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Nanotechnology in Agronomy: Innovations in Crop Management

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Abstract:

Agriculture is facing unprecedented challenges due to population growth, climate change, soil degradation, and declining resource availability, necessitating innovative and sustainable solutions to enhance crop productivity. Nanotechnology, involving the manipulation of materials at the nanoscale (1–100 nm), has emerged as a transformative tool in agronomy. It offers novel approaches for improving input efficiency, crop health, and environmental sustainability. This review explores the multifaceted applications of nanotechnology in crop management, focusing on nano-fertilizers, nano-pesticides, smart delivery systems, and nanosensors. Nano-fertilizers improve nutrient-use efficiency through targeted and controlled nutrient release, while nano-pesticides enhance the precision and efficacy of plant protection agents, minimizing ecological harm. Smart nanosystems enable real-time monitoring and need-based input application, aligning with the principles of precision agriculture. The paper also discusses the mechanisms through which nanoparticles influence plant physiology and their potential role in enhancing stress tolerance. While the benefits are substantial, concerns regarding nanoparticle accumulation, environmental toxicity, and human health risks underscore the need for rigorous safety assessments and regulatory frameworks. Looking forward, integrating nanotechnology with artificial intelligence and green synthesis approaches may pave the way for climate-resilient, resource-efficient, and sustainable agricultural systems.

Keywords: Nano-fertilizers**,** Precision agriculture**,** Crop productivity**,** Smart delivery systems**,** Sustainable agronomy

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1 Introduction:

Agriculture, the backbone of global food security, is under increasing pressure to enhance productivity while ensuring environmental sustainability. Rapid population growth, climate change, depleting natural resources, and deteriorating soil health have all intensified the demand for innovative strategies to increase crop yields and minimize environmental degradation. Conventional agricultural practices, particularly the excessive use of chemical fertilizers and pesticides, have led to issues such as nutrient imbalances, pest resistance, soil and water pollution, and declining biodiversity. To overcome these limitations, it is imperative to adopt advanced, sustainable, and precise technologies in crop production systems. nanotechnology, which involves the manipulation of materials at the nanoscale (1–100 nm), has emerged as a promising frontier in agricultural sciences, particularly in agronomy. The unique physicochemical properties of nanomaterials such as high surface-area-to-volume ratio, increased reactivity, and enhanced mobility enable more efficient delivery and utilization of agricultural inputs. In crop management, nanotechnology offers a range of innovative solutions, including nano-fertilizers, nano-pesticides, smart delivery systems, and nanosensors, all designed to optimize input efficiency, improve crop productivity, and reduce environmental footprints.

One of the most prominent applications of nanotechnology in agronomy is the development of nano-fertilizers, which aim to address the inefficiencies of conventional fertilizers. Traditional fertilizers often suffer from low nutrient-use efficiency (NUE), with significant portions lost through leaching, volatilization, and runoff. Nano-fertilizers are designed to provide targeted and controlled nutrient delivery, ensuring better uptake by crops and minimizing nutrient losses. In addition, nanotechnology contributes to advanced pest and disease management, enabling precise delivery of active compounds with reduced dosages and prolonged efficacy. Smart nanosystems and sensors further aid in real-time monitoring of soil and plant health, supporting precision agriculture and reducing unnecessary inputs.

This review paper aims to explore the recent innovations in nanotechnology within agronomy, focusing on its applications in nutrient management, pest control, disease suppression, and precision farming. It also critically examines the underlying mechanisms of nanoparticle interactions with plants, potential environmental and health implications, and the current regulatory landscape. As nanotechnology continues to evolve, it holds the potential to

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revolutionize crop management practices, contributing to more resilient, productive, and sustainable agricultural systems.

2. Nano-Fertilizers: Enhancing Nutrient Efficiency

The application of nanotechnology in agronomy has led to the development of nano-fertilizers, which are engineered to enhance the delivery, uptake, and utilization of essential plant nutrients. Nano-fertilizers are defined as materials that supply nutrients to crops in nano-sized forms (1–100 nm) or utilize nanocarriers to improve the effectiveness of conventional fertilizers. These formulations are designed to increase nutrient use efficiency (NUE), minimize nutrient losses through leaching, volatilization, and fixation, and reduce the frequency of fertilizer application, thereby contributing to sustainable and precision agriculture (De Rosa *et al*., 2010; Subramanian & Tarafdar, 2011).

Conventional fertilizers often suffer from low nutrient-use efficiency due to rapid solubility, runoff, and environmental losses. In contrast, nano-fertilizers offer advantages such as a higher surface-area-to-volume ratio, improved solubility, better interaction with plant surfaces, and the possibility of controlled and targeted nutrient release (Raliya & Tarafdar, 2013). These features make nano-fertilizers a potential game changer in nutrient management under both conventional and climate-stressed agricultural systems.

2.1 Types of Nano-Fertilizers

Nano-fertilizers can be broadly classified into the following categories based on their composition and mechanism of nutrient delivery:

(a) Nutrient-Loaded Nanoparticles

These are inorganic or organic nanoparticles that directly supply nutrients to plants in nano-form. The particles themselves consist of essential plant nutrients or serve as nutrient carriers. The key advantage is their ability to be absorbed more efficiently due to their nano-scale size, leading to improved bioavailability and rapid plant uptake.

Nano-Zinc Oxide (ZnO): Zinc is essential for enzyme activation and protein synthesis. Studies have demonstrated that foliar or soil application of nano-ZnO enhances plant growth and yield in crops like maize and wheat (Dimkpa *et al*., 2017).

Nano-Iron Oxide (Fe_2O_3): Iron plays a crucial role in chlorophyll synthesis and photosynthesis. Nano-iron particles offer higher mobility in soil and improved uptake by plants, particularly under calcareous or alkaline soil conditions (Prasad *et al*., 2012).

Nano-Urea: A nitrogenous nano-formulation that offers controlled release of urea, minimizing nitrogen losses and improving nitrogen-use efficiency. Research by Indian Agricultural Research Institute (IARI) showed that nano-urea application increased grain yield in wheat by 8–10% while reducing the required nitrogen dose (ICAR-IARI, 2021).

(b) Slow-Release Nanocarriers

These are nano-scale materials that encapsulate or adsorb nutrients and release them gradually over time, synchronized with plant nutrient demand. Slow-release nano-fertilizers prevent nutrient losses and reduce environmental pollution.

Chitosan Nanoparticles: Derived from chitin, chitosan is biodegradable and biocompatible. Chitosan nanoparticles have been widely explored for delivering micronutrients like zinc, copper, and iron. Their cationic nature enables strong binding with negatively charged soil particles and plant membranes, enhancing nutrient retention and uptake (Sabir *et al*., 2014).

Clay-Based Nanomaterials: Halloysite nanotubes and montmorillonite clays are used as carriers for nutrients such as potassium and phosphorus. These materials provide a large surface area for nutrient adsorption and allow for pH-sensitive or moisture-sensitive nutrient release (Kah *et al*., 2018).

Polymer-Coated Nanocarriers: Synthetic biodegradable polymers like polylactic acid (PLA) or polyhydroxybutyrate (PHB) are employed for encapsulating nutrients such as nitrogen and phosphorus. These systems have been shown to enhance crop productivity by ensuring continuous nutrient supply throughout the crop lifecycle (Liu & Lal, 2015).

2.2 Benefits

Nano-fertilizers offer several significant advantages in crop management. They enhance nutrient use efficiency (NUE) by improving the uptake of nutrients due to their small particle size and large surface area, which facilitates better absorption and utilization by plants. Additionally, they reduce nutrient losses that commonly occur through leaching,

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volatilization, and runoff in conventional fertilizer systems. A key advantage is their ability to provide controlled and slow nutrient release, ensuring a consistent nutrient supply throughout the crop's growth period and reducing the frequency of application. Nano-fertilizers also allow for targeted delivery of nutrients to specific plant parts, such as the root zone or foliar tissues, resulting in more efficient nutrient availability. These properties contribute to improved crop growth and yield, as plants receive nutrients more effectively and suffer less from nutrient stress. Furthermore, their use supports environmental sustainability by minimizing excess fertilizer input and reducing contamination of soil and water resources. Some nano-formulations also enhance plant tolerance to abiotic stresses, such as drought, salinity, and heat, by boosting physiological and metabolic responses. Finally, nano-fertilizers are compatible with precision farming technologies, enabling site-specific and need-based nutrient application that aligns with modern sustainable agriculture practices.

3. Nano-Pesticides and Crop Protection

Nano-pesticides represent a novel class of plant protection agents that utilize nanotechnology to enhance the efficacy, precision, and environmental safety of pesticides used in crop protection. These formulations either contain active ingredients in nanoscale forms or involve conventional pesticides encapsulated within nanocarriers such as liposomes, micelles, polymers, or metal and metal oxide nanoparticles (Kah *et al*., 2013). By leveraging nanoscale delivery systems, nano-pesticides facilitate targeted and controlled release of pesticides, allowing the active compounds to be released in response to specific environmental conditions such as pH, temperature, or moisture levels, thereby minimizing wastage and maximizing efficacy (Gogos *et al*., 2012).

For instance, silver nanoparticles (AgNPs) have demonstrated strong antimicrobial properties and have been effective against a wide range of plant pathogens including fungi and bacteria, providing an alternative to traditional chemical pesticides (Jo *et al*., 2009). Similarly, silica and alumina nanoparticles have shown insecticidal action by disrupting the protective cuticle of insects, leading to desiccation and death without the use of toxic chemicals (Barik, 2012). The encapsulation of pesticides in nanomaterials, such as chitosan or polymeric nanoparticles, protects the active ingredient from premature degradation by UV light or microbial activity and enhances the adhesion of pesticides on plant surfaces, reducing runoff losses (Grillo *et al*., 2014).

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Moreover, nano-pesticides can penetrate plant tissues and microbial biofilms more efficiently, providing more effective control of internal or systemic pests and diseases (Kah & Hofmann, 2014). This enhanced delivery not only reduces the frequency and dosage of pesticide applications but also lowers the risk of pesticide resistance development and environmental contamination. However, while the potential benefits are considerable, there is a growing need for comprehensive risk assessment and regulatory guidelines to ensure the safe use of nano-pesticides, particularly concerning their persistence, bioaccumulation, and impact on non-target organisms (Parisi *et al*., 2015).

4. Nanotechnology in Plant Disease Management

Nanotechnology has emerged as a promising approach in plant disease management by enabling the development of nano-based antimicrobial agents such as silver (Ag), copper (Cu), and zinc oxide (ZnO) nanoparticles that exhibit broad-spectrum antifungal, antibacterial, and antiviral activities, thereby effectively suppressing phytopathogens and reducing dependence on conventional chemical pesticides (Choudhury *et al*., 2017; Kalia *et al*., 2021); for instance, silver nanoparticles have been shown to inhibit spore germination and mycelial growth of *Fusarium oxysporum*, a common soil-borne fungus, while chitosan-based nanocomposites can serve both as carriers and elicitors of plant immune responses, enhancing systemic resistance without leaving harmful residues (Kashyap *et al*., 2015; Rai *et al*., 2012).

5. Smart Delivery Systems and Nanosensors

represent an advanced application of nanotechnology in agronomy, enabling the precise, real-time monitoring and controlled release of nutrients, agrochemicals, and environmental signals**;** these systems use stimuli-responsive nanocarriers (such as pH-, temperature-, or moisture-sensitive materials) that release nutrients or pesticides only when needed, while nanosensors detect critical parameters like soil moisture, nutrient levels, pest presence, or disease onset, thereby supporting precision farming and minimizing resource wastage (Kah *et al*., 2018; Sekhon, 2014).

6. Mechanisms of Nanoparticle Action in Plants

Nanoparticles influence plant growth and physiology through multiple mechanisms, including enhanced nutrient solubility, increased bioavailability, and improved translocation

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within plant tissues. Due to their ultra-small size and high surface area-to-volume ratio, nanoparticles can easily penetrate plant cell walls and membranes, facilitating more efficient nutrient uptake and intracellular movement (Rico *et al*., 2011). Once inside the plant, they may stimulate enzymatic activity, improve photosynthetic efficiency, and promote the synthesis of proteins and hormones involved in plant development (Raliya & Tarafdar, 2013). Certain nanoparticles, such as nano-ZnO or nano-Fe, have been shown to increase chlorophyll content and boost antioxidant enzyme activity, thereby enhancing stress tolerance against drought, salinity, and pathogens (Dimkpa *et al*., 2017). Additionally, nanoparticles may act as elicitors by triggering systemic resistance mechanisms and enhancing metabolic pathways that contribute to plant defense (Wang *et al*., 2016). Their controlled-release properties ensure sustained nutrient availability, aligning nutrient supply with plant demand and reducing physiological stress. These mechanisms collectively lead to improved plant growth, nutrient use efficiency, and resilience under adverse environmental conditions.

7. Environmental and Health Considerations

While nano-fertilizers offer significant agronomic advantages, their potential environmental and health impacts remain a growing concern**,** as the long-term accumulation of nanoparticles in soil, water, and plant tissues may pose risks to soil microbiota, ecosystem functions, and human health through the food chain; studies have shown that some engineered nanoparticles, such as ZnO and TiO_2, can induce oxidative stress in plants and disrupt soil microbial diversity, highlighting the urgent need for thorough toxicological evaluations and the establishment of regulatory guidelines for their safe use (Kah *et al*., 2018; Rico *et al*., 2011; OECD, 2016).

8. Future Perspectives

As the global agricultural sector strives to meet the increasing demands of food security, climate resilience, and environmental sustainability, nanotechnology presents a transformative opportunity in the field of agronomy. Future research should prioritize the development of eco-friendly, biodegradable, and cost-effective nanomaterials that ensure both agronomic efficiency and environmental safety. Integrating artificial intelligence (AI), machine learning, and remote sensing with nanosensors could pave the way for ultra-precise, real-time crop monitoring and input management systems.

There is immense potential to design next-generation smart nanocarriers capable of multi-functional roles delivering nutrients, agrochemicals, and growth regulators simultaneously in a crop-specific and climate-responsive manner. Advancing green synthesis methods using plant extracts, fungi, or microorganisms can reduce the ecological footprint of nanomaterial production and enhance biocompatibility.

However, to fully harness the benefits of nanotechnology in agriculture, there is a critical need for establishing standardized safety protocols, risk assessment models, and global regulatory frameworks**.** Long-term field studies and lifecycle analyses must be conducted to understand nanoparticle behavior, persistence, and potential bioaccumulation in agroecosystems. Collaborative efforts among researchers, policymakers, farmers, and industry stakeholders will be essential to ensure that nanotechnology is scaled responsibly and ethically for agricultural applications.

9. Conclusion

Nanotechnology offers a promising and innovative platform to revolutionize crop management practices in agronomy. Through nano-fertilizers, nano-pesticides, smart delivery systems, and nanosensors, it enhances input efficiency, reduces environmental losses, and improves crop productivity and resilience. The mechanisms by which nanoparticles interact with plant systems allow for targeted delivery, controlled release, and stress mitigation, making them valuable tools for sustainable agriculture.

Despite these advantages, the potential risks associated with nanomaterial accumulation in soil and plant systems, and their impact on non-target organisms and human health, necessitate careful examination. As the field advances, responsible innovation underpinned by scientific validation, risk governance, and stakeholder engagement will be crucial to ensuring the safe and effective integration of nanotechnology into mainstream agronomic practices. With continued research and regulatory support, nanotechnology can become a cornerstone of future-ready, climate-smart, and environmentally sustainable agriculture.

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