



# International Journal of Research in Agronomy

E-ISSN: 2618-0618  
P-ISSN: 2618-060X  
© Agronomy  
NAAS Rating: 5.20  
[www.agronomyjournals.com](http://www.agronomyjournals.com)  
2025; 8(4): 170-172  
Received: 07-01-2025  
Accepted: 11-02-2025

**Chuncha Laxmi Prasanna**  
Ph.D. Scholar, Department of Soil  
Science and Agricultural Chemistry,  
University of Agricultural Sciences,  
GKVK, Bangalore, Karnataka, India

**Rashmi Mohapatra**  
Associate Professor (Botany) and Head,  
Department of Centre for Indigenous  
Knowledge on Herbal Medicines and  
Therapeutics, Kalinga Institute of  
Social Sciences (KISS), Deemed to be  
University, Bhubaneswar, Odisha, India

**Sonali Sangwan**  
Assistant Professor, Department of Bio-  
Sciences & Technology Maharishi  
Markandeshwar Engineering College,  
Maharishi Markandeshwar (Deemed to  
be University), Mullana, Ambala,  
Haryana, India

**Dr. Sandeep Upadhyay**  
Teaching cum Research Associate  
Department of Soil Science Rani  
Lakshmi Bai Central Agricultural  
University, Jhansi, Uttar Pradesh,  
India

**Anu Seng Chaupoo**  
Teaching Assistant, Department of  
Horticulture, Faculty of Agricultural  
Sciences Rajiv Gandhi University, Rono  
Hills, Doimukh, Arunachal Pradesh,  
India

**Dr. Pravin P Pawar,**  
Assistant Professor, Department of  
Physics Thakur College of Science and  
Commerce, Kandivali, Mumbai,  
Maharashtra, India

**Dr. Milind Janardan Kulkarni**  
Assistant Professor in Physics  
Department of Physics R. D. and S. H.  
National College and S. W. A. Science  
College, Mumbai, Maharashtra, India

**Dr. Shubham Gupta**  
Assistant Professor Department of  
School of Agricultural Sciences and  
Engineering, IFTM University,  
Moradabad, Uttar Pradesh, India

**Corresponding Author:**  
**Chuncha Laxmi Prasanna**  
Ph.D. Scholar, Department of Soil  
Science and Agricultural Chemistry,  
University of Agricultural Sciences,  
GKVK, Bangalore, Karnataka, India

## Exploring the potential of nanotechnology in crop protection and soil health

**Chuncha Laxmi Prasanna, Rashmi Mohapatra, Sonali Sangwan, Sandeep Upadhyay, Anu Seng Chaupoo, Pravin P Pawar, Milind Janardan Kulkarni and Shubham Gupta**

**DOI:** <https://www.doi.org/10.33545/2618060X.2025.v8.i4c.2761>

### Abstract

Nanotechnology has emerged as a groundbreaking innovation in agriculture, offering precise and sustainable solutions for crop protection and soil health management. By leveraging nanomaterials such as nanoparticles, nanoemulsions, and nanocapsules, researchers have developed advanced systems for targeted agrochemical delivery, enhanced nutrient uptake, and improved soil fertility. This review critically examines recent advancements in nanotechnology applications, including nanopesticides, nanofertilizers, and nanosensors, while addressing their environmental and safety implications. We also discuss challenges and future prospects for integrating nanotechnology into sustainable agricultural practices. The findings highlight nanotechnology's potential to revolutionize modern farming while emphasizing the need for regulatory frameworks to ensure safe and large-scale adoption.

**Keywords:** Nanotechnology, nanopesticides, nanofertilizers, soil health, sustainable agriculture, nanosensors, environmental safety

### 1. Introduction

Modern agriculture faces unprecedented challenges from population growth, climate change, and environmental degradation. The global population is projected to reach 9.7 billion by 2050, requiring a 70% increase in food production. However, conventional agricultural practices have led to significant ecological consequences, including pesticide resistance in over 500 weed and insect species and the degradation of nearly 33% of the world's arable land (FAO, 2015). These challenges demand innovative solutions that can enhance productivity while minimizing environmental impact.

Nanotechnology has emerged as a transformative approach in agriculture, offering precise solutions at the molecular level. Engineered nanomaterials (1-100 nm) exhibit unique properties such as high surface area-to-volume ratio and quantum effects that enable targeted delivery of agrochemicals. Recent advancements include nano-encapsulated pesticides that reduce chemical usage by 30-70% while maintaining efficacy (Kah *et al.*, 2018) [6], and nanofertilizers that improve nutrient use efficiency by 40-60% compared to conventional formulations. However, the rapid development of agricultural nanotechnology has outpaced regulatory frameworks, raising concerns about potential ecosystem impacts. This review provides a comprehensive analysis of current applications, environmental implications, and future directions for nanotechnology in sustainable agriculture.

### 2. Nanotechnology in Crop Protection

#### 2.1 Nanopesticides

Nanopesticides represent a paradigm shift in pest management by overcoming the limitations of conventional formulations. Traditional pesticides suffer from low absorption rates (typically <20%), photodegradation, and non-target effects (Kah & Hofmann, 2014) [6]. Nanoformulations address these issues through enhanced bioavailability, with studies showing 2-3 times greater

foliar adhesion and penetration compared to conventional sprays (Nuruzzaman *et al.*, 2016) <sup>[8]</sup>. For instance, chitosan-based nanocapsules loaded with lambda-cyhalothrin demonstrated 85% pest mortality at half the standard dosage while reducing environmental persistence by 40%.

Recent innovations focus on smart delivery systems that respond to environmental triggers. pH-sensitive polymeric nanoparticles release their payload only in the alkaline gut of target insects, minimizing off-target effects (Adak *et al.*, 2022) <sup>[1]</sup>. Metallic nanoparticles like silver (Ag) and copper oxide (CuO) exhibit broad-spectrum antimicrobial properties, with AgNPs showing 80% inhibition of fungal pathogens at concentrations as low as 50 ppm (Jo *et al.*, 2021) <sup>[15]</sup>. However, the potential accumulation of these metal nanoparticles in soil ecosystems requires careful evaluation, as studies indicate they may alter microbial community composition at concentrations above 100 mg/kg (Ge *et al.*, 2022) <sup>[3]</sup>.

## 2.2 Nanoherbicides

The evolution of herbicide-resistant weeds has become a major threat to global food security, with over 250 documented cases worldwide. Nanoherbicides offer a solution through enhanced cellular penetration and reduced environmental persistence. Mesoporous silica nanoparticles (MSNs) loaded with glyphosate have demonstrated 95% weed control efficacy at half the recommended field dose, while reducing soil leaching by 60% compared to commercial formulations (Grillo *et al.*, 2021) <sup>[4]</sup>. This targeted approach is particularly valuable for managing resistant weed biotypes that have evolved mechanisms to exclude conventional herbicides.

Advanced encapsulation techniques are improving herbicide performance and safety. Alginate-chitosan nanocapsules containing atrazine showed 30-day sustained release in field trials, maintaining effective concentrations while preventing groundwater contamination (Campos *et al.*, 2022) <sup>[2]</sup>. Lipid-based nanoemulsions of essential oils (e.g., clove and peppermint) have emerged as biodegradable alternatives, achieving 70-80% weed suppression without leaving toxic residues. These developments are particularly promising for organic farming systems where synthetic herbicides are prohibited, though scale-up challenges and production costs remain barriers to widespread adoption.

## 3. Nanotechnology in Soil Health Management

### 3.1 Nanofertilizers

Conventional fertilizers suffer from low nutrient use efficiency (NUE), with only 30-50% of applied nutrients typically absorbed by crops (Liu *et al.*, 2022) <sup>[7]</sup>. Nanofertilizers address this through controlled release mechanisms and enhanced uptake pathways. Zinc oxide nanoparticles (ZnO NPs) applied to wheat crops at 50 ppm increased grain yields by 27% compared to conventional zinc sulfate, while reducing total zinc input by 60% (Raliya *et al.*, 2023) <sup>[9]</sup>. Similarly, nano-encapsulated phosphorus fertilizers demonstrated 60% higher uptake efficiency in maize, significantly reducing runoff losses (Liu *et al.*, 2022) <sup>[7]</sup>. These improvements are attributed to nanoparticles' ability to bypass soil fixation processes and directly interact with root membranes.

The next generation of nanofertilizers incorporates smart responsiveness to environmental conditions. Temperature-sensitive hydrogels loaded with nitrogen nutrients release their payload only when soil temperatures exceed 25°C, coinciding with peak plant demand. Carbon-based nanomaterials like graphene oxide have shown remarkable effects on nutrient

cycling, increasing nitrogen fixation rates by 40% through enhanced electron transfer in root nodules. However, long-term studies are needed to assess potential accumulation effects, as some carbon nanomaterials persist in soils for over 5 years.

### 3.2 Soil Remediation

Soil contamination with heavy metals and pesticides poses significant risks to food safety and ecosystem health. Nanotechnology offers innovative remediation strategies through enhanced adsorption and catalytic degradation. Iron oxide nanoparticles (Fe<sub>3</sub>O<sub>4</sub>) effectively immobilize cadmium in paddy soils, reducing rice grain accumulation by 75% through formation of stable Fe-Cd complexes. Titanium dioxide nanoparticles (TiO<sub>2</sub>) exhibit remarkable photocatalytic properties, degrading 90% of chlorpyrifos residues within 48 hours under sunlight exposure. These approaches are particularly valuable in developing countries where conventional remediation methods are often cost-prohibitive.

Emerging nanocomposites combine multiple functionalities for enhanced remediation. Graphene-zeolite hybrids have demonstrated simultaneous removal of heavy metals (Pb, Cd) and organic pollutants (atrazine) through synergistic adsorption and catalytic breakdown (Zhou *et al.*, 2023) <sup>[12]</sup>. Magnetic nanoparticles functionalized with humic acids show promise for in situ remediation, allowing easy recovery after treatment through magnetic separation. While these technologies show great potential, their large-scale application requires careful consideration of energy inputs and potential nanomaterial transformation products in the environment.

## 4. Environmental and Safety Concerns

The environmental fate of nanomaterials remains a critical knowledge gap in agricultural applications. Ecotoxicology studies reveal size- and coating-dependent effects, with uncoated silver nanoparticles (AgNPs) showing an LC50 of 10 mg/kg for earthworms - a concentration that could be reached after repeated applications (Shoultz-Wilson *et al.*, 2023) <sup>[10]</sup>. Soil microbial communities exhibit sensitivity to metal oxide nanoparticles, with ZnO concentrations above 100 ppm reducing dehydrogenase activity by 40% and altering bacterial diversity (Ge *et al.*, 2022) <sup>[3]</sup>. These findings highlight the need for rigorous risk assessment frameworks that consider both acute and chronic exposure scenarios.

Regulatory agencies are beginning to address these challenges through updated guidelines. The European Union's 2022 revision of REACH regulations includes specific provisions for nanomaterials, requiring comprehensive life cycle assessments. The U.S. EPA has added several nanomaterials to its Emerging Contaminant list, signaling increased regulatory scrutiny (USEPA, 2023) <sup>[11]</sup>. However, significant gaps remain in standardized testing protocols, particularly for long-term ecosystem effects and nanomaterial transformations under field conditions. International collaboration will be essential to develop harmonized regulations that facilitate innovation while ensuring environmental safety.

## 5. Future Perspectives

The next decade will likely see nanotechnology transition from experimental applications to mainstream agricultural practice. Key developments will include AI-optimized nanoformulations that predict optimal release kinetics based on weather patterns and crop growth stages. Advances in green synthesis methods using plant extracts and microbial systems could reduce production costs by 40-60% while minimizing toxic byproducts.

Circular economy approaches are emerging, with researchers developing recyclable nanocatalysts for pesticide degradation and nutrient recovery systems from agricultural waste.

Critical research priorities include: 1) Long-term (10+ year) field studies on nanomaterial fate and transport, 2) Development of biodegradable nanocarriers that mineralize after use, and 3) Socioeconomic analyses to ensure equitable access to nanotechnology solutions. Multidisciplinary collaborations between materials scientists, ecologists, and policymakers will be essential to realize nanotechnology's potential while addressing its challenges. The establishment of international nanoagriculture research consortia could accelerate progress through shared infrastructure and data standards.

## 6. Conclusion

Nanotechnology offers transformative solutions to pressing agricultural challenges, from precision pest management to enhanced soil remediation. The reviewed studies demonstrate significant advances in efficacy and efficiency, with nanoformulations typically outperforming conventional products by 30-80% across various metrics. However, responsible implementation requires balancing innovation with precaution, particularly regarding long-term ecosystem impacts. Three key recommendations emerge: First, investment in large-scale field trials to validate laboratory findings under real-world conditions. Second, development of international standards for nanomaterial characterization and risk assessment. Third, establishment of extension programs to educate farmers about proper nanotechnology use. By addressing these priorities, the agricultural sector can harness nanotechnology's potential while ensuring sustainable food systems for future generations.

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