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Review Article

Newly engineered nanoparticles as potential therapeutic agents for plants to ameliorate abiotic and biotic stress

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Abstract
Food scarcity is a global concern that is growing every year. Biotic stress factors like pathogenic fungi, bacteria, viruses, and nematode pests aggravate the situation by imparting detrimental effects on crops by unfavourably affecting their growth and yield. Abiotic stress factors include extreme heat and cold, drought, high salinity, floods, and heavy metal toxicity. Annually, millions of hectares of agricultural land worldwide are lost to these stress elicitors. To combat these stress factors, plants have developed strong defense mechanisms, including protective physical barriers, the overexpression of certain genes, and the production of secondary metabolites. Nanotechnology offers numerous novel and sustainable substitutes for conventional agriculture due to its potential uses in this field. Newly engineered nanoparticles (NENPs) are synthesized nanoparticles that are 1-100 nm in size and possess unique properties that help plants combat abiotic and biotic stress factors efficiently. NENPs are designed to ameliorate stress, alleviate nutrient inadequacy in soil, improve plant nutritional value, and overall boost crop productivity. This review illustrates the applications of various NENPs, which help plants cope with biotic and abiotic stresses. It highlights the effective induced changes that develop in the morphology, physiology, and biochemistry of different plants under stress and the role of NENPs. This review also highlights the toxic and deleterious effects of NENPs on the soil when used in higher doses and concludes with the prospects of NENPs in agriculture.

Keywords: Applications, Newly engineered nanoparticles, Plant abiotic stress, Plant biotic stress, Toxicity

INTRODUCTION

Plants are exposed to various hostile and harsh environmental stresses as sessile organisms. Environmental stress is an unfavourable circumstance that impairs a plant's growth and development abilities. It can be categorized as biotic or abiotic. Biotic stress is any stress a biological organism brings, whether it takes the form of an infection or some other type of attack. The organisms that generate biotic stress include microorganisms like bacteria, fungi, parasites, viruses, and some higher organisms like insects and pests. On the other hand, abiotic stress refers to environmental conditions that are extreme and detrimental to plant growth. These include environmental conditions like high and low temperatures, high salinity, droughts, floods, nutritional imbalances, and heavy metal toxicity (Gull *et al*., 2019). Either type of stress causes atypical, suboptimal growth conditions for plants, adversely affecting crop yield, quality, and quality, thereby presenting a significant challenge to the agriculture sector. In addition to endangering the farmers' livelihoods, this loss of crop productivity also threatens food security. Furthermore, the nation incurs financial losses because the agriculture and food industries are the lifeblood of any developing country's economy. To feed the world's population, it is anticipated that agricultural production ought to increase by 35–50% between 2012 and 2050 (FAO, 2019). According to a report from the Food and Agricultural Organization of the United Nations (FAO), dated June 2021, 40% of the world's crops alone are lost to pests every year, costing billions of dollars to the countries. Almost 147 million hectares of land are affected by soil disintegration, comprising 94 million hectares due to water erosion, 23 million hectares owing to salinity, alkalinity, or acidification, 14 million hectares due to flooding, 9 million hectares due to wind erosion, and 7 hectares due to a combination of variables brought on by many forces. India has 6.74 million acres of salt-affected land. According to estimates, around 10% more land every year becomes salinized, and by 2050, about 50% of the world's agricultural land will be affected by salinity (Kumar and Sharma, 2020). All these figures suggest that biotic and abiotic stresses pose a daunting challenge to all nations worldwide.

Although plants cannot escape hostile conditions, they are not completely vulnerable to stressful environmental conditions. They have evolved to develop defense mechanisms over time to cope with various factors that threaten their survival. Any environmental stress triggers a response in plants to adapt to the condition. Depending on the type of crop, the type of stress, and the extent of stress, the stress response can be physiological, morphological, or a modification in the biochemical process (El-Saadony *et al*., 2022). The stress-tolerance response displayed by plants, for instance, involves the production of secondary metabolites and expressing specific genes (Ashapkin *et al*., 2020). Nonetheless, they are insufficient to protect the plants from the damage that the stress factors cause. Over the years, science and technology have developed to find ways to help plants better adapt to their ever-changing environment. The use of chemical pesticides and insecticides became prevalent to protect plants against predators, and some plants were even genetically modified to become resistant to biotic and abiotic stress (Dormatey *et al*., 2020). However, the drawbacks outweigh the advantages. Some of these methods are expensive and not always successful in attaining the desired effect, while others raise ethical issues and pose health hazards (Giudice *et al*., 2021; Dormatey *et al*., 2020). These reasons encouraged the researchers to continue their search for more efficient and effective solutions. Nanotechnology is a multifaceted emerging field that finds its application in several areas and has caught the attention of researchers in the past few decades to employ its use in plant biotechnology.

Nanotechnology involves using nano-sized particles, ranging from 1-100 nm in size that are engineered depending on their intended use. Recently, newly engineered nanoparticles (NENPs) have gained popularity due to their distinctive physiochemical, mechanical, and thermal properties, making them a preferred usage choice (Ahmad *et al*., 2022). Newly engineered nanoparticles are purposefully engineered, as opposed to naturally occurring nanoparticles like montmorillonite (MMT), kaolinite, saponite, etc. (Khan *et al*., 2021). NENPs can be inorganic, organic, or combined depending on their chemistry (He *et al*., 2019). The majority of nanoparticles in use are metals and metal oxide complexes (inorganic nanoparticles), with silver (Ag) being the most popular type. (Ahmad *et al*., 2022). Other inorganic nanoparticles with prevalent use in agriculture are titanium dioxide (TiO_2), zinc (Zn), zinc oxide (ZnO), cesium (Ce), copper (Cu), copper oxide (CuO), selenium (Se), silver (Ag), silicon (Si), silicon oxide (SiO_2), iron oxide (FeO), calcium ($CaCO_3$), magnesium (Mg), magnesium oxide (MgO), and manganese (Mn) nanoparticles (Khalid *et al*., 2022). In agriculture, nanoparticles are used as nanoremediators, nanosensors, nanofertilizers, nanopesticides, nanofungicides, nanocarriers of plant growth regulators (PGR), and nanomaterials for seed germination and plant genetic engineering (Singh *et al*., 2021; Ahmad *et al*., 2022).

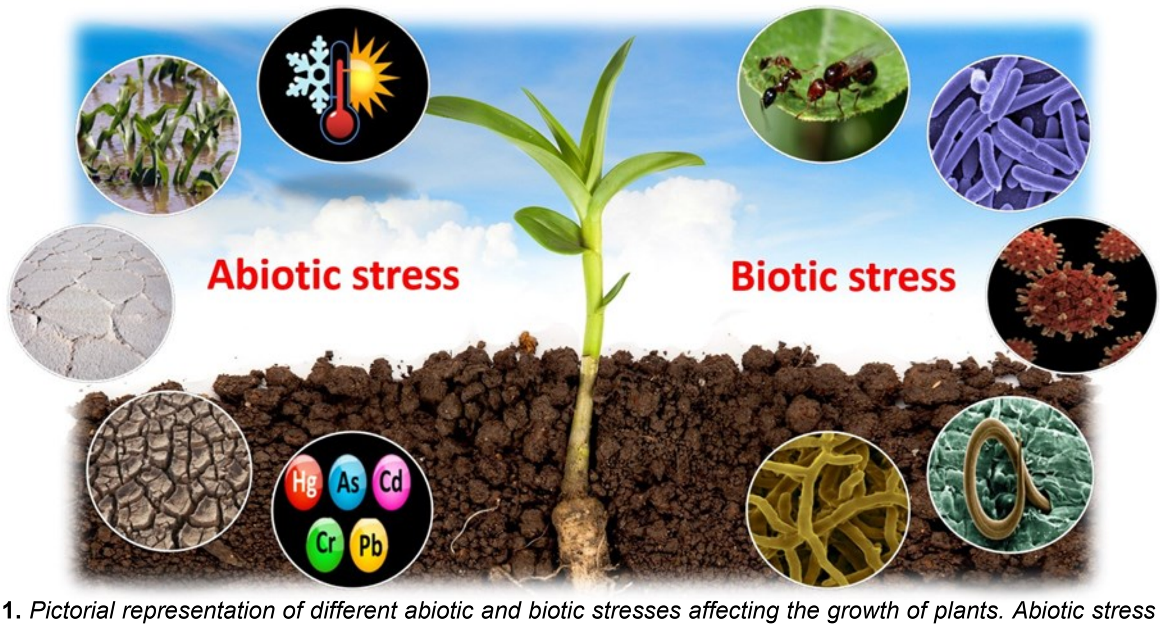

Fig. 1. *Pictorial representation of different abiotic and biotic stresses affecting the growth of plants. Abiotic stress factors include extreme heat and cold, floods, high salinity, drought, and heavy metal toxicity. Biotic factors include pest attacks, bacterial, viral, and fungal infections, and nematode invasions*

NENPs offer a more sustainable form of agricultural practice by increasing the uptake of nutrients, providing crops with higher nutritional value, improving the quality of soil, preventing plant diseases, and resulting in high crop yield (Ahmad *et al*., 2022). They outperform existing methods and procedures regarding effectiveness, safety, convenience, and their environmentally friendly nature. Because of the factors mentioned earlier, NENPs are widely used to protect plants from biotic and abiotic stress and increase crop growth and yield.

NENPs IN PLANT ABIOTIC STRESS

Abiotic stresses have catastrophic consequences for the growth and yield of crops each year. Most of these unfavourable situations can be ascribed to both anthropogenic and natural causes (Manzoor *et al*., 2022; Shahzad *et al*., 2018). Whatever the cause, these environmental factors have a negative impact on the plants and cause morphological, physiological, and biochemical changes, such as alterations in cellular membranes, reactions to phytohormones, photosynthetic efficiency, the deposition of toxic substances, the closing of stomas, the generation of small molecules and reactive oxygen species (ROS), and reduced antioxidant enzyme activity, that affect their health and growth (Ansari *et al*., 2022; Husen, 2022; Mondal *et al*., 2022). High salinity, drought, heavy metal toxicity, and temperature extremes are a few of the numerous abiotic stresses that substantially impact agricultural yield. In response, the concentrations of phytohormones like abscisic acid (ABA) and indole-3-acetic acid (IAA) increase. Furthermore, in stressful situations, salicylic acid (SA), ethylene (ET), and jasmonates (JAs) also play an integral role. (Husen *et al*., 2018, 2019; Mishra *et al*., 2016; Mondal *et al*., 2022; Siddiqi & Husen, 2019). Newly engineered nanoparticles can be employed to further enhance the stress tolerance of crops and protect them from loss. Some of the NENPs that demonstrate efficiency in combating abiotic stress are summarized in Table 1.

NENPs for plants under salt stress

Salinity is an abiotic factor that significantly impacts agricultural yield, causing cultivated and irrigated areas to disappear by 20% and 33%, respectively (Kumar & Sharma, 2020; Shrivastava & Kumar, 2015). Physiological changes brought on by high salt levels include reduced photosynthesis, osmotic inhibition, nutritional imbalance, and the uptake of toxic ions. Morphological changes brought on by high salt levels include reduced shoot growth, succulence, and an enlarged palisade. Biochemical changes include alterations in gene expression, phytohormone levels, protein synthesis, and decreased enzymatic activity (Roșca *et al*., 2023). By altering the metabolic processes and improving the nutritional balance, NENPs intervene with the processes that cause these changes in the plant and assist it to survive its stress (Khalid *et al*., 2022; Zulfiqar & Ashraf, 2021). This has been demonstrated and validated by several research studies conducted on a variety of plants with diverse NENPs. One such experimental study (Gohari *et al*., 2021) demonstrated that the use of cerium oxide nanoparticles (CeO2NPs) significantly mitigated the damages that salt stress caused to grapevine chlorophyll and also reduced levels of MDA and electrolyte leakage (EL). By accelerating photosynthesis, zinc oxide nanoparticles, potent NENPS, show encouraging efficacy in barley, wheat, and pea plants under salt stress (Adil *et al*., 2022; Ali *et al*., 2022; Elshoky *et al*., 2021). Similarly, numerous studies have shown that NENPs have a beneficial effect on salt stress tolerance. Manganese-doped graphene quantum dots (GQD-Mn) used on *Capsicum annuum* (Ye *et al*., 2022), titanium dioxide nanoparticles (TiO_2 NPs) on *Stevia rebaudiana* (Sheikhalipour *et al*., 2021), copper nanoparticles (CuNPs) on *Zea mays* (Noman *et al*., 2021), CaO NPs on *Triticale callus* (Yazıcılar *et al*., 2021), *SiO_2-NPs* on *Trigonella foenum-graecum* (Ivani *et al*., 2018), and Chitosan nanoparticles (CsNPs) in general, improved the ability of plants to withstand salt stress in general (Gohari *et al*., 2023).

NENPs for plants under drought stress

Every year, drought conditions get worse due to climate change and seasonal variations, which inevitably reduce crop productivity. It is estimated that drought leads to the loss of 70% of the crop yield worldwide (Yadav *et al*., 2020). Drought elicits morphological, physiological, and biochemical changes in plants, such as turgor loss, decreased antioxidant enzyme activity, ion accumulation, decreased photosynthesis and leaf growth, and the production of reactive oxygen species

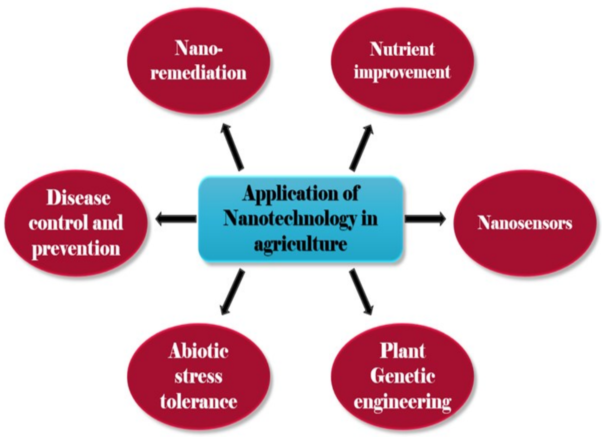

Fig. 2. *Various applications of nanotechnology in the field of agriculture*

Table 1. Different NENPs used to combat different abiotic stress factors

Abiotic stress	NENPs	Plant species	Effects	Reference (s)
Salinity	ZnO-NPs	*Triticum aestivum* (wheat)	Reduced electrolyte leakage, malondialdehyde, and hydrogen peroxide. Accumulation of abscisic acid, photosynthetic pigments, hormone, osmolytes, and antioxidant enzymes	Chattha *et al*., 2022; Adil *et al*., 2022
	manganese-doped graphene quantum dots (GQD-Mn)	*Capsicum annuum*	Increased photosynthetic rate	Ye *et al*., 2022
	TiO_2	*Zea mays* L	Improved seed viability, leaf hydration status, and antioxidant enzyme activity	Shah *et al*., 2021
	Mn-NPs	*Capsicum annuum* L.	Regulated molecular response modulated by high salt content	Ye *et al*., 2020
	Si-NPs	*Musa acuminata*	Decreased oxidative stress	Mahmoud *et al*., 2020
	SiO_2	*Lycopersicum esculentum*	Enhanced seed germination, weight gain, and development of root	Haghighi *et al*., 2012
	AgNPs	*Pennisetum glaucum L.* (pearl millet)	Decreased oxidative stress, enhanced plant height, water content, and proline contents	Khan *et al*., 2020
Drought	Fe_3O_4	*Glycine max* L. (Soybean)	Reduction in oxidative stress due to increased chlorophyll and protein content, hydration status, and seed oil	Dola *et al*., 2022
	Ca-NPs	*Brassica napus* (canola)	Enhanced plant biomass and nutrient uptake, improved photosystem II efficiency and enzymatic and non-enzymatic antioxidants, as well as gas exchange.	Ayyaz *et al*., 2022
	Zu-NPs	*Zea mays* (maize)	Enhanced grain biomass	Van Nguyen *et al*., 2021
	TiO_2	*Triticum aestivum* L.	Enhanced photosynthetic performance, antioxidant defense, and growth	Faraji, & Sepehri, 2020
	ZnO	*Solanum melongena* L	Improved growth traits and higher fruit yield	Semida *et al*., 2021
	SwCNTs (Single-walled carbon nanotubes)	*Glycine max*	Improved resistance to drought during germination	Wenli *et al*., 2020
	Si-NPs	*Hordeum vulgare*	Altered antioxidative properties, and synthesis of certain compounds	Ghorbanpour *et al*., 2020.
Osmotic stress	Thiourea-capped apatite nanostructure (TU–ANP)	*Zea mays* (maize)	Increase the generation of osmolytes and the activity of antioxidant enzymes while preserving photosynthetic pigments.	Faryal *et al*., 2022
Heat	Si NP	*Triticum aestivum*	Repair of the chloroplast and nuclear ultrastructure-induced aberrations and improved photochemical performance of the photosystem II	Younis *et al*., 2020
	Ag-NP	*Triticum aestivum*	Promoted heat resistance	Iqbal *et al*., 2019
Cold	ZnO-NP	*Oryza sativa* L	Regulated transcription factors for the freezing response and the antioxidant system	Song *et al*., 2021
	Ag-NP	*Arabidopsis thaliana*	Stimulate the expression of the genes that produce antioxidants	Kohan-Baghkheirati and Geisler-Lee, 2015
Cadmium toxicity	TiO_2 NP	*Zea mays* L	Elevated activity of glutathione S-transferase (GST) and superoxide dismutase (SOD)	Lian *et al*., 2020
	ZnO NPs	*Linum usitatissimum* (Linseed)	Reduced electrolyte leakage, malondialdehyde, and hydrogen peroxide. Accumulation of antioxidant enzymes	Ramzan *et al*., 2022
	CaO NPs	*Hordeum vulgare* (Barley)	Improved plant biomass, activities of anti-oxidative enzymes, the content of non-enzymatic antioxidants and expression of anti-oxidative enzymes genes, reduced malondialdehyde (MDA)	Nazir *et al*., 2022
	Fe_3O_4 and ZnO- NPs	*Nicotiana tabacum* (tobacco)	Enhanced plant growth, especially root growth	Zou *et al*., 2022
	Fe_2O_3-NPs	*Oryza sativa* (rice)	Regulated phytohormones, phytochelatin, inorganic homeostasis, and the expression of genes associated with Cd uptake and transport and reduced Cd-induced oxidative stress	Zhou *et al*., 2023
	Si NPs	*Zea mays* L.	Early growth and enhanced physio-biochemical.	Hussain *et al*., 2019

(ROS) (El-Saadony *et al*., 2022). Through boosting photosynthetic activity, encouraging root development, and re-establishing ionic equilibrium, NENPs are vital in alleviating the effects of drought stress. (Khalid *et al*., 2022). For instance, iron-NPs (Fe3O4) improved the response to arid conditions in *Glycine max* L as demonstrated by Dola *et al*., 2022, and ZnO NPs have been recognized as efficacious against drought stress in *Coriandrum sativum L* and *Triticum aestivum* (Ahmed *et al*., 2023; Raeisi Sadati *et al*., 2022). Another research study investigated how calcium nanoparticles (Ca-NPs) assisted hydroponically cultivated *Brassica napus* plants in coping with drought stress. (Ayyaz *et al*., 2022). In response to drought stress, selenium nanoparticles (Se-NPs) have also positively affected pomegranate plants. (Zahedi *et al*., 2021).

NENPs for plants under stress from heavy metal toxicity

The ecosystem is gravely endangered by the excessive, improper, and reckless disposal of heavy metals by industries, and this is a growing concern for the entire world. Heavy metals like cadmium (Cd), chromium (Cr), lead (Pb), and mercury (Hg) are not only toxic to the plants exposed to them but are also hazardous to any other organism that consumes them. Heavy metals enter the body through the intrinsic transport system of an organism and make their way into the deepest tissues when they build up and obstruct the flow and exchange of vital molecules, which can endanger the life of the organism or, at the very least result in some form of impairment (Khalid *et al*., 2022). Hazardous levels of heavy metals impair several metabolic processes, including photosynthesis and respiration, affect enzymatic activity, cause protein structure breakdown, disruption of the cytoplasmic membrane integrity, and cause the formation of reactive oxygen species (ROS) (El-Saadony *et al*., 2022). When it comes to heavy metal toxicity, NENPs step in to save the plants. One such instance is ZnO NPs, which have been demonstrated to be a successful method for reducing chromium stress in *Zea mays* while also being environmentally beneficial (Ramzan *et al*., 2023). Moreover, iron oxide nanoparticles (nFe_2O_3) have demonstrated effectiveness in mitigating the stress brought on by cadmium ions in *Oryza sativa* L by reducing oxidative stress and modulating phytohormones. (Zhou *et al*., 2023)

NENPs for plants under temperature stress

Another hostile circumstance that disturbs plants is the temperature extremes that emerge as a result of global warming. Drought accompanies this stress, making it much more difficult for plants to develop in their environment. The rate of photosynthesis, water content, gas exchange, and enzyme activity in plants are all severely influenced by extreme heat and cold (Khalid *et al*., 2022). In order to combat heat stress, NENPs help plants increase the expression of genes that produce heat proteins (Khalid *et al*., 2022). When *Zea mays* is under heat stress, CeO_2 nanoparticles increase the synthesis of H_2O_2 and upregulate the HSP70 gene (Wang *et al*., 2022). Silver nanoparticles (Ag-NPs) and Selenium nanoparticles (Se-NPs) have also proven to be effective against heat stress in *Triticum aestivum* and Sorghum, respectively, by providing protection and improving the growth of the plant (Djanaguiraman *et al*., 2018; Iqbal *et al*., 2019). Likewise, chitosan nanoparticles help *Musa acuminata var.* Baxi resists the effects of cold stress by encouraging the formation of osmoprotectants. (Wang *et al*., 2021).

NENPS IN PLANT BIOTIC STRESS

Plants are equally at risk from phytopathogens and herbivory infection as from the severe environment. In addition to endangering crop life, they also reduce crop productivity, which adds to a food crisis. According to figures, plant diseases are accountable for 16% of crop growth and yield losses worldwide. (Ficke *et al*., 2018; Mondal *et al*., 2022). Invasions by bacteria, fungi, viruses, pests, and insects are examples of the biotic stress that plants experience. Like any other organism, plants have an advanced immune system to fend off these invaders. In addition to the physical barriers like wax, cuticle, and trichome that act as passive immunity to drive away pathogens and pests, plants also synthesize secondary metabolites that can be lethal to predators (Ahmad *et al*., 2022). NENPs can be employed as a preventive and therapeutic measure to give an additive effect against these pathogens. Nano-fertilizers, nano-pesticides, and nano-herbicides are synthesized using NENPs that offer a more sustainable, safer, cost-effective, and eco-friendly means of preventing plant biotic stress as a precautionary strategy as opposed to the conventional techniques (Ahmad *et al*., 2022). Some of the NENPs that demonstrate efficiency in combating abiotic stress are summarized in Table 2. To enhance soil nutrients, a variety of NENPs are used as nano fertilizers to improve grain quality, blooming, and fruit quality and increase the photosynthetic rate, germination, plant development, and crop production. For instance, ZnO-NPs improve the general development and output of wheat, maize, coffee, and squash. Similarly, it has been found that ZnS, MnO, Fe/SiO2, FeS2, FeO, MnSO4, and TiO2 all function as nanofertilizers (Guleria *et al*., 2023).

NENPs against fungal, bacterial, and viral infections

As potential biotic stress relievers, NENPs provide a safer alternative to chemical compounds that have been in use for a long time. Many metal nanoparticles have antimicrobial potential, and this property is utilized to engineer nano fungicides and nano bactericides either alone or in conjunction with other compounds. Fol-

Table 2. Different NENPs used to combat different biotic stress factors

Biotic stress	NENPs	Target species	Plant Species	Effect	Reference(s)
Bacterial infection	Silica nanoparticles (SNPs)	*Ralstonia solanacearum*	*Solanum lycopersicum* (tomato)	Preserve ROS equilibrium and stimulate genes associated with salicylic acid during disease stress	Wang *et al*., 2022
	zinc oxide quantum dots (ZnO QDs)	*Acidovorax citrulli*	*Cucumis melo* (melon)	Increased the expression of oxidative stress-related genes after producing hydroxyl radicals.	Wang *et al*., 2023
	MgO-NPs	*Ralstonia solanacearum*	*Solanum lycopersicum* (tomato)	Upregulation of genes associated with salicylic acid, jasmonic acid, and ethylene	Imada *et al*., 2016
	thymol-loaded chitosan nanoparticles (TCNPs)	*Xanthomonas campestris pv campestris*	brassica crops	Bactericidal activity causes cell membrane damage and variation in membrane potential.	Sreelatha *et al*., 2022
Fungal infection	Mesoporous Silica (MoS_2) encapsulated with pesticides	*Rhizoctonia solani*, *Fusarium graminearum*	*Triticum aestivum* (wheat)	Antifungal	Dong *et al*., 2021
	Cu-doped ZnO NPs, Cu-NPs	*B. cinerea*, S.*sclerotiorum*	*Lactuca sativa* (Lettuce)	Enhance antioxidant activity and influence photosynthetic factors.	Tryfon *et al*., 2022
	TiO_2 NPs	*Puccinia striiformis*	*Triticum aestivum* (wheat)	Induce the up- and down-regulation of proteins that improve defense and disease resistance.	Satti *et al*., 2022
	Ag NPs	*R. solani* *F. moniliforme*	*Oryza sativa*	Antifungal activity	Manikandaselvi *et al*., 2020
Viral infection	Ag-NPs	Cucumber mosaic virus (CMV)	*Cucurbita* pepo L (cucumber)	Increase in antioxidant enzymes total phenolic and flavonoid content, upregulation of pathogenesis-related genes and polyphenolic pathway genes	Abdelkhalek *et al*., 2022
Nematode infection	Cu-doped ZnO NPs, Cu-NPs	*Meloidogyne javanica*	*Lactuca sativa* (Lettuce)	Enhance antioxidant activity and has an impact on photosynthetic factors.	Tryfon *et al*., 2022
Pests	Chitosan-based rotenone NPs	*Solenopsis invicta*	Agricultural crops	Reduced the red fire ant venom's alkaloid content	Zheng *et al*., 2022
	Silica NP	*Eurygaster integriceps*	*Triticum aestivum* (wheat)	Reduced oviposition and larval populations of the Sunn-pest	Alizadeh *et al*., 2022
	Ag-NPs, Au-NPs	*Pericallia Ricini*	*Ricinus communis* (Castor bean)	Reduced the body weight of larva, increased mortality of pest.	Sahayaraj *et al*., 2016
	Ag-NPs	*Earias insulana*	*Gossypium sp.*	Reduced invasion of the green ball caused by *E. insulana* larvae	Al Shater *et al*., 2020

lowing this discovery, numerous experiments were conducted to see how well these NENPs work against fungi, bacteria, and viruses that are detrimental to plants (Ahmad *et al*., 2022). CuNPs and CeO_2 provide protection to plants against fungal diseases caused by *Fusarium* species, like Root fungal disease caused by *Fusarium oxysporum* (Adisa *et al*., 2018; Brahmanwade *et al*., 2016; Borgatta *et al*., 2018). Likewise, MoS_2 (Mesoporous Silica) or Cyclodextrin show antifungal activity against *Rhizoctonia solani* and *Fusarium graminearum* that cause rice sheath blight and wheat sheath blight (Dong *et al*., 2021). *Xanthomonas campestris pv campestris* (Xcc), a bacterium that causes black rot disease in brassica crops, is susceptible to thymol-loaded chitosan nanoparticles' (TCNPs) bactericidal activity (Sreelatha *et al*., 2022). MgO-NPs are effective against *Ralstonia solanacearum*, a bacterium responsible for causing bacterial wilt disease, as (Imada *et al*., 2016) demonstrated in tomato plants. A scientific study illustrated that zinc oxide quantum dots (ZnO QDs) improved the growth of melon seedlings infected with *Acidovorax citrulli* which causes bacterial Fruit Blotch Disease (Wang *et al*., 2023). Another study explored the antiviral effects of biosynthesized silver nanoparticles (Ag-NPs) against the cucumber mosaic virus (CMV) in squash (*Cucurbita* pepo L.)

(Abdelkhalek *et al*., 2022).

NENPS as nano pesticides and nano insecticides

Chemical and biological pesticides and insecticides each have drawbacks, and because NENPs offer a better option than the other two, they are growing in popularity. Unlike chemical and biopesticides, where off -targeting, toxicity and slower results are frequently a problem, nano pesticides are quick, environmentally safe, and typically do not damage organisms that are not their target. These nanoparticles, efficient against harmful pests and insects, are used to create nanopesticides and nano insecticides. A few examples of metal oxides used as nanopesticides and nano insecticides are silicon dioxide (SiO2 NPs), magnesium hydroxide (MgOH NPs), copper oxide (CuO NPs), zinc oxide (ZnO NPs), and magnesium oxide (MgO NPs) (Rankic *et al*., 2021; Thabet *et al*., 2021). Chitosan-based rotenone NPs are effective insecticides against *Solenopsis invicta* (red fire ants) that cause loss of crops (Zheng *et al*., 2022). Deltamethrin-loaded KIT-6 Mesoporous Silica NPs found by (Alizadeh *et al*., 2022) are effective against *Eurygaster integriceps* (shield bug) that spoil wheat and barley crops.

TOXICITY ISSUES WITH NENPs

Due to their diverse utility and effective results, NENPs are being increasingly used in the agriculture sector, which will inevitably lead to their accumulation in soil. At lower concentrations, nanoparticles usually pose no threat to the environment but several studies have stated the toxic effects of NENPs on crops when used in higher concentrations. Their prevalence in the soil even substantially impacts the soil microbiota. Moreover, they affect vital microbial mechanisms, including nitrogen fixation, mineralization, and processes that encourage plant growth and overall development (Khan *et al*., 2021). These NENPs are responsible for causing both favourable and unfavourable morphological, physiological, and genetic variations in plants, as depicted in Fig. 3. Different concentrations of the same metal nanoparticles demonstrate different effects in different species of plants (Ranjan *et al*., 2021). For instance, treatment of 500 mg/L of Ag-NPs reduced the length of shoot and root of *R.sativus* sprouts to almost half in a study (Zuverza-Mena *et al*., 2016). Similarly, Wang in his study illustrated that 100 mg/L or more of Ag-NPs affected root elongation in *Arabidopsis thaliana.* (Wang *et al*., 2020)

A scientific study revealed that *Oryza sativa* when treated with a range of concentrations of CuO-NPs had effects on its photosynthetic rate in a dose-dependent manner (Da Costa, & Sharma, 2016). Another study elaborated on the positive effects of TiO2-NPs on *Coriandrum sativum* when used in lower concentrations and devastating effects on the root cell membrane and growth when used in higher concentrations (Hu *et al*., 2020). Apart from the effects NENPs have on plants, they are more harmful to soil and the microorganisms

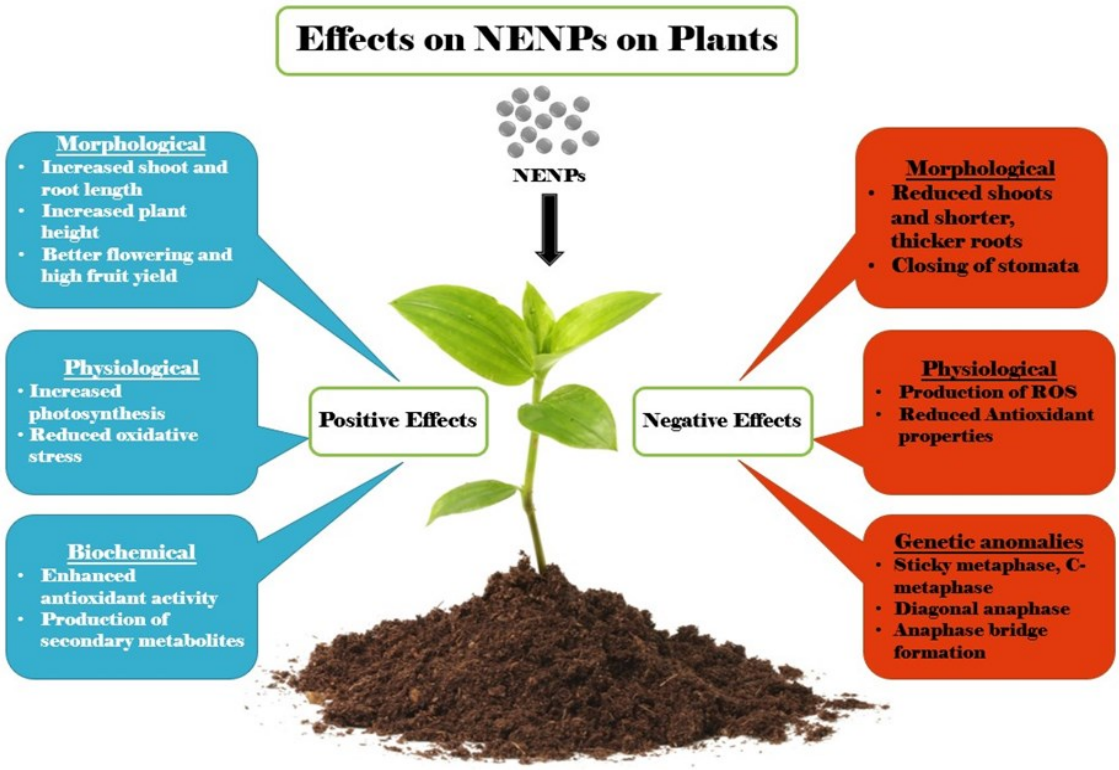

Fig. 3. *Effects of Newly engineered nanoparticles on plants*

inhabiting the soil when they release metal ions upon degradation. Consequently, both the biotic and abiotic components of the ecosystem are affected. Further studies on the toxicological effects of NENPs are required to be conducted to decide the permissible doses of these and devise proper ways of using them on plants to minimize their hazardous effects.

FUTURE PROSPECTS

Catering to the food needs of the population in a world with a growing population is already challenging, and it is further exacerbated by environmental issues that adversely affect crop yield. NENPs are the solution to the problems that the agriculture sector is now facing concerning plant stress management, nutrient deficiencies, poor soil quality, and crop production. Nanoparticles have the potential to entirely replace the obsolete, hazardous, and ineffective techniques that have long prevailed in agriculture and the food sector. There is a considerable amount of research data to support the efficacy of nanoparticles in various crops with a high rate of efficacy. To further investigate the potential of nanoparticles, there are still several areas where comprehensive and accurate data are lacking. To begin with, studies need to be conducted to determine the concentrations at which these NENPs can be employed safely to provide their highest output while causing the least amount of environmental hazard. (García-Ovando *et al*., 2022). This is strongly influenced by the target organism and the kind of nanoparticles being employed. Furthermore, research to comprehend NENPs' mode of action, their interaction with the plant system, and all expected implications and genetic alterations will aid in the study of NENPs' intricate details. Lastly, a critical evaluation of the threat to human health and biodiversity will aid in developing more effective usage protocols for these nanoparticles (García-Ovando *et al*., 2022).

Conclusion

NENPs have the potential to revolutionize research in agriculture. They can be used in various ways to promote the sustainable development of agricultural crops. These particles protect the plants from stress factors and encourage their development and production. Each NENP type mentioned in the review has demonstrated effectiveness against various stress factors. They are a better alternative to conventional plant protection methods due to their high efficiency, even when used in controlled doses. In conclusion, NENPs have a bright future in the agricultural sector. The appropriate efforts will prove to be a boon in addressing global food problems due to the loss of crops to abiotic and biotic factors.

Conflict of interest

The authors declare that they have no conflict of interest.

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