DOI: 10.54083/BRT/08.01.26/06-09

Bio. Res. Today 2026, 8(1):06-09

Biotica Research Today

e-ISSN: 2582-6654

January, 2026

Article ID: RT1862

Popular Article

Securing Futures through Crop Protection with Nanotechnology

Pranab Dutta*, Lydia Vanlaltani, Manihar Talukdar and Abhigyan Bhattacharyya

College of Post Graduate Studies in Agricultural Sciences, Central Agricultural University (Imphal), Umiam, Meghalaya (793 103), India

Open Access

Corresponding Author

Pranab Dutta

: pranabdutta74@gmail.com

Conflict of interests: The author has declared that no conflict of interest exists.

How to cite this article?

Dutta, P., Vanlaltani, L., Talukdar, M. *et al*., 2026. Securing Futures through Crop Protection with Nanotechnology. *Biotica Research Today* 8(1), 06-09. DOI: 10.54083/BRT/08.01.26/06-09.

Abstract

Food demands are influencing developments in agriculture to address food challenges such as pests, soil erosion and climatic change as the population of the world continues to increase. Nanotechnology, especially phytonanotechnology, has now been used in modern agriculture where nanoparticles (NPs) of 1-100 nm are used to manage crops. The four major types of NPs, metallic, ceramic, carbon and polymer are significant especially the metallic NPs that have antibacterial properties such as zinc oxide, titanium dioxide, copper and silver. Plant size, chemical composition and plant development are factors that influence the degree to which NPs are effective against pathogens. They act by interfering with cell membrane and generating reactive oxygen species. Carrying out safety research on metal nanoparticles in crops is important. Some of the agricultural applications of nanotechnology encompass nanofertilizers to deliver nutrients efficiently, nano biosensors to monitor the levels of environmental contaminants and nano pesticides as an alternative to conventional pesticides to improve soil fertility and productivity of crops and lengthening of food shelf life.

Keywords: Antibacterial, Nanobiosensors, Nanofertilizers, Phytonanotechnology

Introduction

The need for food, particularly the production of staple crops, rises in tandem with the global population. Therefore, raising output requires alleviating unfavorable environmental conditions brought on by insect and disease issues, soil erosion and climate change. Modern agriculture must employ cutting-edge technologies like nanotechnology to address these issues. The production and study of nanoparticles (NPs), which are tiny particles with sizes ranging from 1 to 100 nm, are the focus of nanotechnology. NPs are purposefully designed and produced to have characteristics pertaining to their size, shape, surface and chemical makeup. The use of NPs in plant science and agricultural production systems, or phytonanotechnology, is currently gaining traction. Nanoparticles (NPs) come in four primary varieties: metallic, ceramic, carbon and polymeric. Because of their antibacterial qualities, metal nanoparticles and metal oxide nanoparticles can manage and fight phytopathogens and crop pests. Thus, a key component of nanotechnology in agriculture nowadays is the use of nanoparticles of zinc oxide (ZnO NPs), titanium dioxide (TiO_2 NPs), copper (Cu NPs), silver (Ag NPs), *etc.* to control plant diseases. How NPs affect plants depends on several factors, including the chemilcal nature: the plant's size, shape, coating agents, concentration, species and developmental stage. Therefore, a thorough investigation is required to ascertain the safety of employing metal nanoparticles in crops.

General Mechanism of Nanoparticles against Pathogen

The general mechanism of nanoparticles against pathogens can be categorised into four main pathways.

1. Disruption of the Protecting Layer and Framework

Metallic nanoparticles (Ag, ZnO) adhere to the cell wall and change its structure by forming "pits" or perforations that increase permeability of the membrane and may induce cell lysis. They can interfere with the proton motive force in the

Article History

RECEIVED on 01st January 2026 RECEIVED in revised form 10th January 2026 ACCEPTED in final form 11th January 2026

cell membrane, which is necessary to produce energy. The release of intracellular materials like ATP, proteins and ions can cause cell death.

2. Reactive Oxygen Species (ROS) Generation

NPs can generate ROS in several ways. The photolytic hypothesis states that metal oxide nanoparticles (NPs), like zinc oxide and titanium oxide, create a corresponding hole in the valence band (H^+) when they absorb light irradiation energy greater than or equal to the band gap. This is because the electrons (e^-) in the valence band are stimulated and move to the conduction band.

3. Release of Toxic Metal Ions

Release of toxic metal ions: Ag and other metal nanoparticles release ions (Ag^+) that directly hinder the activity of pathogens. After being gradually released from metal oxide and absorbed via cell membrane, metal ions interact directly with the functional groups of proteins and nucleic acids, such as mercapto (-SH), amino (-NH) and carboxyl (-COOH) groups. This alters cellular architecture, affects enzyme functioning, interferes with regular cellular processes and eventually ends the microorganism's growth.

4. Interaction with Biological Components

NPs can interact directly with intracellular contents after they have crossed the cell membrane. To stick to negatively charged microbes, metallic nanoparticles need to have a positive surface charge. Because metallic nanoparticles (NPs) are positively charged in water, their adherence to cell membranes is facilitated by the electrostatic interaction between the positively charged NPs and the negatively charged microbial cell membrane. AgNPs can denature DNA in addition to disrupting cell division and resulting in chromosomal abnormalities like mutations, DNA strand breakage and oxidative DNA base damage. These are examples of genotoxicity caused by NP.

Application of Nanotechnology in Agriculture

Numerous prospective applications of nanotechnology in agriculture could enhance soil health and crop output. Some goods, which are a part of nanotechnology, have these potential benefits and are collectively referred to as nanomaterials. These materials include products such as nanobiosensors, nanopesticides and nanofertilizers. In this article, we discuss several developments and applications of nanomaterials in agriculture.

Nanofertilizers

Nanomaterials, particularly nanofertilizers, are a viable alternative to conventional chemical fertilizers, which have low use efficiency due to leaching and volatilization. Nanofertilizers can act as nutrient sources or carriers, increasing crop productivity. For example, phosphatic nanofertilizers and urea and hydroxyapatite nanocomposites exhibit enhanced growth rates and seed yields by permitting regulated nutrient release and lowering NH_3 volatilization: phosphatic nanofertilizers and urea and hydroxyapatite nanocomposites, for example, exhibit enhanced growth rates and seed yields. Nowadays, zeolite, polyacrylic acid, chitosan and clay minerals are used for manufacturing soil and foliar fertilizers.

Nanopesticides

Nanopesticides are changing agricultural farming system by giving farmers targeted, effective and possibly more environmentally friendly options to traditional pesticides. These chemicals are made at the nanoscale. These formulations, which include nanoemulsions, nanocapsules and metal-based nanoparticles, make agrochemicals easier to dissolve, more stable and more available to living things. This means that smaller amounts can be used and the environment is safer.

Nano-biosensors

Nanobiosensors are sophisticated biosensors that are designed to identify specific substances at minimal concentrations. They are described as being highly sensitive, stable, rapid in kinetics of electron-transfer and high ratio of surface to volume. They employ nanoscale materials as bioreceptors on transducers to detect various analytes, including soil contaminants and organophosphates and neonicotinoid pesticide residues. Furthermore, another product of nanotechnology, electronic noses, is used to monitor manufacturing processes, evaluate the health of plants and identify toxins in soil.

Smart Delivery System

The smart and efficient delivery of various agrochemicals, DNA and oligonucleotides to the plant cell is a crucial aspect of precision agriculture. Agrochemicals increase production costs and contaminate the environment because they are usually unable to reach the agricultural target sites and the pests they are meant to control. However, nanoparticles provide an effective method of administering agrochemicals due to their special qualities, such as their large surface area, rapid mass transfer and ease of attachment. As a result, agrochemicals are integrated with several micro- or submicroscopic particles by a variety of processes, including encapsulation, ionic or weak bond attachment, absorption, *etc.*

Food Packaging

To lower the quality and quantity of food material losses, a variety of organic, inorganic and mixed nanoparticles are used to prevent food items from being effectively lost. They prolong the shelf life of the food items in addition to acting as a physical barrier. Mechanical and thermal stability are enhanced by a variety of nanomaterials, such as zinc nanoparticles (ZnO-NPs), chitosan nanoparticles (CNPs), silver nanoparticles (AgNPs) and nanocellulose. Additionally, several of these materials have antimicrobial properties.

Application of Nanotechnology in Plant Health Management (Table 1 and 2)

Antimicrobial Properties

Many goods made using nanotechnology have several antibacterial properties that make them a good choice for future formulation and pesticide production. Nanomaterials are antibacterial compounds that can prevent the growth and development of numerous harmful diseases in addition

Table 1: Nanoparticles in Plant Disease Management

Nanoparticle	Disease	Target Organism	Mode of Action	Affected Plant	References
CuO-NPs	Bacterial wilt	*Ralstonia solanacearum*	Antibacterial activity; incidence reduction	Tomato	Dutta *et al.*, 2023
Cu-NPs green synthesis using *Curcuma caesia* Roxb. leaf extract	Leaf spot of turmeric	*Colletotrichum capsici*	Antifungal activity	Lakadong turmeric	Kumari *et al.*, 2023
Methyl eugenol nanogels	Oriental fruit fly *(Bactrocera dorsalis*)	Methyl eugenol	Attractant delivery via nanogels	Fruit crops	Baghat *et al.*, 2013

Table 2: Nanoparticles for abiotic stress management

Nanoparticle	Crop	Problem	Mode of action	References
ZnO-NPs	Maize (*Zea mays*)	Stress tolerance and growth	Improved root/shoot biomass (30%), enhanced antioxidant enzyme activity under drought stress.	Faizan *et al.*, 2021
TiO_2-SiO_2NPs (Titanium dioxide and Silica)	*Oryza sativa*	Growth Promotion	Improved growth and decreased cadmium toxicity through increased antioxidant defences and decreased Cd transport in plants.	Rizwan *et al.*, 2019

to acting as an efficient delivery machinery. Numerous synthetic nanoparticles, including ZnO, CaO, MgO, AgNPs, Cu, TiO_2 and others, have demonstrated efficacy against *Rhizopus stolonifera, Alternaria alternata, Fusarium graminearum* and *F. oxysporum.* By preventing the growth of conidia and conidiophores, which ultimately led to the death of the fungal hyphae, these NPs have successfully controlled the fungal infections.

Plant Disease Diagnostic

In place of time-consuming and lab-based procedures, nanotechnology provides a faster and field-based way to diagnose a variety of plant diseases using various devices, including nanobiosensors, nano-barcoding, quantum dots, *etc.* Nanobiosensors, which were used for colorimetric assays and could detect the pathogen by detecting a change in the color of the fluid, used gold and carbon-based nanoparticles. In quantum dot-based biosensors, aptamers and antibodies identify and ensnare pathogenic germs. To guarantee a speedier identification of the harmful bacteria, the first signal found is subsequently enhanced. It also provides quantitative imaging and fluorescence.

Nano-priming

Researchers interested in the physiology of plant stress and how to control it have been captivated by nanopriming, which is the process of exposing different nanomaterials to plants (usually seeds). Many nanoparticles, such as AgNPs and zinc oxide NPs, have been shown to decrease salt stress in crops like wheat and rapeseed and increase germination rates and speeds. Nanopriming has several beneficial effects on seedlings in addition to seeds. In crops including wheat, Brassica napus, pearl millet, French beans and others, nano-priming with different nanoparticles like SiO_2 NPs, ZnO NPs and AgNPs increases root and shoot length as well as other biochemical parameters.

Challenges & Future Prospect

Considering the substantial advantages and widespread use of these particles, their mechanisms of hazardous effects are still unknown. The main challenge is the toxicity of metallic NPs (inhaling certain NPs may trigger gene changes, allergic reactions, or localized lung inflammation). When the concentration of NPs grows, it can lead to an increase in cytotoxicity to mammalian cells and tissues, beneficial bacteria, in people, as well as the environment. A recent study found that some bacterial pathogens can develop resistance to antimicrobial nanoparticles through a variety of mechanisms, including oxidative stress caused by nanoparticle transformation, membrane alterations, reversible adaptive resistance, irreversible alterations to cell division and modifications to bacterial motility and resistance. These goods must be evaluated in the field to close the gap between scientific and industrial circles and give the public an accurate and unbiased perception. Encapsulation, surface-functionalization of metallic nanoparticles and reduction of size are recommended methods for reducing the toxicity of nanoparticles in human cells.

Conclusion

Nanotechnology is revolutionizing agriculture by enhancing farming practices and bosting crop yields by precise delivery of nutrients and pesticides, while improving the overall crop value. To meet the projected global need for food, the introduction of engineered nanomaterials and their uses in sustainable agriculture have completely changed the farming sector because of their novelty, quick growth and scale. The main objective of sustainable farming is to protect the environment from contamination and nanomaterials provide a guarantee of better input management and conservation for plant development. The promise of nanomaterials encourages a new green revolution with reduced farming hazards. Nevertheless, our knowledge of the ecotoxicity, permissible limit and absorption capacity of different nanomaterials is incomplete. Further research is therefore necessary to comprehend the behavior, destiny and interactions of changed agricultural inputs with biomacromolecules found in biological systems and ecosystems.

Acknowledgement

The authors acknowledge the support received from College of Post Graduate Studies in Agricultural Sciences, Central Agricultural University (Imphal), Umiam, Meghalaya for providing the necessary interest for the smooth submission of the article.

References

Bhagat, D., Samanta, S.K., Bhattacharya, S., 2013. Efficient management of fruit pests by pheromone nanogels. *Scientific Reports* 3, 1294. DOI: https://doi.org/10.1038/srep01294.

Dutta, P., Kumari, A., Mahanta, M., Upamanya, G.K., Heisnam, P., Borua, S., Kaman, P.K., Mishra, A.K., Mallik, M., Muthukrishnan, G., Sabarinathan, K.G., Puzari, K.R., Vijayreddy, D., 2023. Nanotechnological approaches for management of soil-borne plant pathogens. *Frontiers in Plant Science* 14, 1136233. DOI: https://doi.org/10.3389/fpls.2023.1136233.

Faizan, M., Faraz, A., Mir, A.R., Hayat, S.,2021. Role of zinc oxide nanoparticles in countering negative effects generated by cadmium in *Lycopersicon esculentum*. *Journal of Plant Growth Regulation* 40, 101-115. DOI: https://doi.org/10.1007/s00344-019-10059-2.

Kumari, A., Dutta, P., Pathak, M., Thakuria, D., 2023. Green synthesis of copper nanoparticles mediated by *Curcuma caesia* Roxb. leaf extract and assessment of its antifungal activity against *Colletotrichum capsici*. *Indian Phytopatholohy* 54(7), 14625-14651.

Rizwan, M., Ali, S., Rehman, M.Z., Malik, S., Adrees, M., Qayyum, M.F., Alamri, S.A., Alyemeni, M.N., Ahmad, P., 2019. Effect of foliar applications of silicon and titanium dioxide nanoparticles on growth, oxidative stress and cadmium accumulation by rice (*Oryza sativa*). *Acta Physiologiae Plantarum* 41, 35. DOI: https://doi.org/10.1007/s11738-019-2828-7.