



# Agronano-mediated applications for the alleviation of stress and boosting of crop health for the future of smart high-yield agriculture

Dipayan Bandyopadhyay and Dipan Adhikari\*

Department of Botany, University of Kalyani, Nadia, West Bengal- 741235

Department of Botany (UG & PG), Hooghly Mohsin College, Hooghly, West Bengal- 712101

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### ABSTRACT

Nanotechnology acquired prominence in the third decade of the twenty-first century due to its rapid growth and widespread application in a variety of disciplines, including medical science, the pharmaceutical business, energy conservation, and the food industry. Nanotechnology (NT) is the study and application of nanomaterials (NMs), which range in size from 0.1 to 100 nm. Sustainable agriculture is critical for the growing civilization and its massive population. The goal of nanomaterials (NMs) in agriculture is to protect crops from a variety of pests, microbial diseases, and fungal diseases while reducing the amount of toxic chemicals that are spread, minimizing nutrient losses in fertilization, and increasing yielding capacity through the use of nanochemicals, nanopesticides, and nanofertilizers without decontaminating agricultural land or irrigation water. Nanotechnology has the ability to sense crop health and monitor soil quality in agricultural regions. Researchers have discovered that a number of nanoparticles, including Cu, Zn, Ni, ZnO, Fe, Ag, Al, TiO<sub>2</sub>, and Al<sub>2</sub>O<sub>3</sub>, have deleterious effects on plant development, metabolism, and stress regulation. In addition to investigating how nanoparticles (NPs) help to regulate oxidative stress—the generation of excessive amounts of ROS—and other types of abiotic stress in plant cells, this study focuses on the current benefits and applications of nanotechnology for the improvement of sustainable agriculture. However, nanoparticles have been shown to be non-regulatory for earthworms and some beneficial rhizosperic bacterial populations. Thus, judicious application of nanoparticles is strongly advised to improve plant immunity without hampering the overall homeostasis of environment.

### Introduction

The term "nano" refers to any object that is atomic in nature, minuscule, minute, and small. Ultrafine structures with at least one dimension ranging in size from 1 to 100 nm are known as nanomaterials (NMs) [1]. Scientists have made great efforts to synthesize nanomaterials (NMs) using various physical, chemical, and biological techniques in


\*Address for correspondence

Department of Botany (UG & PG), Hooghly Mohsin College,  
Hooghly, West Bengal- 712101

Email: [dipanadhikari@gmail.com](mailto:dipanadhikari@gmail.com)

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**List of abbreviation:** NMs: Nanomaterials; NPs: Nanoparticles; PGRs: Plant growth regulators; ROS: Reactive oxygen species; CuO: Copper oxide; ZnO: Zinc oxide; MgO: Magnesium oxide; MgOH: Magnesium hydroxide; Al<sub>2</sub>O<sub>3</sub>: Aluminum oxide; TiO<sub>2</sub>: Titanium dioxide; Au: Gold; 1O<sub>2</sub>: Singlet oxygen; O<sub>2</sub><sup>-</sup>: Superoxide; H<sub>2</sub>O<sub>2</sub>: Hydrogen peroxide; OH<sup>-</sup>: Hydroxy radical; ETC: Electron Transport Chain; SOD: Superoxide dismutase; CAT: Catalase; APX: Ascorbate peroxidase; GPX: Glutathione peroxidase; GR: Glutathione reductase; MDA: Malondialdehyde; Fe<sub>2</sub>O<sub>3</sub>: Ferric oxide; Ag: Silver; Si: Silicon; Ni: Nickel; CeO<sub>2</sub>: Cerium oxide; Cd: Cadmium; ELISA: Enzyme linked immuno sorbent assay; PCR: Polymerase chain reaction; miRNA: micro RNA.

order to further the development of "Nanoscience" and "Nanotechnology." When it comes to separating and purifying nanoparticles from micro emulsion-like substances and using a lot of surfactants, these procedures have a number of drawbacks. One type of green technology that is favourable, easy to use, quick, green, and time-efficient is the production of nanoparticles (NPs) from plant cell extraction. Reducing hazardous environmental contaminants and enhancing plant growth regulators (PGRs) and insecticides, as well as improving fertilization, are some of the ways that environmentally friendly prepared NPs can increase agricultural fields' potential and sustainability. Nanomaterials (NMs) are widely used in industries, pharmaceuticals, medicine, and crop protection for sustainable agriculture, among other areas of daily life [2]. While NMs may cause oxidative stress, they also mitigate it, which can result in phytotoxicity [3-4]. The NMs found in agricultural soil interact with plants and shield them from oxidative stress brought on by other elements like salt, temperature, and so on [5]. One type of condition where the cell's redox balance is upset due to the uncontrollably high generation of reactive oxygen species (ROS) is oxidative stress. Oxidative stress results in an unrestricted formation of reactive oxygen species (ROS), which in turn destroys biological materials, alters their structural and functional characteristics, disrupts plant metabolism, and finally results in cell death [6, 7, 8]. The goal of the current study is to provide light on how NMs—such as nanopesticides, nanochemicals, and nanofertilizers are used in agricultural soil to promote the safe growth and development of both cash and food crops. This chapter also discusses how NMs control oxidative stress in plants and how plants use antioxidants as defence mechanisms to rid themselves of reactive oxygen species.

## **Nanotechnology application in agriculture: Nano-agrochemicals**

### *Nanopesticides*

Pesticides are crucial to agriculture because they help keep pests (such as rodents, ants, mice, cockroaches, aphids, crickets, and caterpillars) under control and maintain the growth and development of crops. The term "nanopesticide" refers to pesticides with two or three dimensions and a nanostructure ranging from 1 to 200 nm that are applied as agrochemical ingredients (Acl).

Nanoencapsulation is the process of enclosing active chemicals in a protective layer that is nanoscale. Pesticides that have been nanoencapsulated are employed to effectively manage pests, but residue buildup must be prevented. To control pathogenic and pest attack, nanomaterials (NMs) such as copper oxide (CuONPs), zinc oxide (ZnONPs), magnesium hydroxide (MgOHNPs), and magnesium oxide (MgONPs) were created. Encapsulated nanopesticides are becoming increasingly popular among pesticide manufacturers. Environmental elements including light, humidity, and temperature can cause them [9].

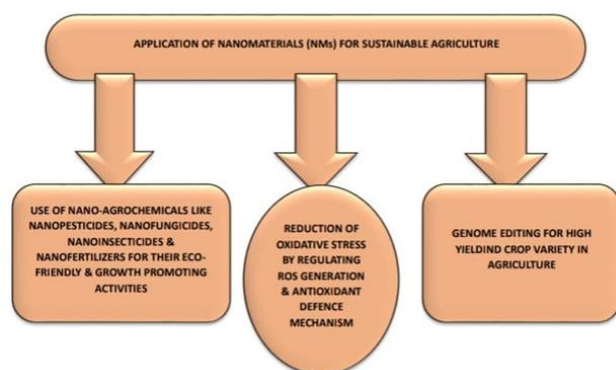
### *Nanofungicides*

The main cause of the decline in crop production and financial gains is fungus diseases. Therefore, it is imperative to focus on developing fungicides with an inhibitory action to manage fungal pathogens that are soil-borne, air-borne, and seed-borne in order to safeguard and extend the shelf life of harvested crops. Because of their excellent solubility, permeability, minimal phytotoxicity, and low dose requirement, nanofungicides are in considerable demand right now. These materials are safe and environmentally acceptable, and they can be used to treat plant illnesses. By triggering the plant's defensive mechanisms or incapacitating microorganisms, NPs enhance the disease resistance of plants. The formulation of insecticides based on nanoparticles can be aided by their antifungal characteristics [10]. Various researchers have researched the synthesis of silver nanoparticles in detail because to its various advantages over other nanoparticles, including Cu, Zn, Au, ZnO, Al<sub>2</sub>O<sub>3</sub>, and TiO<sub>2</sub>. Environmentally representative nanofungicides are preferred over non-target regions or creatures that have the potential to directly or indirectly lower soil fertility and sustainability.

### *Nano-insecticides*

Chemicals known as insecticides are applied to agricultural land to either kill insects or stop them from behaving destructively toward crop plants. However, a lot of chemicals are excessively hazardous and poisonous to the aquatic and terrestrial ecosystems, as well as to biological sources. Currently, cutting-edge nanoscience research is developing botanical pesticides based

on nanotechnology using active ingredients derived from plant extracts or essential oils [11]. For instance, neem leaves (*Azadirachta indica* A. Juss) extract, citrus limon [(L.) Osbeck] leaves extract, acacia gum, and *Punica granatum* L. peels were used in the green synthesis of MgOH [12,13]. Experiment demonstrates that, in addition to pesticides, they have a significant impact on plant growth and molecular farming through the use of nanovectors, which are anticipated to replace viral vectors in farming [14].

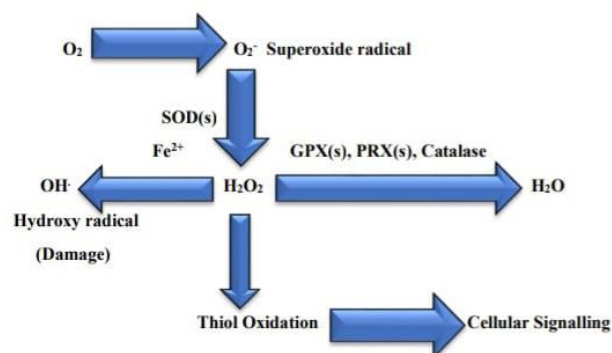


**Figure 1.** Schematic flowchart on the application of nanomaterials (NMs) for sustainable agriculture.

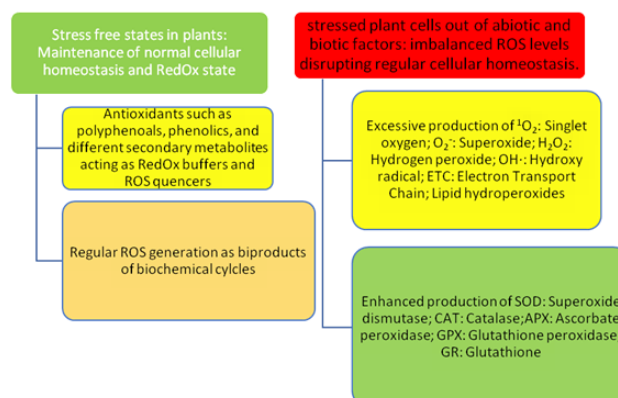
### Nanomaterials and regulation of oxidative stress

Oxidative stress is a phenomenon that arises when a cell's redox homeostasis becomes out of balance because the production of ROS is greater than that of antioxidants, which have the ability to detoxify free radicals [8,15,16]. Free radicals, which are extremely reactive molecules produced from oxygen ions, are known as reactive oxygen species (ROS). The most prevalent ROS in biological systems is singlet oxygen ( $^1O_2$ ), superoxide radical ( $O_2^-$ ), hydrogen peroxide ( $H_2O_2$ ), and hydroxy radical ( $OH\bullet$ ). These chemicals have the potential to cause oxidative cell death due to their high reactivity and toxicity [17]. ROS are produced in a variety of subcellular compartments, including the mitochondria via the electron transport chain (ETC), the chloroplast via the Mehler reaction, and the peroxisomes by photorespiration ( $C_2$  cycle) [18]. There exists a direct correlation between elevated ROS accumulation and environmental stress. Excessive levels of reactive oxygen species (ROS) cause physiological capability loss and ultimately cell death in organisms. UV radiation, ionizing and non-ionizing radiation, heavy metals, xenobiotic chemicals, heat stress, and various phytopathogens are examples of external stimuli that can cause cellular homeostasis to be disrupted and lead to the production of reactive oxygen species (ROS) in plant cells [19].

### Generation and interconversion of reactive oxygen species in plant cell



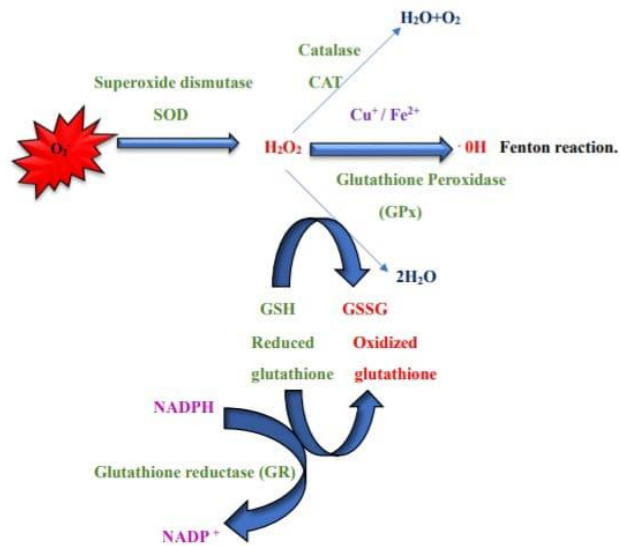
**Figure 2.** Schematic representation of ROS generation and interconversion.



**Figure 3.** Abiotic stress induced imbalance between ROS and antioxidants that triggers oxidative imbalance in cellular homeostasis in plants (schematic representation).

ROS have an impact on living cells and tissues that is both positive and negative [15, 16]. Aerobic organisms must produce ROS at a low to moderate level within their cellular compartments [15]. Lipid peroxidation and protein carbonylation are specific classes of reactions that ROS can generally produce. The process by which unsaturated lipids oxidize into saturated residues like hydroperoxide is known as lipid peroxidation. However, ROS can oxidize to the unsaturated nucleus of amino acids (tyrosine, histidine, tryptophan, phenylalanine, etc.) during protein carbonylation. In both situations, a downstream reaction results in the development of a peroxide product, which can also gradually degrade biomolecules. Under various oxidative stress conditions, plants' effective antioxidant defence system scavenges the excess reactive oxygen species (ROS) produced within the cell. Both enzymatic and non-enzymatic components make up the antioxidant safety net [20]. Non-enzymatic components include flavonoids, tocopherol, carotenoid, polyamine, alkaloids, and phenolic compounds; enzymatic components include glutathione reductase (GR), ascorbate peroxidase (APX), glutathione dismutase (SOD), and catalase (CAT) [15, 17]. The generation of reactive oxygen species (ROS), such as hydroxy radical ( $OH\bullet$ ), is a key initiator of lipid peroxidation, which degrades lipoprotein and produces a cascade of end

products including conjugated dienes and malondialdehyde (MDA) [16].



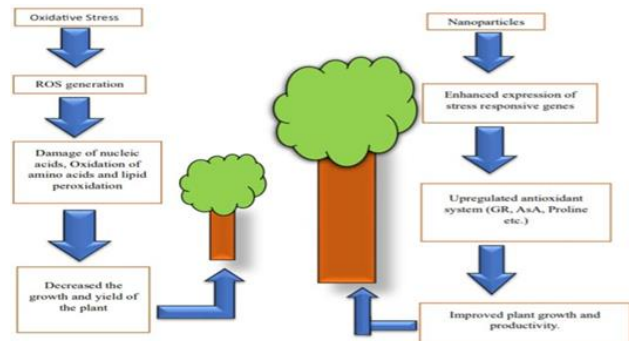
**Figure 4.** Detoxification of reactive oxygen species (ROS) by enzymatic antioxidant activity in plant cell.

Scientists found metals (Au-gold, Ag-silver), metallic oxides (CuO, TiO<sub>2</sub>, Fe<sub>2</sub>O<sub>3</sub>, MgO, CeO<sub>2</sub>), carbon nanotubes and quantum dots (cadmium selenides and cadmium sulphides) are four categories of NMs that are used in wide array of application [21,22,23]. Role, function and other impacts of NMs on plants is very complicated and contradictory [23]. NMs play an important role in plant growth and productivity. The role of NMs in alleviating oxidative stress mainly induced by abiotic stress like UV radiation, heavy metal, drought, alkalinity, salinity and temperature [24].

### Mechanisms of alleviation of oxidative stress in plant by nanomaterials (NMs)

Plants have an intrinsic defence system that fights against oxidative stress, known as antioxidant system [35]. Antioxidants help plants to quench excessive level of ROS generation and withstand other stressful situations [35]. NMs have significant role in the migration of oxidative stress and enhance the production of antioxidants [1,35].

In addition to managing oxidative stress and preserving redox equilibrium, nanomaterials can occasionally produce it [3]. Due to these two characteristics, it is vital to understand the precise metabolic activities of NMs and their interactions with plants. Lipid peroxidation and electrolytic leakage were reduced as a result of antioxidant formation, which suppressed the ROS level. Researchers discovered that foliar application of Si and TiO<sub>2</sub>-NPs reduced lipid peroxidation and electrolytic leakage by boosting the activity of



**Figure 5.** General mechanisms of nanoparticles in plants to regulate the redox homeostasis under oxidative stress conditions [36].

antioxidant enzymes such as SOD, CAT, and APX, consequently relieving oxidative stress in rice plants exposed to cadmium (Cd) stress [37]. Now that nanoscience is being investigated as a topic related to biochemistry and redox biology, there is an urgent need to understand the precise mechanism of ROS avoidance by nanoparticles (NPs).

### Regulation of biotic stress elicited by Plant pathogens in agricultural crops through nanomaterials (NMs)

Human civilization depends on plant resources. There are three basic needs: shelter, food, and fiber. These needs are increasing on a daily basis as the world's population grows. Crop yields are significantly affected by dwindling agricultural lands caused by society's rapid urbanization and industrialization. Plant infections are another barrier that contributes to biotic stress in agricultural crops, causing the plants to become partially compromised before dying. It poses a significant threat to food security and productivity. Plant diseases have caused havoc during numerous significant calamities. For example, *Phytophthora infestans* in Ireland caused the Irish Potato Famine in the 1840s, and *Helminthosporium oryzae* in rice caused the Great Bengal Famine of 1943. The vast bulk of research on plant biological stress aims to mitigate catastrophic yield loss, either directly or indirectly [38]. The administration of previously stated insecticides, fungicides, pesticides, and fertilizers is the principal strategy for managing biotic stress in agricultural crops. Engineered sensors made of nanoparticles are used to monitor stress produced by pathogens and the environment. Researchers discovered that nanosensors were effective at identifying fungal pathogens that cause plant illnesses that are soil-borne, air-borne, seed-borne, and others. An electrochemical sensor capable of identifying the causal agent of *Solanum lycopersicum* bacterial specks (*Pseudomonas syringae* DC3000) with a detection limit of 214 pM [39]. The researchers employed Au-NPs to identify soil-borne pathogens

**Table 1.** Regulation of oxidative stress elicited by abiotic stress in various plants mediated through NMs presented in the following table.

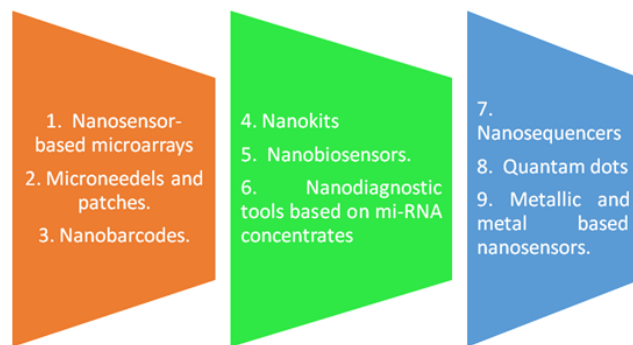
Nanomaterials and effective dose	Plants exposed	Abiotic stress	Activities	References
Titanium oxide (TiO <sub>2</sub> )/5ppm	<i>Spinacea oleracea</i> L.	UV radiation	Reduced oxidative stress by significantly lowering level of superoxide radical, hydrogen peroxide and malondialdehyde (MDA) by enhancing the antioxidant enzymes like SOD, CAT, APX, GPX etc.	25
Zincoxide (ZnO)/1.5ppm	<i>Cicer arietinum</i> L.	Cold stress (4°C)	Lower level of ROS generation and lipid peroxidation; improvement of biomass.	26
Silver nanoparticle (Ag-NP)/20-60mg/cm <sup>3</sup>	<i>Pelargonium sp.</i>	Dark storage	Chlorophyll and carotenoid content elevated, boost up the production of ascorbate peroxidase and glutathione peroxidase significantly and reduce the oxidative stress.	27
Titanium oxide-Nanoparticles (TiO <sub>2</sub> -NPs)-10mg/l	<i>Linum usitatissimum</i> L.	Drought	Physiological and biochemical parameters improved, increased photosynthetic pigments like chlorophylls & carotenoids, lower production of hydrogen peroxide and reduced lipid peroxidation.	28
TiO <sub>2</sub> -NP/10ppm	<i>Dracocephal ummoldavica</i> L.	Water deficit stress	Mitigated oxidative stress and membrane damage by decreasing H <sub>2</sub> O <sub>2</sub> and MDA and also increasing proline content.	29
ZnO-NP (60mg/l)	<i>Lupinus termis</i> Forssk.	Salinity (0-150mM NaCl)	Increased phenolic compounds and antioxidant content; improved photosynthetic pigment and osmoregulation.	30
ZnO-NP (5-10ppm)	<i>Leucaena leucocephala</i> (Lam.) de wit	Cadmium and Lead (Heavy metal stress)	Seedling growth improved, photosynthetic pigments and total soluble protein was increased, oxidative stress was lowered via activation of antioxidant machinery that resulted in elevation in SOD, CAT and POX level in leaves.	31
Si-NP (Silicon nanoparticle), 1200mg/l	<i>Triticum aestivum</i> L.	Cadmium (Heavy metal stress)	Oxidative stress was reduced with improved antioxidant status. Plant biomass, chlorophyll content and gas exchange attributes of leaves were improved; concentration of cadmium (Cd) in plant tissue was decreased.	32
TiO <sub>2</sub> (25 and 50mg/l)	<i>Crocus sativus</i> L.	UV-B radiation	Antioxidant activity increased with total phenolic and flavonoid content in stigma.	33
ZnO-NPs (5ppm/l)	<i>Oryza sativa</i> L.	Water stress	Regulated plant growth, reduced ROS content and improved antioxidant system.	34

such as *Ralstonia solanacearum*, which causes bacterial wilt in potatoes [40]. As a result, nanosensor-based remote sensing technology is an excellent approach to identify, anticipate, and control

insects, pests, and plant diseases, protecting both commercial and agricultural crops while also preserving the environment.

## Nanotechnology mediated detection of Plant Pathogen

Pathogenic infections of agricultural crops are one of the principal causes of low productivity and high prices, which have emerged as major issues in the worldwide scene [40]. Various diagnostic procedures for detecting plant pathogens, such as polymerase chain reaction (PCR) and enzyme linked immune sorbent assay (ELISA), are used at random in diagnostic laboratories around the world [41]. However, these types of diagnostic procedures are restricted in rural areas and developing countries due to a lack of laboratory equipment and specialists [42]. The current research describes the use of several nanotechnology technologies to show early and rapid detection methods for plant pathogenic diseases.



**Figure 6.** Nanotechnology based detection tools for probing early stages of pathogenesis in plants [43].

### How Nanomaterials (NMs) can act as 'Nanoweapons' against Phytopathogens?

- Nanomaterials (NMs) have the unique optical properties for highly sensitive and useful detection of plant pathogens [44].
- NMs damage to the membrane transporter and nutrient absorption systems of pathogen.
- Nanoparticles generate reactive oxygen species (ROS) inside the pathogenic cell and developed nanotoxicity which results damage of nucleic acids (DNA/RNA), uncontrolled cell signalling, cytotoxicity, genotoxicity and programmed cell death [8, 45].
- Due to nanotoxicity, toxic ions released that hampers cell permeability and activity of membrane proteins [46].
- Depending on the size and doze, nanoparticles are intended to provide unique and enhanced antibiotic activity against plant pathogens [47].

### Environmental Risks and Commercial limitations of Nanoparticles

The unique properties of nanomaterials (NMs) have the ability to make it applicable in agriculture. These optimistic properties such as- I) enhanced bioavailability of the active constituent, II) improved solubility of pesticides/fungicides/insecticides, III) releasing of active constituent by depending on pH level, IV) transferring of RNAi molecule for disease management, V) Detoxification of ROS and regulation of oxidative stress in plants etc.

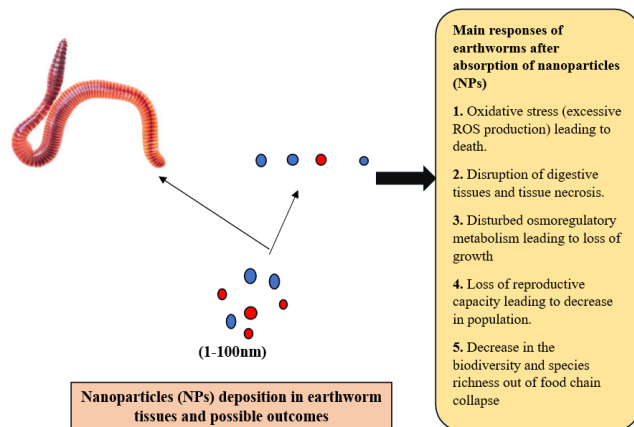
Though nanomaterials (NMs) have various potential applications and advantages in agriculture, such as promoting stress tolerance in crops, they also have a number of negative and hazardous impacts on our ecosystem and biological species. Nanoparticle-mediated pollution poses a threat to the natural flora and fauna, including beneficial bacteria, fungi, and soil-nematodes (Soil microflora), by causing long-term nanotoxicity in their bodies, decreasing soil fertility, low levels of nutrient solubilization, and reducing the activities of plant growth-promoting rhizobacteria (PGPR) in soil [48,49].

Despite their severe environmental impact, nano-agrochemicals continue to be denied market approval. In terms of the usage of nanoparticles (NPs)-based fungicides, pesticides, insecticides, or herbicides, regulatory bodies or pharmaceutical enterprises have not supplied the appropriate ratio of nano substances and their maximum level of effective dose without causing harm to the environment. Furthermore, investigations and research are required for the environmentally benign usage of nanoparticles (NPs) in agriculture and their commercialization. Furthermore, scientists should produce a fresh formulation of practical answers that our farmers may easily implement without disrupting their existing farming practices and skills. [50]. More research with in-vitro approaches is highly needed, particularly for agricultural applications of NMs, determining dose levels, regulatory guidelines, crop adaptation and use at the field level [51].

### Harmful Effects of Nanoparticles (NPs) on Earthworms

Earthworms are soil-dwelling invertebrate animals from the phylum 'Annelida' that play an important role in improving soil quality by enhancing plant nutrients. The nutritional quality of soil varies according to the species of earthworms present in the field. Earthworms can be found in a wide range of soil types and horizons, so they are divided into three ecological groups: epigeic species that live on the surface and in the litter (e.g., *Eisenia fetida*), endogeic species that live in the organic horizons, and dig horizontal burrows (e.g., *Aporrectodea caliginosa*), and anecic species living in vertical and

deep burrows and consuming excessive amounts of soil (e.g., *Lumbricus terrestris*)



**Figure 7.** Adverse/hazardous effects of Nanoparticles (NPs) on earthworms.

referred to as "farmers' friends." Researchers have revealed that nanoparticles (NPs) have certain negative effects on earthworms' physiological functioning and general environmental activities. Several scientific investigations have revealed harmful effects on earthworm growth, reproduction, and development, species diversity, and digestive and immunological systems. The most common earthworm species is *Pheretima posthuma* and, which is often used as a standard test organism to detect pollution levels in the environment. [52].

### Conclusion and future perspective

Combining elements of physics, chemistry, botany, biotechnology, environmental biology, ecotoxicology, and agricultural science, nanotechnology is a broad topic of study. Nanomaterials (NMs), which have atomic sizes

**Table 2.** Nanomaterials (NMs) mediated nanotoxicity in living microorganisms (bacteria, algae, fungi) and earthworms including their harmful effects are tabulated below: (In-vitro approach).

Type of Nanoparticles (NPs)	Size Range of NPs(nm)	Living microorganisms (bacteria/algae/fungi) and earthworms	Harmful/ Toxic effects	References
ZnO/Zn	30-50/60-80	Nitrifying bacteria ( <i>Nitrosomonas/Nitrobacter</i> )	Nitrification rate reduction, excessive ROS production, amo-A gene expression/alteration	<b>53</b>
Al <sub>2</sub> O <sub>3</sub>	<50	<i>Pseudomons stutzeri</i> (ATCC14405)	katBgene over expression.	<b>54</b>
CuO	30-50	<i>Chlorella pyrenoidosa</i>	Membrane damage, ROS generation, Mitochondria depolarization.	<b>55</b>
Ag	1-10	<i>Sketonema costatum</i>	Growth inhibition	<b>56</b>
Cu	2-60	<i>Trametes versicolor</i> (CBAS 614)	Decreased lignocellulolytic enzymes production.	<b>57</b>
CuO/ZnO	<50/<100	<i>Saccharomyces scerevisiae</i>	Cell density reduction/Cell wall, vacuole and nucleus change.	<b>58</b>
MoO <sub>3</sub>	92	<i>Eisenia fetida</i>	Death rates with weight loss	<b>59</b>
Magnetite nanoparticles	17-28	<i>Eudrilus eugeniae</i>	The colour of the earthworm's skin changed from brown to black due to increasing NPs.	<b>60</b>

Earthworms secrete a variety of organic acids and enzymes, which combine with soil and support the growth of soil microflora, bacteria, fungus, and actinomycetes. These microbes aid in nitrogen fixation, nutrition solubilization, and boost plant growth and yield capability. As a result, earthworms are crucial for a sustainable ecology and are usually

ranging from 0.1 to 100 nm, can be both beneficial and harmful to the environment. Researchers ought to focus on utilizing NMs by emphasizing and enhancing their environmentally friendly qualities in the right amounts and applying them to their biological origins. Nanomaterials are widely used in

agriculture to boost high yielding capacity and sustainability. In order to protect agricultural crops from pests and increase their fertility, NMs are primarily utilized as nanopesticides, nanofertilizers, nanoinsecticides, nanofungicides, and nanoherbicides. These applications are covered in this study. Our research further illustrates the function of NMs in protecting cells against redox homeostasis imbalances, which result in excessive production of ROS, and in triggering the antioxidant defense system. NMs would further be enhanced as a weapon for generating heat shock proteins [61] to balance physiological homeostasis epigenetic memory [62] in plants to combat abiotic and biotic stresses [8]. But our of excess ROS production the normal plant health might get stressed out [63, 64] of disrupted cellular homeostasis leading to enhanced cellular lipid hydroperoxide formation leading to cytotoxicity [65, 66, 67, 68, 69, 70, 71]. The variable kinds of NMs, the appropriate dosage for each form of abiotic stress (salinity, cold, drought, etc.), and the way in which they affected distinct plant species must be elucidated with different omics approaches. For a better understanding, scientific illustrations of the use of NMs in sustainable agriculture, ROS synthesis and their inter-conversion, and antioxidant defence mechanisms are to be provided. Even while nanoscience is seeing a variety of cutting-edge research projects, there are still a number of gaps in the field. For instance, it is still unclear and conflicting exactly how nanomaterials (NMs) controlled and activated the antioxidant system against reactive oxygen species (ROS). Therefore, it is necessary to accurately understand the interaction between plants and NMs under various stressful conditions and their impacts on long-term exposure before entering the new and more advanced phase of agriculture based on NMs. An institute dedicated to nanotechnology research should develop appropriate regulations for the safe use of nanoparticles (NMs), their range of applications to biological organisms, and how to properly dispose of them to prevent any negative effects on the environment or human health. Additionally, NMs once are effectively and sensitively employed as pathogen diagnosis tools in the form of quantum dots, nano-biosensors, nano-barcoding, miRNA-based diagnosis, etc, would enhance the future prospects of technology-based agricultural management in leaps and bounds. The authors expect that it will satisfy the essential requirements for future nanoscience researchers and students who may wish to focus on the role and application of NMs in agriculture.

### Contribution of authors

Both Mr. Dipayan Bandyopadhyay and Dr. Dipan Adhikari have contributed equally to finalize this

article. Mr. Bandyopadhyay has written this full article and constructed the all-necessary figures/flowcharts and diagrams whereas Dr. Adhikari provided the information and reference to complete the review article.

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### Conflict of Interest

The authors declare no conflict of interest.

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