

Nanotechnology in Agriculture: Current Status, Applications and Future Opportunities

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Abstract

Nanotechnology has emerged as a transformative technology with significant potential to address the growing challenges of modern agriculture, including food security, declining soil fertility, environmental degradation, and climate change. The application of nanomaterials in agriculture has led to the development of innovative products such as nanofertilizers, nanopesticides, nanosensors, and nano-enabled delivery systems that enhance agricultural productivity while minimizing environmental impacts. Nanofertilizers improve nutrient-use efficiency through controlled nutrient release, enhanced nutrient uptake, and reduced losses caused by leaching, volatilization, and fixation. Similarly, nanopesticides provide targeted pest and disease management, increased stability of active ingredients, and reduced chemical application rates, thereby lowering environmental contamination. Despite the considerable advantages of nano-enabled agricultural technologies, concerns regarding environmental fate, toxicity, bioaccumulation, regulatory frameworks, and long-term sustainability remain important challenges. This review summarizes the current status of nanotechnology in agriculture, with particular emphasis on nanofertilizers, nanopesticides, and their effects on soil–plant systems. Furthermore, future opportunities, research priorities, and challenges associated with the safe and sustainable implementation of nanotechnology in agriculture are discussed.

Keywords: Nanotechnology, Agriculture, Nanofertilizers, Nanopesticides, Soil–Plant Interactions,

Introduction

Agriculture faces unprecedented challenges due to increasing global population, declining arable land, climate change, and the need for sustainable resource management. The world's population is projected to exceed 9.7 billion by 2050, necessitating a substantial increase in food production while minimizing environmental impacts. Conventional agricultural practices rely heavily on chemical fertilizers and pesticides, which often result in low nutrient-use efficiency, environmental contamination,

soil degradation, and adverse effects on non-target organisms (Kah et al., 2018).

Nanotechnology, defined as the manipulation and application of materials with dimensions between 1 and 100 nm, has emerged as a promising tool for enhancing agricultural productivity and sustainability. Nanomaterials exhibit unique physicochemical properties, including high surface area, enhanced reactivity, controlled-release characteristics, and improved mobility, making them suitable for agricultural applications (Nair et al., 2010).

The integration of nanotechnology into agriculture has led to the development of nanofertilizers, nanopesticides, nanosensors, and nano-enabled delivery systems that improve resource-use efficiency and reduce environmental losses.

Recent studies have demonstrated that nano-enabled agricultural inputs can significantly improve nutrient uptake, crop growth, disease management, and stress tolerance while reducing the quantities of agrochemicals required (Khot et al., 2012). Consequently, nanotechnology is increasingly recognized as a key component of precision agriculture and sustainable crop production systems.

Nanofertilizers

Nanofertilizers are nutrient formulations in which nutrients are encapsulated, coated, or delivered through nanomaterials to enhance nutrient availability and uptake by plants. Compared with conventional fertilizers, nanofertilizers offer controlled nutrient release, reduced nutrient losses through leaching and volatilization, improved nutrient-use efficiency, and increased crop productivity (Subramanian et al., 2015).

The small particle size and high surface area of nanofertilizers facilitate better interaction with plant roots and leaves, enabling efficient nutrient absorption. Nanofertilizers can be applied through soil, seed treatment, or foliar sprays. They provide nutrients according to crop demand, thereby minimizing environmental pollution and reducing fertilizer application rates (Dimkpa & Bindraban, 2018).

Table 1. Major Nanofertilizers and Their Agricultural Applications

Nanofertilizer	Nutrient Delivered	Major Function	Crop Response	Reference
Nano Urea	Nitrogen	Controlled N release	Increased grain yield and NUE	Subramanian et al. (2015)
Nano Zinc Oxide (ZnO)	Zinc	Corrects Zn deficiency	Improved growth and chlorophyll content	Raliya et al. (2015)
Nano Iron Oxide (Fe ₂ O ₃)	Iron	Enhances Fe availability	Improved photosynthesis	Ghafariyan et al. (2013)
Nano Hydroxyapatite	Phosphorus	Slow-release P	Reduced phosphorus	Liu & Lal (2015)

		source	fixation	
Nano Potassium Fertilizer	Potassium	Controlled K release	Improved crop quality and yield	Chhipra (2017)
Nano Silica	Silicon	Stress mitigation	Enhanced drought tolerance	Suriyaprabha et al. (2012)

Nanofertilizers have shown significant potential in increasing nutrient-use efficiency (NUE), often exceeding 80–90%, compared with 30–50% efficiency observed for conventional fertilizers (Dimkpa & Bindraban, 2018). However, large-scale adoption requires comprehensive assessments of environmental safety, cost-effectiveness, and regulatory compliance.

Nanopesticides

Nanopesticides are formulations in which active ingredients are encapsulated, adsorbed, or formulated using nanocarriers to improve pesticide performance. They enhance pesticide stability, increase target specificity, provide controlled release, and reduce environmental contamination (Kah et al., 2013).

Nanocarriers such as polymeric nanoparticles, liposomes, silica

nanoparticles, and metal nanoparticles facilitate the efficient delivery of active compounds to target pests and pathogens. These formulations improve bioavailability and reduce the frequency and quantity of pesticide applications (Khot et al., 2012).

Table 2. Major Nanopesticides and Their Agricultural Applications

Nanopesticide	Active Material	Target Pest/Disease	Major Benefit	Reference
Silver nanoparticles	AgNPs	Fungal pathogens	Strong antimicrobial activity	Jo et al. (2009)
Copper nanoparticles	CuNPs	Bacterial and fungal diseases	Enhanced disease control	Usman et al. (2020)
Nano-encapsulated Azadirachtin	Neem-based pesticide	Insect pests	Controlled release and longer persistence	Anjali et al. (2010)
Silica nanoparticles	SiO ₂ NPs	Stored grain insects	Physical insecticidal action	Debnath et al. (2011)
Chitosan nanoparticles	Chitosan	Plant pathogens	Biodegradable and antimicrobial	Divya & Jisha (2018)
Nanoeulsio	Variou	Broad-	Improved	Kah et al.

n formulations	insect icides	spectr um pests	dispers ion and efficac y	(201 3)
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Nanopesticides can significantly reduce pesticide application rates while maintaining effective pest control. Additionally, their controlled-release properties reduce off-target effects and environmental contamination. Nevertheless, concerns remain regarding nanoparticle persistence, ecotoxicity, and impacts on beneficial organisms.

Effect of Nanomaterials on Soil-Plant Systems

The interaction of nanomaterials with soil and plants is complex and depends on nanoparticle characteristics, soil properties, plant species, and environmental conditions. Nanomaterials can positively influence plant growth by improving nutrient availability, stimulating enzymatic activity, enhancing photosynthesis, and increasing stress tolerance (Rico et al., 2011).

In soil systems, nanoparticles may alter microbial communities, nutrient cycling, and soil enzyme activities. Certain nanomaterials such as nano-ZnO, nano-TiO₂, and nano-SiO₂ have been reported to stimulate plant growth and increase biomass production. For

example, nano-TiO₂ enhances photosynthetic efficiency and nitrogen metabolism, resulting in improved crop performance (Yang et al., 2006).

However, excessive concentrations of nanoparticles may induce phytotoxicity through oxidative stress, membrane damage, and disruption of metabolic processes. Metal-based nanoparticles, including silver and copper nanoparticles, can negatively affect beneficial soil microorganisms and alter soil ecological balance (Rico et al., 2011). Accumulation of nanoparticles in edible plant tissues may also raise concerns regarding food safety and human health.

Studies indicate that the environmental behavior of nanomaterials is strongly influenced by aggregation, dissolution, transformation, and interactions with soil organic matter. Therefore, long-term investigations are necessary to evaluate their environmental fate and ecological impacts before widespread agricultural deployment (Dimkpa & Bindraban, 2018).

Conclusions

Nanotechnology represents a transformative approach for achieving sustainable agricultural intensification.

Nano-enabled fertilizers and pesticides offer substantial improvements in nutrient-use efficiency, pest management, crop productivity, and environmental protection compared with conventional agricultural inputs. Nanofertilizers provide controlled nutrient release and enhanced nutrient uptake, while nanopesticides improve pesticide efficacy and reduce chemical losses.

Despite these advantages, uncertainties regarding environmental fate, toxicity, bioaccumulation, and long-term ecological consequences remain. Future research should focus on developing biodegradable nanomaterials, establishing regulatory frameworks, conducting life-cycle assessments, and evaluating field-scale performance under diverse agroecological conditions. The successful integration of nanotechnology into precision agriculture could play a pivotal role in ensuring global food security while minimizing environmental impacts.

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