based climate change mitigation efforts.

However, potential negative effects of nanoparticles on soil ecosystems require careful consideration. Some studies have reported that certain nanoparticles at high concentrations can inhibit soil microbial activity, disrupt nutrient

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cycling, or accumulate in soil food webs (Grillo *et al.*, 2021). The long-term fate of engineered nanoparticles in agricultural soils remains incompletely understood, necessitating comprehensive environmental risk assessments before widespread deployment. Sustainable implementation of nanotechnology for soil health requires balancing benefits against potential risks through appropriate selection of nanomaterials, application rates, and monitoring protocols.

**Table 1: Applications of Nanotechnology in Climate-Smart Agriculture.**

Application Area	Nanomaterial Type	Primary Function	Climate-Smart Benefits	Current Status
Nutrient Management	Nano-fertilizers (nano-urea, nano-NPK), nutrient-loaded nanocarriers	Controlled-release nutrient delivery, enhanced uptake efficiency	Reduced fertilizer use (25-50%), lower N <sub>2</sub> O emissions (40-50%), improved nutrient retention during heavy rainfall	Field trials, limited commercial products
Pest Management	Nano-pesticides, metal/metal oxide nanoparticles, nano-encapsulated active ingredients	Targeted pest control, enhanced bioavailability, slow release	Reduced pesticide application (60-80%), minimized non-target effects, decreased resistance development	Laboratory and greenhouse testing, emerging products
Water Management	Nano-hydrogels, zeolite nanoparticles, nanoclays	Improved soil water retention, reduced evaporation	Increased water holding capacity (40-60%), reduced irrigation needs (30-50%), enhanced drought tolerance	Field demonstrations, some commercial products
Crop Monitoring	Nanosensors (carbon nanotubes, quantum dots, gold nanoparticles)	Real-time detection of nutrients, water stress, pathogens	Early stress detection, precision input application, optimized resource use	Prototype development, limited field deployment
Soil Health	Nano-biochar, zero-valent iron nanoparticles, polymer nanoparticles	Soil remediation, carbon sequestration, improved soil structure	Enhanced soil fertility, long-term carbon storage, reduced erosion	Research stage, field trials ongoing
Disease Management	Metal nanoparticles (silver, copper oxide), nano-encapsulated fungicides	Antimicrobial activity, enhanced penetration	Improved disease control, reduced fungicide use, multiple modes of action	Laboratory efficacy testing, initial field trials
Stress Tolerance	SiO <sub>2</sub> , TiO <sub>2</sub> , ZnO nanoparticles, nano-encapsulated hormones	Anti-transpirant effects, induced stress responses	Enhanced drought and heat tolerance, maintained productivity under stress	Greenhouse and field research

## CONCLUSIONS

Nanotechnology offers transformative potential for developing climate-smart agricultural systems that are productive, resilient, and environmentally sustainable. Through applications in nutrient management, pest control, precision sensing, water conservation, and soil health improvement, nanomaterials address multiple climate-related challenges simultaneously. Nano-fertilizers enhance nutrient use efficiency while reducing greenhouse gas emissions, nano-pesticides provide targeted pest control with minimal environmental impact, nanosensors enable data-driven precision agriculture, and nano-enabled water management technologies optimize irrigation in drought-stressed environments. Collectively, these innovations contribute to both climate change adaptations by enhancing agricultural resilience and mitigation by reducing agriculture's environmental footprint.

The successful implementation of agricultural nanotechnology requires addressing challenges related to environmental and health safety, regulatory development, economic accessibility, and knowledge generation. Comprehensive risk assessments considering nanoparticle fate, transformation, and ecological impacts are essential for ensuring sustainable deployment. Developing appropriate regulatory frameworks that encourage innovation while protecting human health and the environment will facilitate responsible technology adoption. Reducing production costs and building capacity in resource-limited settings will ensure that nanotechnology benefits reach small-holder farmers who face disproportionate climate change impacts.

Future advancement of nano-enabled climate-smart agriculture demands interdisciplinary collaboration integrating nanoscience, agronomy, ecology, engineering, economics, and social sciences. Participatory research approaches involving farmers in technology development and evaluation will ensure practical relevance and social acceptance. Integration with complementary technologies such as artificial intelligence, robotics, and biotechnology will maximize benefits and create synergistic solutions for complex agricultural challenges.

As climate change continues to intensify pressures on agricultural systems, the need for innovative solutions becomes increasingly urgent. Nanotechnology represents a promising pathway toward sustainable agriculture that feeds growing populations while protecting planetary boundaries. With careful attention to safety, equity, and sustainability,

nano-enabled agricultural innovations can contribute significantly to global food security and climate change mitigation efforts in the decades ahead.

### CHALLENGES AND FUTURE PERSPECTIVES

While nanotechnology holds tremendous promise for climate-smart agriculture, several challenges must be addressed to realize its full potential. Environmental and human health safety concerns represent the foremost barrier to widespread adoption. The novel properties that make nanomaterials useful in agriculture also raise questions about their behavior in biological systems and ecosystems (Gardea-Torresdey *et al.*, 2014). Nanoparticles may cross biological barriers, accumulate in organisms, and exert toxic effects through mechanisms distinct from bulk materials. Although research to date has not identified widespread acute toxicity from agricultural nanomaterials at realistic exposure levels, long-term effects and multigenerational impacts remain poorly characterized.

The potential for nanoparticle accumulation in food crops represents a particular concern for food safety. Studies have shown that certain nanoparticles can be taken up by plant roots, translocated to edible tissues, and potentially enter the food chain (Zuverza-Mena *et al.*, 2017). While some nanoparticles may provide nutritional benefits (such as iron or zinc nanoparticles addressing micronutrient deficiencies), others could pose health risks if accumulated in food. Establishing maximum residue limits, developing detection methods, and conducting bioavailability and toxicity studies for nanoparticles in food crops are essential steps for ensuring consumer safety.

Regulatory frameworks for agricultural nanotechnology remain underdeveloped in most countries, creating uncertainty for both developers and users of nano-enabled agricultural products (Kah *et al.*, 2018). Existing regulations developed for conventional agricultural inputs may not adequately address the unique properties and behaviors of nanomaterials. Developing appropriate regulatory frameworks requires balancing innovation encouragement with precautionary principles, considering both product-specific risks and broader implications for agricultural systems and ecosystems. International harmonization of regulatory approaches would facilitate technology transfer and ensure consistent safety standards.

Economic factors significantly influence adoption of agricultural nanotechnology. Production costs for many nanomaterials exceed those of conventional agricultural inputs, limiting accessibility particularly for small-holder farmers in developing countries who face the greatest climate change impacts (Grillo *et al.*, 2021). Scaling up manufacturing processes, improving production efficiency, and developing cost-effective synthesis methods using locally available materials could reduce costs and enhance accessibility. Economic analyses must also account for the indirect benefits of nanotechnology such as reduced environmental remediation costs, improved human health, and enhanced ecosystem services.

Knowledge gaps regarding nanoparticle fate and behavior in agricultural environments constrain risk assessment and management. How nanoparticles transform under field conditions, interact with soil components, affect non-target organisms, and move through agricultural landscapes requires investigation across diverse soil types, climates, and cropping systems (Dimkpa *et al.*, 2019). Understanding these processes is essential for designing nanomaterials that maximize benefits while minimizing risks. Long-term field studies complementing laboratory research would provide crucial insights into real-world performance and environmental impacts.

Infrastructure and capacity building represent additional challenges, particularly in developing regions. Successful implementation of nano-enabled precision agriculture requires not only the technologies themselves but also supporting infrastructure such as internet connectivity, data management systems, and technical support services (Rai *et al.*, 2021). Building farmer capacity through training and education ensures effective technology use and enables informed decision-making. Extension services must evolve to address nanotechnology-related questions and provide guidance on appropriate application methods, safety precautions, and integration with existing farming practices.

Future research directions for agricultural nanotechnology should prioritize development of multifunctional nanomaterials that simultaneously address multiple climate-related challenges. For example, nanocarriers could be designed to deliver nutrients, pesticides, and drought-tolerance enhancing compounds in a single application, reducing labor and energy requirements. Developing nanomaterials from renewable, biodegradable sources would enhance sustainability and reduce environmental persistence concerns. Green synthesis methods using plant extracts, microorganisms, or agricultural wastes offer environmentally friendly alternatives to energy-intensive chemical synthesis approaches (Manikandan *et al.*, 2020).

Integration of nanotechnology with other emerging technologies such as artificial intelligence, robotics, and biotechnology will amplify benefits for climate-smart agriculture. Machine learning algorithms analyzing data from nanosensor networks could generate predictive models for crop stress, pest outbreaks, and optimal input application timing with unprecedented accuracy. Nano-enabled gene delivery systems could accelerate crop improvement by facilitating precise genome editing for climate resilience traits. Autonomous robots equipped with nanosensors could perform targeted interventions at individual plant level, maximizing efficiency while minimizing environmental impacts.

Participatory approaches involving farmers, researchers, policymakers, and consumers in technology development and deployment decisions will enhance social acceptance and ensure technologies address real needs. Understanding farmer perceptions, concerns, and preferences regarding nanotechnology is essential for designing products and

practices that are practically implementable and culturally appropriate (Grillo *et al.*, 2021). Public engagement and transparent communication about benefits and risks can build trust and support informed decision-making about nanotechnology adoption.

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