Environmental Science and Pollution Research (2023) 30:93323–93344
https://doi.org/10.1007/s11356-023-29150-z

REVIEW ARTICLE

Nanotoxicity assessment in plants: an updated overview

Hira Zafar[1] · Rabia Javed[2] · Muhammad Zia[1]

Received: 18 February 2023 / Accepted: 30 July 2023 / Published online: 7 August 2023

Abstract

Nanotechnology is rapidly emerging and innovative interdisciplinary field of science. The application of nanomaterials in agricultural biotechnology has been exponentially increased over the years that could be attributed to their uniqueness, versatility, and flexibility. The overuse of nanomaterials makes it crucial to determine their fate and distribution in the in vitro (in cell and tissue cultures) and in vivo (in living species) biological environments by investigating the nano-biointerface. The literature states that the beneficial effects of nanoparticles come along with their adverse effects, subsequently leading to an array of short-term and long-term toxicities. It has been evident that the interplay of nanoparticles with abiotic and biotic communities produces several eco-toxicological effects, and the physiology and biochemistry of crops are greatly influenced by the metabolic alterations taking place at cellular, sub-cellular, and molecular levels. Numerous risk factors affect nanoparticle's accumulation, translocation, and associated cytogenotoxicity. This review article summarizes the contributing factors, possible mechanisms, and risk assessment of hazardous effects of various types of nanoparticles to plant health. The methods for evaluating the plant nanotoxicity parameters have been elaborated. Conclusively, few recommendations are put forward for designing safer, high-quality nanomaterials to protect and maintain environmental safety for smarter agriculture demanded by researchers and industrialists.

Keywords Nanotoxicology · Factors affecting toxicity of nanoparticles · Reactive oxygen species · Phytotoxicity · Genotoxicity

Introduction

Nanotechnology deals with the study of nanoparticles having at least one dimension in 1 to 100 nm. Nanomaterials (NMs) can occur naturally, derived from anthropogenic sources or manufactured by the manipulation of matter, and present in aggregated or disintegrated forms. Nanoparticles (NPs) possess unique and tunable properties that make them distinguishable from their bulk counterparts (Khan et al. 2019a). The alteration of physicochemical features results in changing the reactivity of NMs by the presence of more or less reactive sites on the surface. Particles at nanoscale are being extensively used by the wide range of industries including pharmaceutical, electromagnetic, optoelectronics, dentistry, cosmetics, catalysis, biomedical, agricultural, and environmental industries (Javed et al. 2022a). The wide-ranging applications of NPs in innumerable domains have enabled them to be utilized in developing novel tools, products, and processes at ultrafine level (Yaqoob et al. 2020).

Potential of nanotechnology has surged the investment to nanoresearch by which well-fabricated and well-characterized NPs are applied in diverse fields of science (Ali et al. 2016). NPs can be broadly categorized into organic and inorganic NPs. Inorganic NPs include metal and metal oxide NPs, while organic NPs can be polymeric or carbon-based NPs. Regardless of the significant impact of NMs on plants to protect them against pathogens and for maintaining the soil health and cleaner environment, extensive employment

---

Hira Zafar and Rabia Javed contributed equally.

Highlights
- Toxic effects are produced in plants by metal, metal oxide, polymeric, and carbon-based nanoparticles.
- Risk factors play key role in determining the cytogenotoxicity of nanoparticles in biological systems.
- Assessment of phytotoxicity is performed by evaluating physiological, biochemical, and molecular parameters of plants.

Responsible Editor: Gangrong Shi

✉ Rabia Javed
rjaved@grenfell.mun.ca

[1] Department of Biotechnology, Quaid-i-Azam University, Islamabad 45320, Pakistan

[2] School of Science and the Environment, Grenfell Campus, Memorial University of Newfoundland and Labrador, Corner Brook, Newfoundland A2H 5G4, Canada

of NMs in agriculture and environment has provoked alarming concerns due to their rising adverse effects (Millán-Chiu et al. 2020). The study of such toxic or hazardous materials is known as "toxicology" and the term toxicity when coined with nanotechnology gives rise to a field of science termed "nanotoxicology." It is a rapidly emerging field that elucidates the potential risks of NPs, sometimes called nanopollutants, in different biological systems by investigating the interplay between NPs and different biological processes (Jamil et al. 2018; Zia-ur-Rehman et al. 2018). The abiotic stress caused by NPs is the leading cause of nanotoxicity. Besides, the NPs' use as pesticide or insecticide carrier can also cause toxicity to plants, soil, water, and air.

Exponential production and utilization of NPs lead to higher ecotoxicity risk. Plants being producers are vital for other trophic groups and provide a potential pathway for NPs' transportation via food chain. Plants absorb essential and non-essential elements to carry out vital life activities (Ullah et al. 2020). NPs reach the plants either directly or through contaminated soil and result in toxicity in non-tolerant species. It is reported that NPs' accumulation in soil is greater than air due to lesser mobility in the former. Though higher plants have defense systems such as enzymatic antioxidants (superoxide dismutase, peroxidase, catalase, etc.) and non-enzymatic antioxidants (anthocyanins, vitamins, carotenoids, polyphenols, etc.) to overcome abiotic or oxidative stress, but bioaccumulation in food chain is still threatening (Hossain et al. 2020; Xiao et al. 2022). Nanotoxicity is very difficult to be eliminated if plants suffer from nanocontamination; however, it can be minimized if used below the threshold level concentration to avoid abiotic chemical stress of NPs. Prior to commercialization of NPs, due to their lower-than-toxic concentration, a thorough assessment is needed to analyze their potential ecological and health impact (Jamil et al. 2018).

As the over-exposure of NPs to the soil, plants, humans, and environment leads to hazardous effects, there is need of a specified model that can screen the NPs from the step of production to elimination. Their life cycles start from the resources of development to final production, then utilization (phase in which all types of environmental compartments including soil, air, and water along with the plants and humans are exposed to NPs), and consequently elimination in the form of waste materials should be finely studied. "Safer by design" is the concept which involves development of such NPs that are most appropriate for a particular application and do not inculcate toxicity via nan-biointeraction. This model ensures environmental safety by promoting risk assessment via toxicity testing and screening (Scimeca and Verron 2022; Sukhanova et al. 2018).

Toxicity of NPs to plants, humans, and environment is an area whose most facets are unexplored and these bio-nanointerfaces should be exploited using advanced experimentation. Many in vitro studies have been conducted to study the toxicity of NPs at early growth phases of plants and few in vivo studies have been reported to evaluate its impact on the whole life cycle of plants. Moreover, NMs' transmission to next generation or transgeneration concept is least explored area. Although past studies have amplified our understanding of phytotoxicity induced by NPs, still little is known about their cytotoxic and genotoxic effects. This article precisely reviews the research studies focusing on phytotoxic effect of NPs under in vitro and in vivo conditions by inculcating the most recent data covering influence of different types of NPs on terrestrial and aquatic plant's morphophysiology and their nutritional content, secondary metabolism, and antioxidative systems. Studies have proved metal and metal oxide NPs to be more toxic than polymeric and carbon-based NPs; hence, our focus is on the toxic effects of metal-based NPs. We have tried to fill the existing knowledge gaps and pitfalls regarding understanding of plant nanotoxicity ultimately affecting humans and environment, and placed a headlight on the research domains that need to be addressed by future studies.

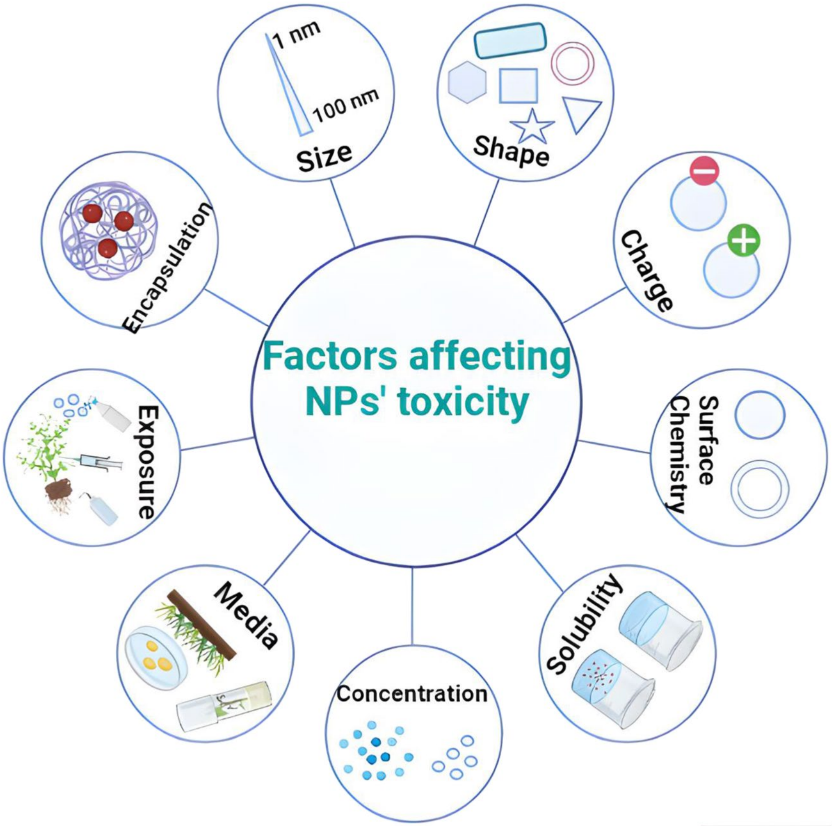
Factors affecting toxicity of nanoparticles

Nanotoxicity is considerably affected by different risk factors that are all interdependent. The synergistic effects of these factors make the phenomenon of nanotoxicity more prominent (Ren et al. 2016). Therefore, the nanotoxicologists identify all the possible risk factors of NMs that could interfere in the protection of human health and environment. It is important to have an understanding about these contributing factors toward nanotoxicity because nano-security is mandatory to ensure biosafety of NMs in the global market (Hou et al. 2018; Jamil et al. 2018; Sukhanova et al. 2018). The possible risk factors contributing to nanotoxicity, particularly plant toxicity, are briefly summarized below and in Fig. 1.

Size

Size is the most important physicochemical characteristics of NMs in determining their bio-reactivity and toxicity. The size of NPs can be controlled by choosing an appropriate synthetic route. Three major routes for fabrication of NPs are physical, chemical, and biological; each containing numerous methodologies and techniques with their specific advantages and specifications. The choice of particular methodology depends upon the intended application according to which protocols are optimized for getting desirable size of NPs. The inverse correlation exists between NPs' size and surface area-to-volume ratio. The uptake, penetration, and interaction of NPs in the cells

Fig. 1 Different factors affecting the toxicity of NPs



depends upon the size of NPs. The smaller the size, more easy is the internalization and vice versa (Naz et al. 2020). It has been reported that the NPs smaller than 5–20 nm can easily pass through the pores of plant cell wall and then through the plasma membrane. But if NPs of > 20 nm have to penetrate, then the cell wall pores stretch for their entry (Nhan et al. 2015). However, the small-sized NPs can be more toxic due to their greater accumulation as well as higher intercellular and intracellular stability. It has been reported that the NPs of smaller size translocate easily and their reactivity is many folds higher than the large-sized NPs, hence, may result in cellular disruption via excessive bioaccumulation of reactive oxygen species (ROS) leading to toxicity (Sajid et al. 2015). The rationale behind is that the defensive system of plant cells activates or triggers after exposure to NPs. But when the NPs' accumulation exceeds, then tolerance to the NPs also decreases, ultimately damaging the physiological, biochemical, and metabolic reactions of the plant system.

Shape and charge

Shape of NMs plays crucial role in nano-biointeractions, also affecting the action mechanisms. More exposed surfaces are more reactive due to large surface area. Similarly, an increased deformation of NPs also exposes the surfaces resulting in generation of ROS and toxicity. It has been observed by researchers that the substrates with which the NPs interact result in alteration of their physicochemical properties to some extent. It results in changing their morphology and surface features resulting in change of charge (Ali et al. 2020). Anionic, cationic, and mixed charged NPs exist that attach to the plant cell wall via electrostatic and non-covalent bonding. The positively charged NPs are attracted to negatively charged surfaces and negatively charged NPs are bound toward the positively charged surface molecules. However, the NPs bearing positive charge result in more toxicity because they can easily bind to the negatively charged DNA, proteins, and enzymes, resulting in cytotoxicity and genotoxicity (Nangia and Sureshkumar 2012; Singh et al. 2019).

Surface chemistry

The binding of NPs is dependent on their surface composition. If NPs are not stable, they may start to aggregate after interaction with particular substrates or ligands. Such physical and chemical reactions result in greater accumulation and hence toxicity of NPs. It has been reported that the non-coated/uncapped NPs get aggregated by which their active surface sites become masked resulting in lower reactivity and more toxicity (Javed et al. 2020).

Coating/capping of NPs widely alter their role and effect on plants in growth media (López-Moreno et al. 2018). For instance, uncapped CeO_2 NPs and CeO_2 NPs capped with citric acid were applied to soil grown *Lycopersicum esculentum* (tomato) plants. The aim of this study was to assess the impact of capped and uncapped CeO_2 NPs on nutritional quality. It was observed that uncapped CeO_2 NPs reduced essential elements like Ca, B, Fe, etc. However, capped CeO_2 NPs lowered macromolecules like starch, reducing sugars, etc. (Barrios et al. 2017). In a recent study, Ag doping of SnO_2 NPs resulted in increasing the toxicity induced by these NPs in *Nicotiana tabacum* (tobacco) cell cultures (Mahjouri et al. 2020). In contrary to this, a study conducted recently employed uncoated and organophosphate-coated CeO_2 NPs to *Lactuca sativa* (lettuce) and the findings of this study stated that the surface modification of NPs reduced solubility, bioavailability, and hence phytotoxicity of NPs to lettuce plant (Zhao et al. 2021).

Solubility

The NPs are easily dissolved in the solvents because of release of metal ions compared to their bulk counterparts. The release of metal ions from NPs is an important factor in determining their solubility and toxicity (Naz et al. 2020). The greater surface area of NPs increases the dissolution and bioavailability which up-scales toxicity in the growth media. In other words, the greater the ionic dissolution of NMs, the higher is their toxicity (Gholami et al. 2020; Hassandoost et al. 2019).

Dosage and concentration

More dosage and concentration of NPs eventually lead to toxicity. Since these parameters play a critical role in determining NPs' toxicity and changes in them increase or decrease nanotoxicity so these should be optimized to get good results and minimize negative outcomes (Orooji et al. 2019) applied anatase and rutile forms of TiO_2 NPs to plants. It was revealed that anatase TiO_2 NPs were more phytotoxic and the toxicity was found to be concentration dependent.

Exposure media and duration

Different media can be utilized for conducting toxicological studies on different plant species such as soil media, agar culture media, and aqueous media. Aqueous media can be Hoagland solution or deionized water. For example, Ag NPs dissolve greater in agar medium in comparison to soil medium. Different exposure media behave differently, and increased exposure duration leads to more accumulation of NPs and toxicity (Cox et al. 2016). Recently, it has been reported that the processes of root and shoot organogenesis of *Stevia rebaudiana* (candy leaf) occur differently in solid and liquid MS culture media. The results depicted highest yield obtained in liquid MS culture while highest steviol glycosides (rebaudioside A and stevioside) content in solid MS culture (Javed and Yücesan 2022). In another study, *Zea mays* (maize) exposed to Al_2O_3 NPs in hydroponic and soil culture media resulted in higher toxicity in hydroponic culture compared to soil media (Ahmed et al. 2022).

Methods of exposure

The primary and secondary routes of exposure to humans and environment exist. Primary routes are the lab or industrial environment where mishandling of instruments and raw materials result in exposure. Other than that, the exposure to NPs might take place during their packaging and transportation which is secondary route (Naz et al. 2020).

The routes of exposure of NPs to plant cells and tissues also play an imminent role in determining their toxicity. There are three basic methods of NP exposure: foliar spray of NPs, direct injection of NPs in the plant parts, and direct injection of NPs in the soil (Jogaiah et al. 2021). All exposure routes have their own merits and demerits. For example, it has been reported that TiO_2 NPs disrupt microbial colonies of rhizosphere while infecting root surface of plants when applied to soil (Waani et al. 2021).

Encapsulation efficiency, delivery, and release kinetics

The NMs can be used itself as nanofertilizers, nanoherbicides, and nanopesticides because of their nutrient enhancing, antibacterial, antifungal, and antiparasitic activities, and these can be used as nanocarriers for loading of chemical fertilizers, pesticides, herbicides, or plant hormones. In case of latter, the desired chemicals or hormones are encapsulated inside the NPs that act as carriers for their delivery into the plant system. All NPs exhibit differential efficiency of encapsulation. Once successfully delivered, the encapsulated NPs are monitored for the release of chemical substances. The main purpose of utilizing NPs as carriers is their targeted and effective delivery along with the slow and sustained release. The effectivity of NPs behaving as nanocarriers is different from one another due to their distinguishing behaviors and properties inside the plants (Guo et al. 2018; Mathur et al. 2022). Besides, the selection of nanocarriers is based on the particular applications for which they have been chosen. For instance, Ag NPs could be used as nanocarriers for efficient delivery of pesticides having antibacterial activity because Ag NPs are themselves extraordinarily antibacterial and believed to work synergistically with the commercial pesticides to protect crops against bacteria (Masum et al. 2019).

Plant species

Different plant species show different levels of phytotoxicity toward NPs leading to species-specific phytotoxicity (Cox et al. 2016). A comprehensive research study elucidated the effect of ZnO NPs on nine different crops, i.e., radish, maize, bean, tomato, pea, cucumber, beet, lettuce, and wheat. Soil amended with four ZnO NP concentrations in which 900 mg/kg was highest concentration was compared with control to study its toxic effect on physiological and biochemical parameters. Biomass reduction was demonstrated by only beet, wheat, and cucumber. Seed germination of only tomato, beat, bean, and lettuce was affected. Photosynthetic pigments and oxidative stress markers also affected the different crops in different manners, i.e., affected only bean, maize, wheat, and pea. This study suggested plant species to be the key element that affected bioavailability and phytotoxicity of ZnO NPs (García-Gómez et al. 2018).

Types of nanoparticles affecting plants

The major types of NPs having influence on plant species are the following:

1. inorganic (metal and metal oxide NPs)
2. organic (polymeric and carbon-based NPs)

Inorganic nanoparticles

The inorganic NPs affecting different plants include metal NPs such as Ag and metal oxide NPs including ZnO, CuO, CdO, FeO, TiO_2, SiO_2, CeO_2, SnO_2, Fe_2O_3, Fe_3O_4, Al_2O_3, Cr_2O_3, La_2O_3, Y_2O_3 NPs, etc. (Ma et al. 2015; Ruttkay-Nedecky et al. 2017). Table 1 represents various metal and metal oxide NPs and their detrimental effects on different plants based on their physicochemical properties, concentration, and route of exposure.

Organic nanoparticles

The organic NPs having influence on plants include polymeric NPs (such as chitosan NPs) and carbon-based NPs (such as mesoporous carbon NPs (MCN) and carbon nanotubes (CNTs), graphene oxide (GO), reduced graphene oxide (rGO), fullerenes) (Chichiriccò and Poma 2015; Jogaiah et al. 2021). Polymeric NPs have many advantages in agricultural biotechnology, for example, these are used as carriers of hormones, nutrients, pesticides, and fertilizers. Low concentrations of polymeric NPs produce positive influence on plant's physiology and biochemistry. However, negative effects are produced at higher concentrations (Mukherjee et al. 2016). Table 2 presents the polymeric and carbon-based NPs that produce detrimental effects on different plant species on the basis of their concentration, route of exposure, and physicochemical features.

Nanotoxicity assessment in plants: current paradigms

The naturally occurring NPs include forest fires, volcanic ash, etc., and incidental NPs are produced from combustion of domestic heating, exhaustion of vehicle engine, etc. However, engineered NMs (ENMs) are manufactured intentionally to obtain desired properties. The nanotoxicological studies are profoundly important to understand the impact of ENMs on different organisms in environment. It significantly quantifies the complex nano-biointeractions (Singh et al. 2022). The tracing of naturally produced and incidental NPs is very difficult. However, the man-made NPs can be screened using state-of-the-art approaches. The synthesis and characterization methods of NPs play crucial role in determining their toxicity. The physical synthesis methods include laser ablation, sputtering, etching, etc. Mostly, hydrothermal, sonochemical, microwave, sol-gel, and co-precipitation methods of chemical synthesis are used. Besides, green synthesis is a very environment-friendly approach for the formation of hazard-free nano-enabled products (Baig et al. 2021). Regarding characterization, scanning electron microscopy (SEM), transmission electron microscopy (TEM), and atomic force microscopy (AFM) are mostly used to study the internalization of NPs in the plant cells. Furthermore, single particle–inductively coupled plasma–mass spectrometry (SP-ICP-MS), X-ray absorption spectroscopy (XAS), and X-ray absorption near edge spectroscopy (XANES) are the advanced techniques for separation of NPs in the suspensions in case of biological and environmental samples (Mourdikoudis et al. 2018). In addition, labeling can determine the fate and behavior of NMs in biological system but the labeling materials should be biocompatible and biodegradable. Sometimes NMs get altered and transformed in context of their aggregation, dissolution, and surface chemistry. Hence, it makes their detection and quantification difficult. Such transformations mainly occur due to redox reactions and generation of ROS by Fenton-type reactions (Tarrahi et al. 2021).

NPs enter into the ecosystem via deliberate or accidental routes. The toxicity of plants makes the management of surrounding environment essential since both aquatic and agricultural plants are affected. NPs also act as carriers for attachment of different toxic molecules to their surface and their transportation within the plant cells. These hazardous

Table 1 Inorganic NPs and their effects on plants leading towards toxicity

Inorganic nanoparticles (NPs)	Physicochemical properties of NPs	Targeted plant species	Concentration of NPs and route of exposure	Findings	Toxicity	Reference
Metal NPs						
Ag NPs	1–10 nm size	*Raphanus sativus* (radish)	0, 125, 250, 500 mg/L	At 500 mg/L, decrease of root and shoot length, reduction of Ca, Mg, B, Zn, Cu, and Mn	Phytotoxicity	Zuverza-Mena et al. (2016)
Ag NPs	PVP-capped 17–18 nm size	*Glycine max* (soybean) *Oryza sativa* (rice)	Soybean: 0–30 mg/L Rice: 0–1 mg/L Foliar spray	Suppressed growth of rice	Phytotoxicity	Li et al. (2017)
Ag NPs		*Arachis hypogaea* (groundnut)	50, 500, 2000 mg/kg Soil culture	Decrease of crop yield	Phytotoxicity	Rui et al. (2017)
Ag NPs		*Egeria densa* (common waterweed) *Juncus effuses* (soft rush)		Increase of SOD and POD activities	Phytotoxicity	Yuan et al. (2018)
Ag NPs		*Triticum aestivum* (wheat)	0, 20, 200, 2000 mg/kg Soil media	Lower biomass, decrease of micronutrients (Fe, Cu, Zn), reduction of amino acids content (histidine, arginine)	Phytotoxicity	Yang et al. (2018)
Ag NPs	< 100 nm	*Triticum aestivum* (wheat)	1 and 5 mM	Suppression of photosynthetic activity, damage of chloroplast and photosystem	Phytotoxicity	Rastogi et al. (2019)
Ag NPs		*Lactuca sativa* (lettuce) *Raphanus sativus* (radish)	Soil media	Decrease of K and Mg in the leaves of *Lactuca sativa*, reduction in yield of *Lactuca sativa* and *Raphanus sativus*	Phytotoxicity	Li et al. (2020)
Metal oxide NPs						
ZnO NPs	< 50 nm size	*Glycine max* (soybean)	0, 50, 500 mg/kg Soil media	Delayed development, reduction in roots and shoots	Phytotoxicity	Yoon et al. (2014)
ZnO NPs		*Brassica nigra* (black mustard)	500, 1000, 1500 mg/L MS media	Inhibition of seed germination and seedling growth, elevation of antioxidative enzymes, and antioxidation activities	Phytotoxicity	Zafar et al. (2016)
ZnO NPs	34 nm size Hexagonal shape	*Stevia rebaudiana* (candyleaf)	0.01, 0.1, 1, 10, 100, 1000 mg/L MS culture media	Decrease of shooting and steviol glycosides, increase of non-enzymatic antioxidant activities	Phytotoxicity	Javed et al. (2017b)

Table 1 (continued)

Inorganic nanoparticles (NPs)	Physicochemical properties of NPs	Targeted plant species	Concentration of NPs and route of exposure	Findings	Toxicity	Reference
ZnO NPs		*Avena sativa* (oat) *Trifolium alexandrinum* (Egyptian clover)	0, 750, 1000, 1250 mg/kg of seeds Filter paper method for incubation	Reduction in shoot and root length	Phytotoxicity	Maity et al. (2018)
ZnO NPs		*Solanum lycopersicum* (potato)	0, 200, 400, 800 mg/dm^3 Hoagland nutrient medium	Inhibition of root and shoot growth, decrease of chlorophyll a and b, enhancement of antioxidant enzymatic activities	Phytotoxicity	Wang et al. (2018)
CuO NPs	~ 30 nm size Spherical shape	*Oryza sativa* (rice)	1–20 mg/L Callus induction media	Inhibition of callus induction	Phytotoxicity	Anwaar et al. (2016)
CuO NPs	47 nm size Monoclinic shape	*Stevia rebaudiana* (candyleaf)	0.01, 0.1, 1, 10, 100, 1000 mg/L MS culture media	Reduction in production of steviol glycosides and plant biomass, enhancement of non-enzymatic antioxidant activities	Phytotoxicity	Javed et al. (2017a)
CuO NPs		*Lactuca sativa* (lettuce) *Brassica oleracea* (cabbage)	0, 10, 250 mg Foliar spray	Decrease in plant weight, water content, and level of photosynthesis, deformation of stomata	Phytotoxicity	Xiong et al. (2017)
CuO NPs	25, 50, 250 nm size	*Glycine max* (soybean)	Soil culture		Phytotoxicity	Yusefi-Tanha et al. (2020)
ZnO NPs CuO NPs	ZnO: 41 nm CuO: 47 nm	*Brassica nigra* (black mustard)	ZnO: 200, 400, 600 mg/kg CuO: 12.5, 25, 50 mg/kg Soil culture	ZnO: Inhibition of seed germination Elevation of phenolics and flavonoids, increase of antioxidant activities	Phytotoxicity	Rehman et al. (2020)
CdO NPs	42 nm size Disc-like shape	*Dodonaea viscosa* (hop bush)	2.5, 5, 10, 20 mg/L MS media	Decrease of plant growth	Phytotoxicity	Nasrullah et al. (2020)
FeO nanorods		*Zea mays* (maize)	25, 50, 100 mg/L Hydroponic culture	Retardation of growth and antioxidative activities	Phytotoxicity	Hasan et al. (2020)
CeO_2 NPs		*Lactuca sativa* (lettuce)	0, 50, 100, 1000 mg/kg Soil culture	At 1000 mg/kg, deterioration of plant growth and production, disruption of SOD, POD, and MDA	Phytotoxicity	Gui et al. (2015)
CeO_2 NPs	19.1 nm size	*Brassica rapa* (wild turnip)	10 and 100 mg/L Soil culture	Variable physiological (plant biomass) and biochemical (CAT, SOD, Chlorophyll, H_2O_2 content) effect on different growth stages		Ma et al. (2016)

Table 1 (continued)

Inorganic nanoparticles (NPs)	Physicochemical properties of NPs	Targeted plant species	Concentration of NPs and route of exposure	Findings	Toxicity	Reference
CeO_2 NPs	16.5 nm size	*Lactuca sativa* (lettuce)	0, 10, 100, 500, 1000, 2000 mg/kg Soil culture	Decrease in chlorophyll content, biomass reduction, alteration of antioxidant enzymatic activities and MDA level	Phytotoxicity	Zhang et al. (2017)
CeO_2 NPs		*Vigna radiate* (mung bean)	250, 500, 1000 mg/L Foliar spray	At 1000 mg/kg, reduction of photosynthetic pigments and retardation of plant growth	Phytotoxicity	Kamali-Andani et al. (2022)
CeO_2 NPs TiO_2 NPs	< 25 nm size	*Hordeum vulgare* (barley)		Toxicity in root cells causing suppression of root elongation	Cytotoxicity and genotoxicity	Mattiello et al. (2015)
ZnO NPs TiO_2 NPs	ZnO: 200 nm TiO_2: 100 nm	*Glycine max* (soybean)	10, 100, 1000 mg/L MS culture	Inhibition of plant growth, decline in conductance of water vapors by stomata and net CO_2 assimilation, alteration in chloroplast structure	Phytotoxicity and cytotoxicity	Leopold et al. (2022)
TiO_2 NPs		*Zea mays* (maize)	0, 5, 10, 20 mg/L Hydroponic culture	Decrease in shoot and root biomass, decline in chlorophyll content	Phytotoxicity	Ağhan (2018)
TiO_2 NPs	< 25 nm size	*Lens culinaris* Medik (lentil)	25, 50, 75, 100, 200 μg/mL Incubation in petri plates	Decrease of growth and photosynthetic pigments, DNA damage, aberrant mitosis	Phytotoxicity and genotoxicity	Khan et al. (2019b)
TiO_2 NPs	~ 30 nm size	*Glycine max* (soybean)	250–1000 mg/L Hoagland nutrient solution	Inhibition of root growth, increase in SOD activity	Phytotoxicity	de Melo et al. (2021)
TiO_2 NPs	26.5 nm size Spherical shape	*Oryza sativa* (rice)	0, 500, 750 mg/kg Soil culture	At 750 mg/kg, inhibition of growth of plant and soil microbes, increase in lipid peroxidation and H_2O_2 production	Phytotoxicity	Waani et al. (2021)
SnO_2 NPs	Ag-doping 10–30 nm size Polygonal shape	*Nicotiana tabacum* (tobacco)	0.1–0.5 mg/mL Cell culture	Reduction of cell viability, enhancement of SOD, POD, phenolics, and flavonoids	Cytotoxicity	Mahjouri et al. (2020)
Zero valent iron (ZVI), Fe_2O_3, Fe_3O_4	ZVI: 20 nm Fe_2O_3: 20 nm Fe_3O_4: 20–30 nm	*Oryza sativa* (rice)	50, 250, 500 mg/L Hydroponic culture	At 500 mg/L, decrease in root volume and leaf biomass, impairment of plant growth, induction of oxidative stress	Phytotoxicity	Li et al. (2021)

Table 1 (continued)

Inorganic nanoparticles (NPs)	Physicochemical properties of NPs	Targeted plant species	Concentration of NPs and route of exposure	Findings	Toxicity	Reference
CuO NPs TiO_2 NPs Fe_2O_3 NPs	CuO: 40 nm size TiO_2: 5 nm size Fe_2O_3: 20 nm size Spherical shape	*Arachis hypogaea* (groundnut)	50, 500 mg/kg Soil culture	Reduction in yield and total amino acids	Phytotoxicity	Rui et al. (2018)
Fe_3O_4 NPs	6.7 nm size	*Cucumis sativus* (cucumber)	50, 500, 2000 mg/L Hydroponic media	Inhibition of plant growth, reduction of antioxidant enzymatic activities	Phytotoxicity	Konate et al. (2018)
Al_2O_3 NPs	13 nm size	*Triticum aestivum* (wheat)	0, 5, 25, 50 mg/L Incubation by filter paper method	Decline in root elongation, cellular damage of root cortex cells, decrease of total protein content	Cytotoxicity and genotoxicity	Yanık and Vardar (2015)
Al_2O_3 NPs	22 nm size	*Zea mays* (maize)	0.05–2 mg/g Hydroponic and soil media	Decline of growth, chlorophyll, phosphorus, and protein content, rise of SOD, POD, CAT, GPX, and GR	Phytotoxicity	Ahmed et al. (2022)
ZnO NPs Mn_3O_4 NPs	ZnO: 35 nm Mn_3O_4: 50 nm	*Solanum lycopersicum* (potato)	250 mg/L Foliar spray	Reduction of β-carotene content	Phytotoxicity	Cantu et al. (2022)
Cr_2O_3 NPs	30–50 nm size	*Glycine max* (soybean)	0, 0.01, 0.05, 0.1, 0.5 g/L Nutrient media	Inhibition of growth, reduction in root and shoot biomass, damage of photosynthetic system, reduction of Rubisco and MDH activity	Phytotoxicity	Li et al. (2018)
La_2O_3 NPs	10–100 nm size	*Zea mays* (maize)	0, 5, 10, 50, 100 mg/L Nutrient solution and Hoagland solution	Decrease of shoot and root biomass, root length, and chlorophyll content	Phytotoxicity	Liu et al. (2018)
Y_2O_3 NPs	30 nm size	*Zea mays* (maize)	0–500 mg/L Incubation in plastic tubes	Delayed seed germination, increase in POD and CAT activity, rise in MDA level	Phytotoxicity	Gong et al. (2019)

SOD, superoxide dismutase; *POD*, peroxidase; *CAT*, catalase; *MDA*, malondialdehyde; *MDH*, malate dehydrogenase; *GPX*, glutathione peroxidase; *GR*, glutathione reductase molecules might get bind to NPs' surface from surrounding pollutant environment or plants' internal cellular environment. According to literature, the nanotoxicity produces various effects on the plants including changes in plant length, height, and biomass; alterations in yield and development; early or late seed germination; elicitation of secondary metabolites; and cytotoxicity leading toward cell cycle disruption and genotoxicity, boosting of antioxidants, triggering of antioxidative enzymes and gene-controlling NPs (abiotic) stress, etc. (Fig. 2). The cytotoxicity of plant cells is analyzed using different macroscopic and microscopic techniques, and the genotoxicity is detected using comet and ames assays, micronucleus assays, chromosomal aberrations, and DNA laddering. It is said that NPs have the intrinsic or inherent ability of destroying the host cells by penetrating into them. Although the defense system of plants is activated, the excessive NMs trapped into the cells ultimately leads to killing of organisms (Conway et al. 2015; Deng et al. 2020; Singla et al. 2019).

Seed germination

Seed germination is the simplest and highly sensitive nanotoxicity assessment test. In a comparative study, SiO_2, Al_2O_3, TiO_2, and ZrO_2 NPs were exposed to *Zea mays* seedlings via cotton, Petri plate, and soil culture methods. The results revealed that only Al_2O_3 and TiO_2, inhibited seed germination and the results obtained by all exposure routes were similar and significant (Karunakaran et al. 2016). Seeds of *Brassica nigra* (black mustard) were exposed to 53-nm-sized CuO NPs that resulted in significant decline in germination of seeds (Zafar et al. 2017). In a study, Rajput et al. (2018) applied CuO NPs to *Hordeum sativum* (barley) in hydroponic system. The findings suggested significant inhibition in seed germination and decrease in rate and efficiency of germination. In another study, Ullah et al. (2020) reported the uptake and translocation of PdS NPs in *Zea mays*. Fifteen-nanometer-sized NPs were applied under hydroponic conditions in 5–50 mg/L of concentrations to *Zea mays* that revealed significant phytotoxicity. The inhibition of seed germination and reduction of biomass of roots and shoots was observed. The detrimental effects of 41-nm-sized ZnO NPs exposed to *Brassica rapa* (wild turnip) in a synthetic soil culture media were estimated. It was found that seed germination was adversely affected by the ZnO NP treatment (Zafar et al. 2020). In a recent study, Cu NPs prepared by plant-mediated green synthesis resulted in inhibition of seed germination in soil grown *Triticum aestivum* (wheat). The NPs were spherical in shape and 23 nm in size. It was found that seed germination was adversely affected beyond 50 mg/L concentration of Cu NPs (Kausar et al. 2022).

Morphophysiology

The prime factors to investigate the toxicity of NPs are growth and development of plants (Movafeghi et al. 2018). The core phytotoxicity evaluating morphological and physiological indices including leaf number and area, biomass, root and stem elongation, etc. (Rafique et al. 2018) observed that at 60 mg/kg concentration of TiO_2 NPs, the chlorophyll content in *Triticum aestivum* raised to 32.3% as compared to control, whereas at 100 mg/kg concentration of TiO_2 NPs, the chlorophyll content decreased to 11.1% as it was impossible for the plant to tolerate NP concentrations above 60 mg/kg. A study was performed using nano-chitosan/tripolyphosphate (TPP) applied to in vitro grown *Capsicum annuum* (bell pepper) in 5, 10, and 20 mg/L of concentrations. The concomitant results were obtained suggesting inhibition of growth and development by the capped chitosan NPs' exposure (Asgari-Targhi et al. 2018). Another study using 15 mg/L of NiO in nano- and bulk form was performed on in vitro grown cultures of *Lycium barbarum* (wolfberry) in MS medium which showed that phytotoxicity depends on metal source. Shoots grown in nano-form showed significant reduction in growth and photosynthetic pigments as a result of oxidative stress as compared to shoots grown in bulk form (Pinto et al. 2019). Another study was conducted to elucidate impact of Ag NPs on *Physalis peruviana* (cape gooseberry) grown under in vitro conditions. It was demonstrated that phytotoxicity is concentration dependent as low concentration promoted germination and increased seedling biomass, while the concentration as high as 15.4 mg/L led to decrease in seedling size and the rooting system of the plant (Timoteo et al. 2019).

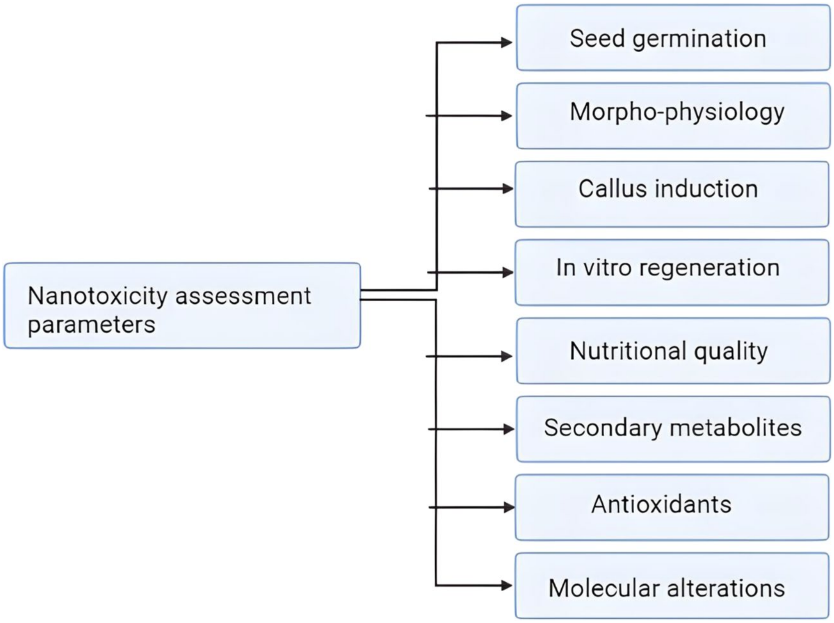
Study of Ag NPs on *Landoltia punctata* (duckweed) showed toxic effect of these NPs. Prominent influence on photosynthetic system was evident with decrease in photosynthetic pigments. Similarly, different physiological and morphological changes were observed by the accumulation of Ag NPs in the plant leaves (Lalau et al. 2020). In another study, CuO NPs given to the natural soil culture in 75, 150, 300, and 600 mg/kg concentrations to different varieties of *Brassica rapa* reduced leaf biomass and chlorophyll content of the treated plants because of the onset of phytotoxicity in a phenotype-dependent manner (Deng et al. 2020). Similarly, Zafar et al. (2020) applied 47-nm-sized CuO NPs and 41-nm-sized ZnO NPs to the synthetic soil in which *Brassica rapa* was allowed to grow. The results revealed significant concentration-dependent decrease in primary root length of the plant. Altogether, detrimental effects of both ZnO and CuO NPs on the plant growth and yield were

Table 2 Organic NPs and their effects on plants leading toward toxicity

Organic nanoparticles (NPs)	Physicochemical properties of NPs	Targeted plant species	Concentration of NPs and Route of exposure	Findings	Toxicity	Reference
Polymeric NPs						
Chitosan NPs	TPP-capped chitosan NPs 233 nm size	*Zea mays* (maize) *Brassica rapa* (wild turnip) *Pisum sativum* (pea)	Incubation in Petri plates	Inhibition of germination	Phytotoxicity	Nakasato et al. (2017)
Chitosan NPs		*Triticum aestivum* (wheat) *Hordeum vulgare* (barley)		At 90 ppm concentration, adverse effects on shooting, rooting, and vigor indexes	Phytotoxicity	Faride et al. (2017)
Chitosan NPs	TPP-capped chitosan NPs 163 nm size	*Capsicum annuum* (bell pepper)	0, 5, 10, 20 mg/L MS media	Decrease in plant growth and development, increase of POD and CAT	Phytotoxicity	Asgari-Targhi et al. (2018)
Carbon-based NPs						
Graphene oxide (GO)		*Avena sativa* (oat)	0–2 mg/L hydroponic culture and soil culture	Inhibition of biomass and length of seedling, reduction of photosynthesis	Phytotoxicity	Chen et al. (2018)
Carbon nanomaterials (CNMs): Fullerene (C60) Graphene oxide (rGO) Multi-walled carbon nanotubes (MWCNTs)		*Oryza sativa* (rice)	Soil culture	Decrease of root length and shoot height, reduction in diameter of root cortical cells, increase of phytohormones (auxin, gibberellin, brassinosteroid), and antioxidant enzymes (POD, SOD)	Phytotoxicity and cytotoxicity	Hao et al. (2018)
Mesoporous carbon NPs (MCN)	MCN1: 150 nm size MCN2: 80 nm size	*Oryza sativa* (rice)	0, 10, 50, 150 mg/L hydroponic culture	Reduction in root and shoot length, increase in production of phytohormones	Phytotoxicity	Hao et al. (2019)

SOD, superoxide dismutase; *POD*, peroxidase; *CAT*, catalase

Fig. 2 Parameters for assessment of nanotoxicity



observed. In a recent study, phytotoxic effect of Y_2O_3 NPs was observed on the growth and translocation of seedlings of *Lycopersicum esculentum*. In hydroponic culture, Y_2O_3 NPs of 20–30 nm size and 1–100 mg/L of concentration were applied to the tomato seedlings and reduction in shoot and root elongation as well as their biomass was elucidated. Overall, the morphology and physiology of crop were adversely affected (Wang et al. 2022).

Callus induction and in vitro regeneration

Different tissue culture studies conducted in plants have shown the adverse influence of NPs supplemented to nutrient medium purposed either for organogenesis, embryogenesis, callus induction, or genetic modification. In vitro culturing systems like cell suspension culture, tissue culture, and hairy root cultures offer controlled conditions to study the effects of NPs on metabolic activities and molecular alterations taking place in plants without an interference of other environmental components which are otherwise problematic in case of in vivo experiments (Kim et al. 2017).

Toxic effects of Ag NPs and Ag^+ ions ($AgNO_3$ salt) were analyzed on callus cells of two *Triticum aestivum* varieties. Microscopic observations showed deformed cells after treatment with high levels of Ag NPs' concentrations. Authors stated that naturally elongated callus cells upon exposure to Ag NPs and Ag^+ ions treatment undergo swelling and reduction; however, no differences between wheat varieties were observed. These visible deformations showed that Ag employed in both forms might act as stress factor (Barbasz et al. 2016). In another study, *Solanum tuberosum* (potato) grown under in vitro conditions was augmented with Ag NPs. The results indicated decrease in glutathione and ascorbate, while increase in superoxide dismutase (SOD) and catalase (CAT) attributed to the phytotoxicity induced at 2 mg/L and above concentrations of Ag NPs (Bagherzadeh Homaee and Ehsanpour 2016). Callus induction of *Trigonella foenum-graecum* (fenugreek) was conducted on MS medium supplemented with CuO NPs impregnated with PVP and PEG. The results depicted increase in total phenolic content, total flavonoid content, total antioxidant capacity, total reducing power, and DPPH-free radical scavenging activity attributed to CuO NPs' toxicity (Ain et al. 2018). In a study, the cell suspension culture of *Arabidopsis thaliana* (thale cress) was exposed to Au NPs and Ag NPs that resulted in alteration of pH of growth media, i.e., the Ag NPs made the media acidic, while Au NPs made it alkaline. The protein composition of cell culture was also changed. Moreover, respiratory activity of cells of suspension culture was reduced as elucidated by the MTT assay (Selivanov et al. 2017).

In another study, Ag NPs supplemented to the MS liquid medium for in vitro regeneration of *Vanilla planifolia* (vanilla creeper) at concentrations of 25, 50, 100, and 200 mg/L resulted in growth reduction at 100 and 200 mg/L concentrations. Besides, lipid peroxidation and non-enzymatic antioxidant activities were significantly risen due to toxicity (Spinoso-Castillo et al. 2017). CuO NPs supplemented to the cell suspension culture of *Nicotiana tabacum* revealed significant toxicity as evidenced by an increase in the production of antioxidant enzymes and malondialdehyde (MDA) as well as loss of cell viability (Mahjouri et al. 2018). In another study, *Stevia rebaudiana* leaf explants grown in MS medium for callus induction were exposed to ZnO and CuO NPs at concentrations of 0.01, 0.1, 1, 100, and 1000 mg/L. Highest inhibition of callus induction occurred at 100 mg/L and 10 mg/L of ZnO and CuO NPs, respectively. The results of this study revealed CuO NPs to be more toxic than ZnO NPs (Javed et al. 2018). Recently, Iqbal et al. (2022) exposed in vitro callus cultures of *Vigna radiata* (mung bean) to ZnO (37.8 nm in size) and CuO NPs (11.5 nm in size) at 0.5 mg/L of concentration on MS growth medium. The NPs acted as nano-stress-elicitors and resulted in significant enhancement of phenolic and glycosidic content.

Nutritional quality

Ag NPs of 2 nm size were applied to *Raphanus sativus* (radish) seedlings by germination paper method and resulted in decrease of macronutrients, i.e., Ca and Mg elements and micronutrients, i.e., Mn, B, Cu, and Zn (Zuverza-Mena et al. 2016). In another study, CeO_2 NPs capped with citric acid and uncapped CeO_2 NPs were employed to soil-raised *Lycopersicum esculentum* plant. The results indicated that citric acid capped CeO_2 NPs lowered macromolecules (total sugars, reducing sugars, and starch). Whereas, uncapped CeO_2 NPs reduced the essential elements (Mn, B, Fe, and Ca) (Barrios et al. 2017). Yang et al. (2018) studied the effect of Ag NPs on the *Triticum aestivum* raised in soil culture having 20, 200, and 2000 mg/kg dosage of NPs. Results indicated severe phytotoxicity evidenced by the significant reduction of micronutrients, viz., Zn, Cu, and Fe. Moreover, histidine and arginine contents were also decreased by 11.8% and 13%, respectively. In another study, the effect of CuO NPs on *Organum vulgare* (oregano) was studied in soil culture. CuO NPs led to decrease in total sugar, reducing sugar, and starch in leaves. Moreover, micro- and macro-elements (B, Zn, Mn, Ca, Mg, P, and S) were significantly reduced in shoots (Du et al. 2018). ZnO NPs of 20 nm size and spherical morphology when exposed to *Setaria italica* (foxtail millet) by foliar spray under field conditions resulted in decrease of total proteins. The NPs were given in 0 and 2.6 mg/L concentrations to the plant (Kolenčík et al. 2019).

In a study, TiO_2 NPs employed to *Triticum aestivum* produced significant alterations that were elucidated at the metabolomics level besides physio-biochemical manifestations. TiO_2 NPs at 0, 5, 50, 150 mg/L of concentrations triggered the production of sugars, tocopherol, and the signaling pathways of tryptophan and phenylalanine in leaves. Whereas, in roots, the tyrosine metabolism was boosted in addition to the upregulation of azelaic acid and monosaccharides. Moreover, serine, valine, and alanine metabolism and biosynthesis of glycolipids were activated. Hence, multiple metabolic pathways were triggered by TiO_2 NPs' oxidative stress (Silva et al. 2020). Lung et al. (2021) studied the impact of 25-nm-sized CuO NPs on nutritional content of *Triticum aestivum* and found that CuO NPs applied via soil culture completely inhibited the accumulation of seventeen elements and the content of Na, Cl, Ba, and Sr was significantly decreased because of the negative effect of NPs. In another study, TiO_2 NPs employed to the soil culture of *Triticum aestivum* caused reduction in its elemental composition. The Na, Fe, Mn, Ba, As, Sb, and Sr contents were badly affected in the wheat plant (Soran et al. 2021).

Secondary metabolites

There is an utmost need to study the plants' secondary metabolism in response to NPs' exposure as they play an important role in plant's performance, adaptation, and communication processes. Recent studies have depicted that plant growth, physiology, and development are highly affected by NPs, but the effect of NPs on plant's secondary metabolism is quite vague (Khan et al. 2019c). The interaction of NPs with plants often leads to the production of ROS that has an ultimate impact upon secondary signaling messengers and transcriptional regulation. This could be noted during induced activation of secondary metabolites where ROS play their role as signaling molecules (Marslin et al. 2017). Recently, Javed et al. (2022b) documented that plant secondary metabolism is modulated by NPs via MAPK phosphorylation pathway, Ca^{2+} flux, and ROS generation, ultimately affecting redox reactions and gene expression (Fig. 3).

Employing signaling molecules as elicitors has been one of the useful technique to produce biotechnologically and pharmaceutically important bioactive compounds in plants. Secondary metabolites in plants are of different kinds including terpenoids, alkaloids, flavonoids, and phenolic compounds. These compounds act as important mediators for interacting with biotic and abiotic elicitors and removal of ROS while battling with different stresses (Hatami et al. 2016; Movafeghi et al. 2018). The production of secondary metabolites has been observed in few studies employing ENPs as abiotic or oxidative stress elicitors. For instance, Hussain et al. (2017) observed enhancement of total flavonoid content (TFC) and total phenolic content (TPC) in the seeds of *Artemisia absinthium* (wormwood) when exposed to Au, Ag, and Cu NPs grown under in vitro conditions in MS growth medium. In another study, treatment with 3 mg/L of CuO NPs under in vitro conditions in agar-free MS medium resulted in greatest yields of gymnemic acid (GA), phenolic compounds, and flavonoids in *Gymnema sylvestre* (gurmar) plant (Chung et al. 2019). A study done on hairy roots of 4-week-old leaves of *Dracocephalum kotschyi* Boiss (a herbaceous plant) inoculated with *Agrobacterium rhizogenes* strain was found to be influenced by SiO_2 NPs at 24 h and 48 h treatment times. Researchers found that the TPC and TFC were improved by SiO_2 NP treatment that was time and concentration dependent. Anticancer flavonoids including xanthomicrol, crisimaritin, and isokaempferide indicated 13-, 13.4-, and 10-fold increment as compared to control (Nourozi et al. 2019).

Enzymatic and non-enzymatic antioxidants

Various studies have reported metal and metal oxide NP-mediated oxidative stress. When ROS production crosses threshold limit, it leads to lipid peroxidation which causes formation of MDA. Amino acid particular site modification, aggregation of reaction products (cross-linked), and peptide chain fragmentation occur causing membrane damage and protein degradation. Certain plant organelles like mitochondria, peroxisomes, and chloroplasts contribute to lethal oxygen intermediate scavenging by using antioxidant defense system in plants. This defense system comprised both enzymatic (peroxidase (POD), glutathione reductase (GR), ascorbate peroxidase (APX), glutathione peroxidase (GPX), glutathione S-transferase (GST), SOD) and non-enzymatic (glutathione (GSH), thiols, phenolics, and ascorbate) components. Antioxidant enzymes and non-enzymatic antioxidants function in scavenging of ROS and defending the plants from toxicity. In extreme cases, progressive DNA damage, electrolyte leakage, and protein oxidation lead to cell death (Ma et al. 2015; Movafeghi et al. 2018).

In an experiment, different concentrations of Ag, Au, and Cu NPs were supplemented in MS medium in which *Artemisia absinthium* seeds were allowed to grow. The stress induced by NPs produced defensive compounds; SOD activity was significantly enhanced besides the increased DPPH-free radical scavenging activity and antioxidant capacity (Hussain et al. 2017). In another study, Al_2O_3 NPs applied via in vitro culturing to *Trigonella faenum-graceum* led to oxidative stress-related responses such as significant decrease in GSH content and increased activity of CAT and APX (Owji et al. 2019). A comparative study showed higher efficiency of Se NPs compared to bulk Se to stimulate organogenesis and growth in *Momordica charantia* (bitter melon) seedlings. However, the higher concentrations of nano-Se resulted in upregulation of CAT and POD activities because of abiotic stress and toxicity induced by Se NPs (Rajaee Behbahani et al. 2020). Recently, Banerjee et al. (2021) determined activation of antioxidant defense enzymes, i.e., CAT, SOD, and GSH, by the induction of oxidative stress of CdSe quantum dots (QDs) in 12.5, 25, and 50 nM concentrations in the roots of *Allium cepa* (onion).

Molecular alterations

Plants are key models to assess toxicity of NPs at gene level. Using different plant models, screening and monitoring of mutagens can be done. It is very cheap and efficient as single mutation can be detected with no requirements of ethical regulations. Nonetheless, very little is known about NPs' induced genotoxicity. NPs' induced oxidative stress leads to mutagenesis like DNA lesions which ends in causing inhibition of plant growth and other alterations. Baskar et al. (2015) observed dose-dependent genotoxicity of Ag NPs in *Brassica rapa* seedlings that resulted in DNA damage. Moreover, triggering of genes involved in the production of secondary metabolites such as anthocyanin and glucosinolates took place at 500 mg/L.

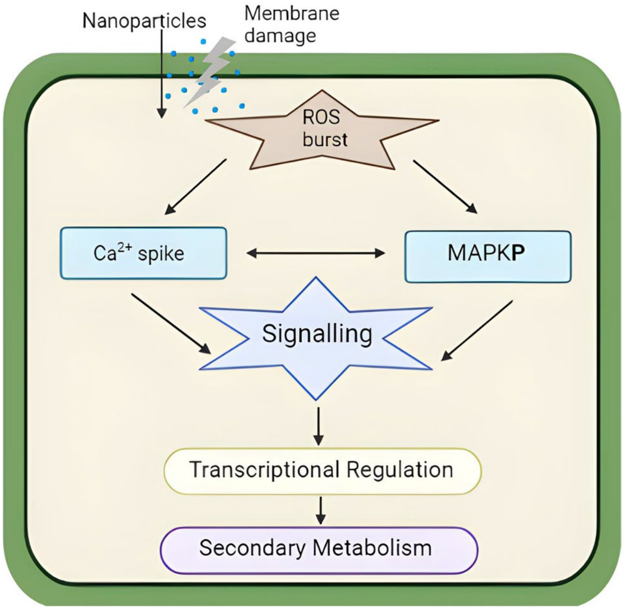


Fig. 3 Diagrammatic illustration of elicitation of secondary metabolism

A study conducted on *Triticum aestivum* revealed molecular alteration upon Al_2O_3 NPs' exposure. Induction of DNA fragmentation revealed by agarose gel electrophoresis results confirmed the genotoxicity triggered by Al_2O_3 NPs (Yanık and Vardar 2015). In a study conducted by Wang et al. (2015), 200 and 300 mg/L of ZnO NP concentrations when employed to *Arabidopsis thaliana* induced toxicity leading to reduced growth and chlorophyll a and b contents of the plant. It also decreased the net photosynthesis rate, and the expression studies done by real time-polymerase chain reaction (RT-PCR) revealed that the expression levels of chlorophyll synthesis genes and photosystem structure genes were significantly low in treated plants compared to the control plants. According to Zhang et al. (2018), Cu NPs were applied to *Triticum aestivum* and the genetic expression of roots of wheat plants exposed to Cu NPs was studied. The 15.6 µM concentration of nano-Cu induced decrease in root cell proliferation and cell death as a result of oxidative stress. It was made evident by the expression of genes that were involved in apoptosis of root cells.

A morphological, metabolomics, and proteomics study on *Phaseolus vulgaris* (common bean) exposed to CeO_2 NPs at the concentrations of 0, 250, 500, 1000, and 2000 mg/L by foliar spray and soil culturing showed dose-dependent membrane disruption as evidenced by an oxidative stress and increase in electrolyte leakage. Metabolic and proteomic damages were observed at higher dosages. Additionally, this study elucidated that spraying of NPs produced stronger impact than their soil application (Salehi et al. 2018). In another study, ZnO NPs in 0, 10, 25, 50, and 100 mg/L dosages were applied to *Vicia faba* (broad bean) during germination of seeds and development of plants from seedlings. Higher concentrations (100 and 200 mg/L) of ZnO NPs induced phytotoxicity. Moreover, genotoxicity evaluated from root meristems showed substantial chromosomal aberrations and increase in DNA lesions. In addition, polyacrylamide gel electrophoresis (PAGE) results confirmed alterations in the expression patterns of all enzymes (Youssef and Elamawi 2020).

Mechanism of phytotoxicity

The NMs if provided to soil culture are absorbed and internalized into the plant roots, entering from root tips or wounds, from here they are taken up to the plant tissues via inter- and intra-cellular mobility in a bottom up manner. Symplastic or apoplastic pathways translocate NPs in different parts of plant through plasmodesmata. In case of aerial exposure by foliar spray of NMs, these are taken up by the cuticle, stomata, hydrathodes, lenticels, or trichomes, from here distributed all over the plant body in a top down manner (Murali et al. 2022). The mechanism of phytotoxicity was reported by Nair and Chung (2017) in *Arabidopsis thaliana* after ZnO NPs and Zn^+ ion exposure. They found that the toxicity mechanisms of NPs and ions were different from each other and the release of metal ions is also an important contributing factor in causing toxicity to plants.

The physical interaction of NPs with cell wall pores disrupts it, and after passing through the cell membrane, they penetrate into the cell cytoplasm via endocytosis. NPs when present in cytoplasm interact physically with endoplasmic reticulum, ribosomes, mitochondria, chloroplast, etc. In a similar fashion, DNA and histone proteins interact with NPs after their entry to the nucleus after passing through the nuclear membrane. Different ROS molecules like hydrogen peroxide (H_2O_2), hydroxyl radical (OH^-), molecular oxygen (O_2), and anionic oxygen (O^{-2}) are produced in plant cells via Fenton-type reactions that are all very lethal, and the generation of ROS plays critical role in determining phytotoxicity of NMs. In response to ROS production, different enzymatic (CAT, POD, SOD, GR, GST, GPX) and non-enzymatic (phenols, flavonoids, thiols, GSH, ascorbic acid (AA), quercetin, anthocyanin) antioxidants as well as hormones (salicylic acid, abscisic acid) are produced under normal physiological conditions for the scavenging of ROS by the process of detoxification (Ma et al. 2015). However, the over-production of ROS results in the formation of toxic intermediates responsible for electrolyte leakage, lipid peroxidation, protein degradation, mitochondrial deterioration, DNA injury, malfunctioning of biomolecules, ultimately collapsing the plant's defense system, and finally ending in apoptosis or necrosis causing cell death (Nhan et al. 2015; Ranjan et al. 2021; Yang et al. 2017) (Fig. 4).

Cytotoxicity

The NMs induce cellular toxicity either directly by stimulation of ROS generation or indirectly by boosting the cellular redox system that eventually activates ROS formation by a Fenton-type reaction. The ROS accumulation impairs cellular redox state as it disrupts translation, compromises mitochondrial respiratory system by interfering with electron transport chain (ETC), inactivates photosystems I and II by impairing the chloroplast, and triggers NADPH-dependent enzymatic systems that ultimately mortalizes the cell (Jomova et al. 2012; Karami Mehrian and De Lima 2016; Regoli and Giuliani 2014).

The cytotoxicity of Al_2O_3 NPs of < 50 nm size was studied in the root tip cells of *Allium cepa*. The NPs were applied at 0.01, 0.1, 1, 10, and 100 μg/mL concentrations that generated an oxidative stress. Results elucidated decrease in mitotic index from 42 to 28%. Moreover, assessments of fluorescence, optical, and confocal laser scanning microscopy revealed different chromosomal aberrations (Rajeshwari et al. 2015). In another study, cytotoxicity of ZnO NPs was elucidated by the meristematic cells of root tips. These cells revealed loss of membrane integrity and damages confirming cytotoxicity in *Allium cepa*, *Nicotiana tabacum*, and *Vicia faba* (Ghosh et al. 2016). The cell suspension culture of *Corylus avellana* (European filbert) was exposed to Ag NPs (2.5, 5, and 10 ppm concentration) by Jamshidi et al. (2016) that resulted in significant decrease of cell viability. In a study, higher concentrations of CeO_2 NPs given to *Nicotiana tabacum* (tobacco BY-2 cells) resulted in induction of cytotoxicity. Recently, generation of ROS and mitochondrial dysfunctioning was revealed by dihydroethidium (DHE) staining and spectrofluorimetric quantitation (Sadhu et al. 2018). In another study, biosynthesized Ag NPs were applied to the roots of *Allium cepa* at different concentrations and exposure durations. The results revealed cytotoxicity measured by macroscopic techniques and spectrophotometry. Ag NPs (20 mg/L) elucidated maximum death of cells of root tips (Heikal et al. 2020). For elucidation of cytotoxicity by different concentrations of CdSe QDs in *Allium cepa*, mitotic frequencies and cell viability analyses were used. The results demonstrated that 25 nM concentration of QDs induced cytotoxicity by oxidative stress (Banerjee et al. 2021).

Genotoxicity

Genotoxicity can be determined at the whole genome, chromosome, and single nuclei level by an evaluation of DNA laddering, chromosomal aberrations, and comet assay, respectively. Previous reports reveal that comet assay, ames assay, micronucleus assays, chromosomal aberrations, and DNA laddering techniques are widely accepted tests for assessment of genotoxicity in plants. Moreover, RT-PCR and random amplified polymorphism DNA (RAPD)-PCR are used to analyze the gene expression (Mahaye et al. 2017; Marmiroli et al. 2022). There exists a positive correlation between ROS generation and damage of DNA. The DNA damage elicits the signaling pathways by which cellular death occurs (Watson et al. 2014). It has been reported that NMs damage DNA via two pathways, i.e., direct and indirect pathways. In direct pathway, NPs directly penetrate through nuclear pores and associate with the DNA strands, disrupting their replication and transcription. But in case of indirect pathway, NPs approach DNA molecules after induction of oxidative stress and generation of ROS. The oxidative burst enables NPs to penetrate into the nucleus and evoke a cascade of cellular events that break the nuclear proteins and mitotic spindles, subsequently arresting the cell cycle and damaging the DNA, finally ending in cell apoptosis. In this way, antioxidative defense mechanism is prohibited via genotoxicity (Magdolenova et al. 2014).

ZnO NP-induced genotoxicity was evaluated in *Allium cepa*, *Nicotiana tabacum*, and *Vicia faba* by 85-nm-sized ZnO NPs' exposure. Detailed assessment showed chromosomal aberrations, DNA strand breaks, and cell cycle arrest in G2/M phase (Ghosh et al. 2016). Abdelsalam et al. (2018) observed the genotoxic effects of Ag NPs on the root tip cells of *Triticum aestivum*. Increase in dose concentration and exposure time resulted in reduction of mitotic cells and induced mitotic abnormalities. Mitotic index was decreased and various types of chromosomal aberrations were analyzed. Additionally, the comprehensive report about the genotoxicity induced by different NPs in higher plants was presented in which the genotoxicity was assessed in model plants, viz., *Nicotiana*, *Allium*, and *Vicia* species using advanced analytical techniques such as comet assays, micronucleus, and chromosomal aberrations (Ghosh et al. 2019). In another study, biogenic Ag NPs applied to *Allium cepa* root tips at 40 mg/L concentration for 4 h were found to cause genotoxicity that was confirmed by comet assay which detected DNA damage in toxic cells (Heikal et al. 2020). Recently, genotoxicity of CdSe QDs caused by oxidative stress was elucidated in the plants of *Allium cepa*. The intact roots of onion bulb were exposed to different concentrations, viz., 12.5, 25, and 50 nM concentrations of QDs. Chromosomal aberrations, micronucleus, and DNA lesions were used for assessment of genotoxicity that demonstrated the 50 nM concentration of QDs to be genotoxic (Banerjee et al. 2021).

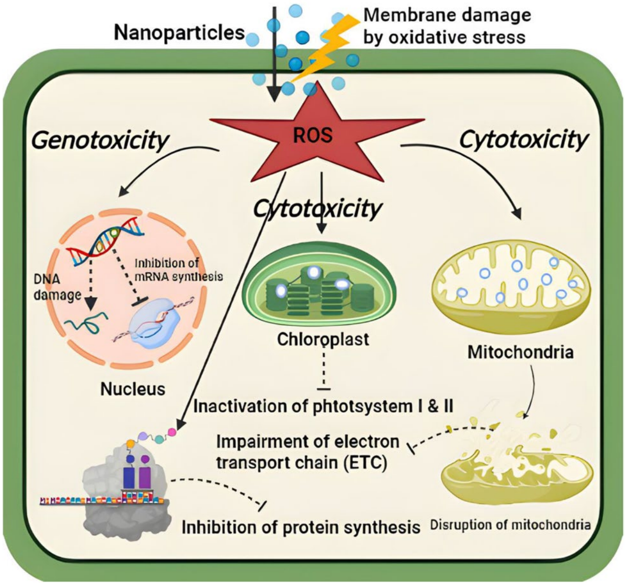


Fig. 4 Diagrammatic representation of mechanism of phytotoxicity (cytotoxicity and genotoxicity) of NPs

Conclusions and future directions

Plants make an integral part of ecosystem and NMs have great influence on them. Hence, it is essential to trace the movement of NMs from outside environment to the terrestrial and aquatic plants. The different factors influencing the toxicity of NPs are size, shape, surface charge, surface chemistry, solubility, concentration, exposure media and duration, methods of exposure, encapsulation efficiency, delivery, release kinetics, and plant species. Various inorganic and organic NPs affect plants; however, the organic NPs have been found to elucidate less detrimental impacts on plants. The nanotoxicity produces alterations at cellular and molecular levels such as seed germination, morphophysiology, in vitro regeneration, callus induction, nutritional quality, secondary metabolites, and enzymatic and non-enzymatic antioxidants. Phytotoxicity including cytotoxicity and genotoxicity can be assessed using different macroscopic and microscopic techniques, comet and ames assays, micronucleus assays, chromosomal aberrations, and DNA laddering. The mechanism of phytotoxicity mainly involves the generation of ROS that eventually leads to apoptosis of plant cells.

Currently, the knowledge is limited regarding deep understanding of nanotoxicological mechanisms and the detrimental effects of NMs on living organisms and environment. Till date, very few studies have been published in the context of the fate, effect, and ultimate consequences of NPs. Henceforth, researchers must exploit this area of research by using the advanced omics approaches, i.e., proteomics, metabolomics, and genomics. Life cycle studies should be conducted to evaluate the cumulative impact of NMs in the food chain. More and more field experiments should be performed because these are environment relevant. Also, investigation of the interaction of NPs with the soil and soil microbes should be done. Moreover, transgenerational influence of NPs should be evaluated. Most importantly, improvements in analysis and assessment techniques of nanotoxicity should be made and real-time in situ methods should be devised because of the transient nature of NMs. Novel microscopic tools should be introduced in the market. Standard guidelines should be approved for in vitro and in vivo nanotoxicity assessment that is robust and accurate. In order to assure the progress in this domain, steps must be taken by policy makers and administrators to provide proper funding to apply NPs in agriculture sector. Furthermore, all NMs must be ensured of being non-hazardous prior to their release by industrialists in the market. This can only be done if NMs are fabricated, keeping in mind of their possible application, i.e., their design must be in synergy to their applicability. In addition, stability of NPs is immensely important to preserve their inherent characteristics which can only be maintained if NPs are fabricated using stabilizers or capping agents. It also confirms the long-term employment of NMs without the risk of being changed by the environmental factors.

In a nutshell, the risk and safety assessment of NPs should be taken into utmost consideration during their development and employment in agriculture and environment to shut down the rising toxicity concerns in this regard and to protect human health. Researchers from various domains must work together through collaboration and capacity building by adopting multidisciplinary approach for setting the direction of possible future research toward mitigation of nanotoxicity.

Acknowledgements The authors are grateful to the Department of Biotechnology, Quaid-i-Azam University, Islamabad, Pakistan and School of Science, and the Environment, Memorial University of Newfoundland and Labrador, Newfoundland, Canada.

Availability of data and materials Not applicable.

Author contribution Hira Zafar: conceptualization, data curation, formal analysis, investigation, and writing—original draft. Rabia Javed: conceptualization, data curation, formal analysis, investigation, methodology, software, supervision, validation, visualization, writing—original draft, and writing—review and editing. Muhammad Zia: conceptualization, formal analysis, methodology, project administration, supervision, and writing—review and editing.

Declarations

Ethical approval Not applicable

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Abdelsalam NR, Abdel-Megeed A, Ali HM, Salem MZM, Al-Hayali MFA, Elshikh MS (2018) Genotoxicity effects of silver nanoparticles on wheat (Triticum aestivum L.) root tip cells. Ecotoxicol Environ Saf 155:76–85. https://doi.org/10.1016/j.ecoenv.2018.02.069

Ağhan (2018) Effects of TiO 2 nanoparticles on maize (Zea mays L..) growth, chlorophyll content and nutrient uptake, pp 6873–6883

Ahmed B, Rizvi A, Syed A, Rajput VD, Elgorban AM, Al-Rejaie SS, Minkina T, Khan MS, Lee J (2022) Understanding the phytotoxic impact of Al3+, nano-size, and bulk Al2O3 on growth and physiology of maize (Zea mays L.) in aqueous and soil media. Chemosphere 300:134555. https://doi.org/10.1016/j.chemosphere.2022.134555

Ain NU, Haq IU, Abbasi BH, Javed R, Zia M (2018) Influence of PVP/PEG impregnated CuO NPs on physiological and biochemical characteristics of Trigonella foenum-graecum L. IET Nanobiotechnol 12(3):349–356. https://doi.org/10.1049/iet-nbt.2017.0102 eCollection 2018 Apr

Ali A, Ovais M, Cui X, Rui Y, Chen C (2020) Safety assessment of nanomaterials for antimicrobial applications. Chem Res Toxicol 33(5):1082–1109. https://doi.org/10.1021/acs.chemrestox.9b00519

Ali A, Zafar H, Zia M, Ul Haq I, Phull AR, Ali JS, Hussain A (2016) Synthesis, characterization, applications, and challenges of iron oxide nanoparticles. Nanotechnol Sci Appl 9:49–67. https://doi.org/10.2147/nsa.S99986

Anwaar S, Maqbool Q, Jabeen N, Nazar M, Abbas F, Nawaz B, Hussain T, Hussain SZ (2016) The effect of green synthesized CuO nanoparticles on callogenesis and regeneration of Oryza sativa L. Front Plant Sci 7:1330. https://doi.org/10.3389/fpls.2016.01330

Asgari-Targhi G, Iranbakhsh A, Ardebili ZO (2018) Potential benefits and phytotoxicity of bulk and nano-chitosan on the growth, morphogenesis, physiology, and micropropagation of Capsicum annuum. Plant Physiol Biochem : PPB 127:393–402. https://doi.org/10.1016/j.plaphy.2018.04.013

Bagherzadeh Homaee M, Ehsanpour AA (2016) Silver nanoparticles and silver ions: oxidative stress responses and toxicity in potato (Solanum tuberosum L) grown in vitro. Hortic Environ Biotechnol 57(6):544–553. https://doi.org/10.1007/s13580-016-0083-z

Baig N, Kammakakam I, Falath W (2021) Nanomaterials: a review of synthesis methods, properties, recent progress, and challenges. Mater Adv 2(6):1821–1871. https://doi.org/10.1039/D0MA00807A

Banerjee R, Goswami P, Chakrabarti M, Chakraborty D, Mukherjee A, Mukherjee A (2021) Cadmium selenide (CdSe) quantum dots cause genotoxicity and oxidative stress in Allium cepa plants. Mutat Res Genet Toxicol Environ Mutagen 865:503338. https://doi.org/10.1016/j.mrgentox.2021.503338

Barbasz A, Kreczmer B, Oćwieja M (2016) Effects of exposure of callus cells of two wheat varieties to silver nanoparticles and silver salt (AgNO3). Acta Physiol Plant 38(3):76. https://doi.org/10.1007/s11738-016-2092-z

Barrios AC, Medina-Velo IA, Zuverza-Mena N, Dominguez OE, Peralta-Videa JR, Gardea-Torresdey JL (2017) Nutritional quality assessment of tomato fruits after exposure to uncoated and citric acid coated cerium oxide nanoparticles, bulk cerium oxide, cerium acetate and citric acid. Plant Physiol Biochem 110:100–107. https://doi.org/10.1016/j.plaphy.2016.04.017

Baskar V, Venkatesh J, Park SW (2015) Impact of biologically synthesized silver nanoparticles on the growth and physiological responses in Brassica rapa ssp. pekinensis. Environ Sci Pollut Res Int 22(22):17672–17682. https://doi.org/10.1007/s11356-015-4864-1

Cantu JM, Ye Y, Hernandez-Viezcas JA, Zuverza-Mena N, White JC, Gardea-Torresdey JL (2022) Tomato fruit nutritional quality is altered by the foliar application of various metal oxide nanomaterials. Nanomaterials (Basel, Switzerland) 12(14). https://doi.org/10.3390/nano12142349

Chen L, Yang S, Liu Y, Mo M, Guan X, Huang L, Sun C, Yang S-T, Chang X-L (2018) Toxicity of graphene oxide to naked oats (Avena sativa L.) in hydroponic and soil cultures. RSC. Advances 8(28):15336–15343. https://doi.org/10.1039/C8RA01753K

Chichiriccò G, Poma A (2015) Penetration Toxicity Nanomaterials Higher Plants 5(2):851–873

Chung I-M, Rajakumar G, Subramanian U, Venkidasamy B, Thiruvengadam M (2019) Impact of copper oxide nanoparticles on enhancement of bioactive compounds using cell suspension cultures of Gymnema sylvestre (Retz.) R. Br. 9(10):2165

Conway JR, Beaulieu AL, Beaulieu NL, Mazer SJ, Keller AA (2015) Environmental stresses increase photosynthetic disruption by metal oxide nanomaterials in a soil-grown plant. ACS Nano 9(12):11737–11749. https://doi.org/10.1021/acsnano.5b03091

Cox A, Venkatachalam P, Sahi S, Sharma N (2016) Silver and titanium dioxide nanoparticle toxicity in plants: a review of current research. Plant Physiol Biochem 107:147–163. https://doi.org/10.1016/j.plaphy.2016.05.022

de Melo GSR, Constantin RP, Abrahão J, de Paiva Foletto-Felipe M, Constantin RP, dos Santos WD, Ferrarese-Filho O, Marchiosi R (2021) Titanium dioxide nanoparticles induce root growth inhibition in soybean due to physical damages. Water Air Soil Pollut 232(1):25. https://doi.org/10.1007/s11270-020-04955-7

Deng C, Wang Y, Cota-Ruiz K, Reyes A, Sun Y, Peralta-Videa J, Hernandez-Viezcas JA, Turley RS, Niu G, Li C, Gardea-Torresdey J (2020) Bok choy (Brassica rapa) grown in copper oxide nanoparticles-amended soils exhibits toxicity in a phenotype-dependent manner: translocation, biodistribution and nutritional disturbance. J Hazard Mater 398:122978. https://doi.org/10.1016/j.jhazmat.2020.122978

Du W, Tan W, Yin Y, Ji R, Peralta-Videa JR, Guo H, Gardea-Torresdey JL (2018) Differential effects of copper nanoparticles/microparticles in agronomic and physiological parameters of oregano (Origanum vulgare). Sci Total Environ 618:306–312. https://doi.org/10.1016/j.scitotenv.2017.11.042

Faride B, Zeinalabedin TS, Mohamad Zaman K, Seyed Ali Mohamad MS, Ali S (2017) Phytotoxicity of chitosan and SiO2 nanoparticles to seed germination of wheat (Triticum aestivum L.) and barley (Hordeum vulgare L.) plants. Notulae Sci Biol 9(2). https://doi.org/10.15835/nsb9210075

García-Gómez C, Obrador A, González D, Babín M, Fernández MD (2018) Comparative study of the phytotoxicity of ZnO nanoparticles and Zn accumulation in nine crops grown in a calcareous soil and an acidic soil. Sci Total Environ 644:770–780. https://doi.org/10.1016/j.scitotenv.2018.06.356

Gholami P, Dinpazhoh L, Khataee A, Hassani A, Bhatnagar A (2020) Facile hydrothermal synthesis of novel Fe-Cu layered double hydroxide/biochar nanocomposite with enhanced sonocatalytic activity for degradation of cefazolin sodium. J Hazard Mater 381:120742. https://doi.org/10.1016/j.jhazmat.2019.120742

Ghosh M, Ghosh I, Godderis L, Hoet P, Mukherjee A (2019) Genotoxicity of engineered nanoparticles in higher plants. Mutat Res Genet Toxicol Environ Mutagen 842:132–145. https://doi.org/10.1016/j.mrgentox.2019.01.002

Ghosh M, Jana A, Sinha S, Jothiramajayam M, Nag A, Chakraborty A, Mukherjee A, Mukherjee A (2016) Effects of ZnO nanoparticles in plants: cytotoxicity, genotoxicity, deregulation of antioxidant defenses, and cell-cycle arrest. Mutat Res Genet Toxicol Environ Mutagen 807:25–32. https://doi.org/10.1016/j.mrgentox.2016.07.006

Gong C, Wang L, Li X, Wang H, Jiang Y, Wang W (2019) Responses of seed germination and shoot metabolic profiles of maize (Zea mays L.) to Y2O3 nanoparticle stress. RSC. Advances 9(47):27720–27731. https://doi.org/10.1039/C9RA04672K

Gui X, Zhang Z, Liu S, Ma Y, Zhang P, He X, Li Y, Zhang J, Li H, Rui Y, Liu L, Cao W (2015) Fate and phytotoxicity of CeO2 nanoparticles on lettuce cultured in the potting soil environment. PloS One 10(8):e0134261. https://doi.org/10.1371/journal.pone.0134261

Guo H, White JC, Wang Z, Xing B (2018) Nano-enabled fertilizers to control the release and use efficiency of nutrients. Curr Opin Environ Sci Health 6:77–83. https://doi.org/10.1016/j.coesh.2018.07.009

Hao Y, Ma C, Zhang Z, Song Y, Cao W, Guo J, Zhou G, Rui Y, Liu L, Xing B (2018) Carbon nanomaterials alter plant physiology and soil bacterial community composition in a rice-soil-bacterial ecosystem. Environ Pollut 232:123–136. https://doi.org/10.1016/j.envpol.2017.09.024

Hao Y, Xu B, Ma C, Shang J, Gu W, Li W, Hou T, Xiang Y, Cao W, Xing B, Rui Y (2019) Synthesis of novel mesoporous carbon nanoparticles and their phytotoxicity to rice (Oryza sativa L.). J Saudi Chem Soc 23(1):75–82. https://doi.org/10.1016/j.jscs.2018.05.003

Hasan M, Rafique S, Zafar A, Loomba S, Khan R, Hassan SG, Khan MW, Zahra S, Zia M, Mustafa G, Shu X, Ihsan Z, Mahmood N (2020) Physiological and anti-oxidative response of biologically and chemically synthesized iron oxide: zea mays a case study. Heliyon 6(8):e04595. https://doi.org/10.1016/j.heliyon.2020.e04595

Hassandoost R, Pouran SR, Khataee A, Orooji Y, Joo SW (2019) Hierarchically structured ternary heterojunctions based on Ce3+/Ce4+ modified Fe3O4 nanoparticles anchored onto graphene oxide sheets as magnetic visible-light-active photocatalysts for decontamination of oxytetracycline. J Hazard Mater 376:200–211. https://doi.org/10.1016/j.jhazmat.2019.05.035

Hatami M, Kariman K, Ghorbanpour M (2016) Engineered nanomaterial-mediated changes in the metabolism of terrestrial plants. Sci Total Environ 571:275–291. https://doi.org/10.1016/j.scitotenv.2016.07.184

Heikal YM, Şuţan NA, Rizwan M, Elsayed A (2020) Green synthesized silver nanoparticles induced cytogenotoxic and genotoxic changes in Allium cepa L. varies with nanoparticles doses and duration of exposure. Chemosphere 243:125430. https://doi.org/10.1016/j.chemosphere.2019.125430

Hossain Z, Yasmeen F, Komatsu S (2020) Nanoparticles: synthesis, morphophysiological effects, and proteomic responses of crop plants. Int J Mol Sci 21(9). https://doi.org/10.3390/ijms21093056

Hou J, Wu Y, Li X, Wei B, Li S, Wang X (2018) Toxic effects of different types of zinc oxide nanoparticles on algae, plants, invertebrates, vertebrates and microorganisms. Chemosphere 193:852–860. https://doi.org/10.1016/j.chemosphere.2017.11.077

Hussain M, Raja NI, Mashwani ZU, Iqbal M, Sabir S, Yasmeen F (2017) In vitro seed germination and biochemical profiling of Artemisia absinthium exposed to various metallic nanoparticles. 3 Biotech 7(2):101. https://doi.org/10.1007/s13205-017-0741-6

Iqbal Z, Javad S, Naz S, Shah AA, Shah AN, Paray BA, Gulnaz A, Abdelsalam NR (2022) Elicitation of the in vitro cultures of selected varieties of Vigna radiata L. with zinc oxide and copper oxide nanoparticles for enhanced phytochemicals production. Front Plant Sci 13:908532. https://doi.org/10.3389/fpls.2022.908532

Jamil B, Javed R, Qazi AS, Syed MA (2018) Nanomaterials: toxicity, risk managment and public perception. In: Rai M, Biswas JK (eds) Nanomaterials: ecotoxicity, safety, and public perception.

Springer International Publishing, Cham, pp 283–304. https://doi.org/10.1007/978-3-030-05144-0_14

Jamshidi M, Ghanati F, Rezaei A, Bemani E (2016) Change of antioxidant enzymes activity of hazel (Corylus avellana L.) cells by AgNPs. Cytotechnology 68(3):525–530. https://doi.org/10.1007/s10616-014-9808-y

Javed R, Ain NU, Gul A, Arslan Ahmad M, Guo W, Ao Q, Tian S (2022a) Diverse biotechnological applications of multifunctional titanium dioxide nanoparticles: an up-to-date review. IET Nanobiotechnol 16(5):171–189. https://doi.org/10.1049/nbt2.12085

Javed R, Mohamed A, Yücesan B, Gürel E, Kausar R, Zia M (2017a) CuO nanoparticles significantly influence in vitro culture, steviol glycosides, and antioxidant activities of Stevia rebaudiana Bertoni. Plant Cell, Tissue Organ Cult (PCTOC) 131(3):611–620. https://doi.org/10.1007/s11240-017-1312-6

Javed R, Usman M, Yücesan B, Zia M, Gürel E (2017b) Effect of zinc oxide (ZnO) nanoparticles on physiology and steviol glycosides production in micropropagated shoots of Stevia rebaudiana Bertoni. Plant Physiol Biochem 110:94–99. https://doi.org/10.1016/j.plaphy.2016.05.032

Javed R, Yücesan B (2022) Impact of Stevia rebaudiana culturing in liquid medium: elevation of yield and biomass, mitigation of steviol glycosides: comparative analysis of culturing of Stevia rebaudiana in solid and liquid media. Proc Pak Acad Sci: Part B (Life and Environ Sci) 59(1):69–75. https://doi.org/10.53560/PPASB(59-1)704

Javed R, Yucesan B, Zia M, Gurel E (2018) Elicitation of secondary metabolites in callus cultures of stevia rebaudiana bertoni grown under ZnO and CuO nanoparticles stress. Sugar Tech 20(2):194–201. https://doi.org/10.1007/s12355-017-0539-1

Javed R, Yucesan B, Zia M, Gurel E (2022b) Nanoelicitation: a promising and emerging technology for triggering the sustainable in vitro production of secondary metabolites in medicinal plants. In: Chen J-T (ed) Plant and nanoparticles. Springer Nature Singapore, Singapore, pp 265–280. https://doi.org/10.1007/978-981-19-2503-0_10

Javed R, Zia M, Naz S, Aisida SO, Ain, N.u., Ao, Q. (2020) Role of capping agents in the application of nanoparticles in biomedicine and environmental remediation: recent trends and future prospects. J Nanobiotechnol 18(1):172. https://doi.org/10.1186/s12951-020-00704-4

Jogaiah S, Paidi MK, Venugopal K, Geetha N, Mujtaba M, Udikeri SS, Govarthanan M (2021) Phytotoxicological effects of engineered nanoparticles: an emerging nanotoxicology. Sci Total Environ 801:149809. https://doi.org/10.1016/j.scitotenv.2021.149809

Jomova K, Baros S, Valko M (2012) Redox active metal-induced oxidative stress in biological systems. Transit Met Chem 37(2):127–134. https://doi.org/10.1007/s11243-012-9583-6

Kamali-Andani N, Fallah S, Peralta-Videa JR, Golkar P (2022) A comprehensive study of selenium and cerium oxide nanoparticles on mung bean: individual and synergistic effect on photosynthesis pigments, antioxidants, and dry matter accumulation. Sci Total Environ 830:154837. https://doi.org/10.1016/j.scitotenv.2022.154837

Karami Mehrian S, De Lima R (2016) Nanoparticles cyto and genotoxicity in plants: mechanisms and abnormalities. Environ Nanotechnology, Monit Manage 6:184–193. https://doi.org/10.1016/j.enmm.2016.08.003

Karunakaran G, Suriyaprabha R, Rajendran V, Kannan N (2016) Influence of ZrO2, SiO2, Al2O3 and TiO2 nanoparticles on maize seed germination under different growth conditions. IET Nanobiotechnol 10(4):171–177. https://doi.org/10.1049/iet-nbt.2015.0007

Kausar H, Mehmood A, Khan RT, Ahmad KS, Hussain S, Nawaz F, Iqbal MS, Nasir M, Ullah TS (2022) Green synthesis and characterization of copper nanoparticles for investigating their effect on germination and growth of wheat. PloS One 17(6):e0269987. https://doi.org/10.1371/journal.pone.0269987

Khan I, Saeed K, Khan I (2019a) Nanoparticles: properties, applications and toxicities. Arab J Chem 12(7):908–931. https://doi.org/10.1016/j.arabjc.2017.05.011

Khan MA, Khan T, Mashwani Z-U-R, Riaz MS, Ullah N, Ali H, Nadhman A (2019c) Chapter Two - Plant cell nanomaterials interaction: growth, physiology and secondary metabolism. In: Das AK (ed) Verma, S.K. Elsevier, Comprehensive Analytical Chemistry, pp 23–54. https://doi.org/10.1016/bs.coac.2019.04.005

Khan Z, Shahwar D, Yunus Ansari MK, Chandel R (2019b) Toxicity assessment of anatase (TiO2) nanoparticles: a pilot study on stress response alterations and DNA damage studies in Lens culinaris Medik. Heliyon 5(7):e02069. https://doi.org/10.1016/j.heliyon.2019.e02069

Kim DH, Gopal J, Sivanesan I (2017) Nanomaterials in plant tissue culture: the disclosed and undisclosed. RSC Adv 7(58):36492–36505. https://doi.org/10.1039/C7RA07025J

Kolenčík M, Ernst D, Komár M, Urík M, Šebesta M, Dobročka E, Černý I, Illa R, Kanike R, Qian Y, Feng H, Orlová D, Kratošová G (2019) Effect of foliar spray application of zinc oxide nanoparticles on quantitative, nutritional, and physiological parameters of foxtail millet (Setaria italica L.) under field conditions. Nanomaterials (Basel, Switzerland) 9(11). https://doi.org/10.3390/nano9111559

Konate A, Wang Y, He X, Adeel M, Zhang P, Ma Y, Ding Y, Zhang J, Yang J, Kizito S, Rui Y, Zhang Z (2018) Comparative effects of nano and bulk-Fe3O4 on the growth of cucumber (Cucumis sativus). Ecotoxicol Environ Saf 165:547–554. https://doi.org/10.1016/j.ecoenv.2018.09.053

Lalau CM, Simioni C, Vicentini DS, Ouriques LC, Mohedano RA, Puerari RC, Matias WG (2020) Toxicological effects of AgNPs on duckweed (Landoltia punctata). Sci Total Environ 710:136318. https://doi.org/10.1016/j.scitotenv.2019.136318

Leopold LF, Coman C, Clapa D, Oprea I, Toma A, Iancu ȘD, Barbu-Tudoran L, Suciu M, Ciorîță A, Cadiș AI, Mureșan LE, Perhaița IM, Copolovici L, Copolovici DM, Copaciu F, Leopold N, Vodnar DC, Coman V (2022) The effect of 100–200 nm ZnO and TiO2 nanoparticles on the in vitro-grown soybean plants. Colloids Surf B: Biointerfaces 216:112536. https://doi.org/10.1016/j.colsurfb.2022.112536

Li CC, Dang F, Li M, Zhu M, Zhong H, Hintelmann H, Zhou DM (2017) Effects of exposure pathways on the accumulation and phytotoxicity of silver nanoparticles in soybean and rice. Nanotoxicology 11(5):699–709. https://doi.org/10.1080/17435390.2017.1344740

Li J, Song Y, Wu K, Tao Q, Liang Y, Li T (2018) Effects of Cr2O3 nanoparticles on the chlorophyll fluorescence and chloroplast ultrastructure of soybean (Glycine max). Environ Sci Pollut Res 25(20):19446–19457. https://doi.org/10.1007/s11356-018-2132-x

Li M, Liu H-l, Dang F, Hintelmann H, Yin B, Zhou D (2020) Alteration of crop yield and quality of three vegetables upon exposure to silver nanoparticles in sludge-amended soil. ACS Sustain Chem Eng 8(6):2472–2480. https://doi.org/10.1021/acssuschemeng.9b06721

Li M, Zhang P, Adeel M, Guo Z, Chetwynd AJ, Ma C, Bai T, Hao Y, Rui Y (2021) Physiological impacts of zero valent iron, Fe3O4 and Fe2O3 nanoparticles in rice plants and their potential as Fe fertilizers. Environ Pollut 269:116134. https://doi.org/10.1016/j.envpol.2020.116134

Liu Y, Xu L, Dai Y (2018) Phytotoxic effects of lanthanum oxide nanoparticles on maize (<i>Zea mays L.</i>). IOP Conf Ser: Earth Environ Sci 113:012020. https://doi.org/10.1088/1755-1315/113/1/012020

López-Moreno ML, Cedeño-Mattei Y, Bailón-Ruiz SJ, Vazquez-Nuñez E, Hernandez-Viezcas JA, Perales-Pérez OJ, la Rosa GD, Peralta-Videa JR, Gardea-Torresdey JL (2018) Environmental behavior of coated NMs: physicochemical aspects and plant interactions.

J Hazard Mater 347:196–217. https://doi.org/10.1016/j.jhazmat.2017.12.058

Soran ML, Lung I, Opriş O, Culicov O, Ciorîță A, Stegarescu A, Zinicovscaia I, Yushin N, Vergel K, Kacso I, Borodi G (2021) The Effect of TiO(2) Nanoparticles on the composition and ultrastructure of wheat. Nanomaterials (Basel, Switzerland) 11(12). https://doi.org/10.3390/nano11123413

Lung I, Opriş O, Soran ML, Culicov O, Ciorîță A, Stegarescu A, Zinicovscaia I, Yushin N, Vergel K, Kacso I, Borodi G, Pârvu M (2021) The impact assessment of CuO nanoparticles on the composition and ultrastructure of Triticum aestivum L. Int J Environ Res Public Health 18(13). https://doi.org/10.3390/ijerph18136739

Ma C, White JC, Dhankher OP, Xing B (2015) Metal-based nanotoxicity and detoxification pathways in higher plants. Environ Sci Technol 49(12):7109–7122. https://doi.org/10.1021/acs.est.5b00685

Ma X, Wang Q, Rossi L, Zhang W (2016) Cerium oxide nanoparticles and bulk cerium oxide leading to different physiological and biochemical responses in Brassica rapa. Environ Sci Technol 50(13):6793–6802. https://doi.org/10.1021/acs.est.5b04111

Magdolenova Z, Collins A, Kumar A, Dhawan A, Stone V, Dusinska M (2014) Mechanisms of genotoxicity. A review of in vitro and in vivo studies with engineered nanoparticles. Nanotoxicology 8(3):233–278. https://doi.org/10.3109/17435390.2013.773464

Mahaye N, Thwala M, Cowan DA, Musee N (2017) Genotoxicity of metal based engineered nanoparticles in aquatic organisms: a review. Mutat Res Rev Mutat Res 773:134–160. https://doi.org/10.1016/j.mrrev.2017.05.004

Mahjouri S, Kosari-Nasab M, Mohajel Kazemi E, Divband B, Movafeghi A (2020) Effect of Ag-doping on cytotoxicity of SnO2 nanoparticles in tobacco cell cultures. J Hazard Mater 381:121012. https://doi.org/10.1016/j.jhazmat.2019.121012

Mahjouri S, Movafeghi A, Divband B, Kosari-Nasab M (2018) Toxicity impacts of chemically and biologically synthesized CuO nanoparticles on cell suspension cultures of Nicotiana tabacum. Plant Cell, Tissue Organ Cult (PCTOC) 135(2):223–234. https://doi.org/10.1007/s11240-018-1458-x

Maity A, Natarajan N, Vijay D, Srinivasan R, Pastor M, Malaviya DR (2018) Influence of metal nanoparticles (NPs) on germination and yield of oat (Avena sativa) and berseem (Trifolium alexandrinum). Proc Natl Acad Sci, India Section B: Biol Sci 88(2):595–607. https://doi.org/10.1007/s40011-016-0796-x

Marmiroli, M., Marmiroli, N., Pagano, L., 2022. Nanomaterials induced genotoxicity in plant: methods and strategies. Nanomaterials (Basel, Switzerland) 12(10). https://doi.org/10.3390/nano12101658.

Marslin G, Sheeba CJ, Franklin G (2017) Nanoparticles alter secondary metabolism in plants via ROS burst. Front Plant Sci 8:832. https://doi.org/10.3389/fpls.2017.00832

Masum MMI, Siddiqa MM, Ali KA, Zhang Y, Abdallah Y, Ibrahim E, Qiu W, Yan C, Li B (2019) Biogenic synthesis of silver nanoparticles using phyllanthus emblica fruit extract and its inhibitory action against the pathogen Acidovorax oryzae strain RS-2 of rice bacterial brown stripe. 10. https://doi.org/10.3389/fmicb.2019.00820

Mathur S, Pareek S, Shrivastava D (2022) Nanofertilizers for development of sustainable agriculture. Commun Soil Sci Plant Anal 53(16):1999–2016. https://doi.org/10.1080/00103624.2022.2070191

Mattiello A, Filippi A, Pošćić F, Musetti R, Salvatici MC, Giordano C, Vischi M, Bertolini A, Marchiol L (2015) Evidence of phytotoxicity and genotoxicity in Hordeum vulgare L. exposed to CeO2 and TiO2 nanoparticles. Front Plant Sci 6:1043. https://doi.org/10.3389/fpls.2015.01043

Millán-Chiu BE, del Pilar Rodriguez-Torres M, Loske AM (2020) Nanotoxicology in Plants. In: Patra JK, Fraceto LF, Das G, Campos EVR (eds) Green Nanoparticles: synthesis and biomedical applications. Springer International Publishing, Cham, pp 43–76. https://doi.org/10.1007/978-3-030-39246-8_3

Mourdikoudis S, Pallares RM, Thanh NTK (2018) Characterization techniques for nanoparticles: comparison and complementarity upon studying nanoparticle properties. Nanoscale 10(27):12871–12934. https://doi.org/10.1039/C8NR02278J

Movafeghi A, Khataee A, Abedi M, Tarrahi R, Dadpour M, Vafaei F (2018) Effects of TiO2 nanoparticles on the aquatic plant Spirodela polyrrhiza: evaluation of growth parameters, pigment contents and antioxidant enzyme activities. J Environ Sci 64:130–138. https://doi.org/10.1016/j.jes.2016.12.020

Mukherjee A, Majumdar S, Servin AD, Pagano L, Dhankher OP, White JC (2016) Carbon nanomaterials in agriculture: a critical review:7. https://doi.org/10.3389/fpls.2016.00172

Murali M, Gowtham HG, Singh SB, Shilpa N, Aiyaz M, Alomary MN, Alshamrani M, Salawi A, Almoshari Y, Ansari MA, Amruthesh KN (2022) Fate, bioaccumulation and toxicity of engineered nanomaterials in plants: current challenges and future prospects. Sci Total Environ 811:152249. https://doi.org/10.1016/j.scitotenv.2021.152249

Nair PMG, Chung IM (2017) Regulation of morphological, molecular and nutrient status in Arabidopsis thaliana seedlings in response to ZnO nanoparticles and Zn ion exposure. Science Total Environ 575:187–198. https://doi.org/10.1016/j.scitotenv.2016.10.017

Nakasato DY, Pereira AES, Oliveira JL, Oliveira HC, Fraceto LF (2017) Evaluation of the effects of polymeric chitosan/tripolyphosphate and solid lipid nanoparticles on germination of Zea mays, Brassica rapa and Pisum sativum. Ecotoxicol Environ Saf 142:369–374. https://doi.org/10.1016/j.ecoenv.2017.04.033

Nangia S, Sureshkumar R (2012) Effects of nanoparticle charge and shape anisotropy on translocation through cell membranes. Langmuir : the ACS J Surf Colloids 28(51):17666–17671. https://doi.org/10.1021/la303449d

Nasrullah M, Gul FZ, Hanif S, Mannan A, Naz S, Ali JS, Zia M (2020) Green and chemical syntheses of CdO NPs: a comparative study for yield attributes, Biological Characteristics, and Toxicity Concerns. ACS Omega 5(11):5739–5747. https://doi.org/10.1021/acsomega.9b03769

Naz S, Gul A, Zia M (2020) Toxicity of copper oxide nanoparticles: a review study. IET Nanobiotechnol 14(1):1–13. https://doi.org/10.1049/iet-nbt.2019.0176

Nhan LV, Ma C, Rui Y, Liu S, Li X, Xing B, Liu L (2015) Phytotoxic mechanism of nanoparticles: destruction of chloroplasts and vascular bundles and alteration of nutrient absorption. Sci Rep 5(1):11618. https://doi.org/10.1038/srep11618

Nourozi E, Hosseini B, Maleki R, Mandoulakani BA (2019) Pharmaceutical important phenolic compounds overproduction and gene expression analysis in Dracocephalum kotschyi hairy roots elicited by SiO2 nanoparticles. Ind Crop Prod 133:435–446. https://doi.org/10.1016/j.indcrop.2019.03.053

Orooji Y, Ghasali E, Emami N, Noorisafa F, Razmjou A (2019) ANOVA design for the optimization of TiO2 coating on polyether sulfone membranes. 24(16):2924

Owji H, Hemmati S, Heidari R, Hakimzadeh M (2019) Effect of alumina (Al(2)O(3)) nanoparticles and macroparticles on Trigonella foenum-graceum L. in vitro cultures: assessment of growth parameters and oxidative stress-related responses. 3 Biotech 9(11):419. https://doi.org/10.1007/s13205-019-1954-7

Pinto M, Soares C, Pinto AS, Fidalgo F (2019) Phytotoxic effects of bulk and nano-sized Ni on Lycium barbarum L. grown in vitro - oxidative damage and antioxidant response. Chemosphere

218:507–516. https://doi.org/10.1016/j.chemosphere.2018.11.127

Rafique R, Zahra Z, Virk N, Shahid M, Pinelli E, Park TJ, Kallerhoff J, Arshad M (2018) Dose-dependent physiological responses of Triticum aestivum L. to soil applied TiO2 nanoparticles: alterations in chlorophyll content, H2O2 production, and genotoxicity. Agr Ecosyst Environ 255:95–101. https://doi.org/10.1016/j.agee.2017.12.010

Rajaee Behbahani S, Iranbakhsh A, Ebadi M, Majd A, Ardebili ZO (2020) Red elemental selenium nanoparticles mediated substantial variations in growth, tissue differentiation, metabolism, gene transcription, epigenetic cytosine DNA methylation, and callogenesis in bittermelon (Momordica charantia); an in vitro experiment. PloS One 15(7):e0235556. https://doi.org/10.1371/journal.pone.0235556

Rajeshwari A, Kavitha S, Alex SA, Kumar D, Mukherjee A, Chandrasekaran N, Mukherjee A (2015) Cytotoxicity of aluminum oxide nanoparticles on Allium cepa root tip--effects of oxidative stress generation and biouptake. Environ Sci Pollut Res Int 22(14):11057–11066. https://doi.org/10.1007/s11356-015-4355-4

Rajput V, Minkina T, Fedorenko A, Sushkova S, Mandzhieva S, Lysenko V, Duplii N, Fedorenko G, Dvadnenko K, Ghazaryan K (2018) Toxicity of copper oxide nanoparticles on spring barley (Hordeum sativum distichum). Sci Total Environ 645:1103–1113. https://doi.org/10.1016/j.scitotenv.2018.07.211

Ranjan A, Rajput VD, Minkina T, Bauer T, Chauhan A, Jindal T (2021) Nanoparticles induced stress and toxicity in plants. Environ Nanotechnol, Monit Manage 15:100457. https://doi.org/10.1016/j.enmm.2021.100457

RASTOGI A, ZIVCAK M, TRIPATHI DK, YADAV S, KALAJI HMJP (2019) Phytotoxic effect of silver nanoparticles in Triticum aestivum: improper regulation of photosystem I activity as the reason for oxidative damage in the chloroplast. 57(1):209–216. https://doi.org/10.32615/ps.2019.019

Regoli F, Giuliani ME (2014) Oxidative pathways of chemical toxicity and oxidative stress biomarkers in marine organisms. Mar Environ Res 93:106–117. https://doi.org/10.1016/j.marenvres.2013.07.006

Rehman RU, Khan B, Aziz T, Gul FZ, Nasreen S, Zia M (2020) Postponement growth and antioxidative response of Brassica nigra on CuO and ZnO nanoparticles exposure under soil conditions. IET Nanobiotechnol 14(5):423–427. https://doi.org/10.1049/iet-nbt.2019.0357

Ren C, Hu X, Zhou Q (2016) Influence of environmental factors on nanotoxicity and knowledge gaps thereof. NanoImpact 2:82–92. https://doi.org/10.1016/j.impact.2016.07.002

Rui M, Ma C, Tang X, Yang J, Jiang F, Pan Y, Xiang Z, Hao Y, Rui Y, Cao W, Xing B (2017) Phytotoxicity of Silver Nanoparticles to Peanut (Arachis hypogaea L.): Physiological responses and food safety. ACS Sustain Chem Eng 5(8):6557–6567. https://doi.org/10.1021/acssuschemeng.7b00736

Rui M, Ma C, White JC, Hao Y, Wang Y, Tang X, Yang J, Jiang F, Ali A, Rui Y, Cao W, Chen G, Xing B (2018) Metal oxide nanoparticles alter peanut (Arachis hypogaea L.) physiological response and reduce nutritional quality: a life cycle study. Environmental Science. Nano 5(9):2088–2102. https://doi.org/10.1039/C8EN00436F

Ruttkay-Nedecky B, Krystofova O, Nejdl L, Adam V (2017) Nanoparticles based on essential metals and their phytotoxicity. J Nanobiotechnology 15(1):33. https://doi.org/10.1186/s12951-017-0268-3

Sadhu A, Ghosh I, Moriyasu Y, Mukherjee A, Bandyopadhyay M (2018) Role of cerium oxide nanoparticle-induced autophagy as a safeguard to exogenous H2O2-mediated DNA damage in tobacco BY-2 cells. Mutagenesis 33(2):161–177. https://doi.org/10.1093/mutage/gey004

Sajid M, Ilyas M, Basheer C, Tariq M, Daud M, Baig N, Shehzad F (2015) Impact of nanoparticles on human and environment: review of toxicity factors, exposures, control strategies, and future prospects. Environ Sci Pollut Res 22(6):4122–4143. https://doi.org/10.1007/s11356-014-3994-1

Salehi H, Chehregani A, Lucini L, Majd A, Gholami M (2018) Morphological, proteomic and metabolomic insight into the effect of cerium dioxide nanoparticles to Phaseolus vulgaris L. under soil or foliar application. Sci Total Environ 616-617:1540–1551. https://doi.org/10.1016/j.scitotenv.2017.10.159

Scimeca JC, Verron E (2022) Nano-engineered biomaterials: safety matters and toxicity evaluation. Mater Today Adv 15:100260. https://doi.org/10.1016/j.mtadv.2022.100260

Selivanov NY, Selivanova OG, Sokolov OI, Sokolova MK, Sokolov AO, Bogatyrev VA, Dykman LA (2017) Effect of gold and silver nanoparticles on the growth of the Arabidopsis thaliana cell suspension culture. Nanotechnol Russ 12(1):116–124. https://doi.org/10.1134/S1995078017010104

Silva S, Ribeiro TP, Santos C, Pinto DCGA, Silva AMS (2020) TiO2 nanoparticles induced sugar impairments and metabolic pathway shift towards amino acid metabolism in wheat. J Hazard Mater 399:122982. https://doi.org/10.1016/j.jhazmat.2020.122982

Singh A, Sharma R, Rawat S, Singh AK, Rajput VD, Fedorov Y, Minkina T, Chaplygin V (2022) Chapter 3 - Nanomaterial-plant interaction: views on the pros and cons. In: Rajput VD, Minkina T, Sushkova S, Mandzhieva SS, Rensing C (eds) Toxicity of nanoparticles in plants. Academic Press, pp 47–68. https://doi.org/10.1016/B978-0-323-90774-3.00015-5

Singh AV, Laux P, Luch A, Sudrik C, Wiehr S, Wild AM, Santomauro G, Bill J, Sitti M (2019) Review of emerging concepts in nanotoxicology: opportunities and challenges for safer nanomaterial design. Toxicol Mech Methods 29(5):378–387. https://doi.org/10.1080/15376516.2019.1566425

Singla R, Kumari A, Yadav SK (2019) Impact of Nanomaterials on Plant Physiology and Functions. In: Husen A, Iqbal M (eds) Nanomaterials and plant potential. Springer International Publishing, Cham, pp 349–377. https://doi.org/10.1007/978-3-030-05569-1_14

Spinoso-Castillo JL, Chavez-Santoscoy RA, Bogdanchikova N, Pérez-Sato JA, Morales-Ramos V, Bello-Bello JJ (2017) Antimicrobial and hormetic effects of silver nanoparticles on in vitro regeneration of vanilla (Vanilla planifolia Jacks. ex Andrews) using a temporary immersion system. Plant Cell, Tissue Organ Cult (PCTOC) 129(2):195–207. https://doi.org/10.1007/s11240-017-1169-8

Sukhanova A, Bozrova S, Sokolov P, Berestovoy M, Karaulov A, Nabiev I (2018) Dependence of nanoparticle toxicity on their physical and chemical properties. Nanoscale Res Lett 13(1):44. https://doi.org/10.1186/s11671-018-2457-x

Tarrahi R, Mahjouri S, Khataee A (2021) A review on in vivo and in vitro nanotoxicological studies in plants: a headlight for future targets. Ecotoxicol Environ Saf 208:111697. https://doi.org/10.1016/j.ecoenv.2020.111697

Timoteo CO, Paiva R, Dos Reis MV, Claro PIC, Ferraz LM, Marconcini JM, de Oliveira JE (2019) In vitro growth of Physalis peruviana L. affected by silver nanoparticles. 3 Biotech 9(4):145. https://doi.org/10.1007/s13205-019-1674-z

Ullah H, Li X, Peng L, Cai Y, Mielke HW (2020) In vivo phytotoxicity, uptake, and translocation of PbS nanoparticles in maize (Zea mays L.) plants. Sci Total Environ 737:139558. https://doi.org/10.1016/j.scitotenv.2020.139558

Waani SPT, Irum S, Gul I, Yaqoob K, Khalid MU, Ali MA, Manzoor U, Noor T, Ali S, Rizwan M, Arshad M (2021) TiO2 nanoparticles dose, application method and phosphorous levels influence genotoxicity in Rice (Oryza sativa L.), soil enzymatic activities and plant growth. Ecotoxicol Environ Saf 213:111977. https://doi.org/10.1016/j.ecoenv.2021.111977

Wang X, Liu X, Yang X, Wang L, Yang J, Yan X, Liang T, Bruun Hansen HC, Yousaf B, Shaheen SM, Bolan N, Rinklebe J (2022) In vivo phytotoxic effect of yttrium-oxide nanoparticles on the growth, uptake and translocation of tomato seedlings (Lycopersicon esculentum). Ecotoxicol Environ Saf 242:113939. https://doi.org/10.1016/j.ecoenv.2022.113939

Wang X, Yang X, Chen S, Li Q, Wang W, Hou C, Gao X, Wang L, Wang S (2015) Zinc oxide nanoparticles affect biomass accumulation and photosynthesis in Arabidopsis. Front Plant Sci 6:1243. https://doi.org/10.3389/fpls.2015.01243

Wang XP, Li QQ, Pei ZM, Wang SC (2018) Effects of zinc oxide nanoparticles on the growth, photosynthetic traits, and antioxidative enzymes in tomato plants. Biol Plant 62(4):801–808. https://doi.org/10.1007/s10535-018-0813-4

Watson C, Ge J, Cohen J, Pyrgiotakis G, Engelward BP, Demokritou P (2014) High-throughput screening platform for engineered nanoparticle-mediated genotoxicity using CometChip technology. ACS Nano 8(3):2118–2133. https://doi.org/10.1021/nn404871p

Xiao Y, Li Y, Shi Y, Li Z, Zhang X, Liu T, Farooq TH, Pan Y, Chen X, Yan W (2022) Combined toxicity of zinc oxide nanoparticles and cadmium inducing root damage in Phytolacca americana L. Sci Total Environ 806:151211. https://doi.org/10.1016/j.scitotenv.2021.151211

Xiong T, Dumat C, Dappe V, Vezin H, Schreck E, Shahid M, Pierart A, Sobanska S (2017) Copper oxide nanoparticle foliar uptake, phytotoxicity, and consequences for sustainable urban agriculture. Environ Sci Technol 51(9):5242–5251. https://doi.org/10.1021/acs.est.6b05546

Yang J, Cao W, Rui Y (2017) Interactions between nanoparticles and plants: phytotoxicity and defense mechanisms. J Plant Interact 12(1):158–169. https://doi.org/10.1080/17429145.2017.1310944

Yang J, Jiang F, Ma C, Rui Y, Rui M, Adeel M, Cao W, Xing B (2018) Alteration of crop yield and quality of wheat upon exposure to silver nanoparticles in a life cycle study. J Agric Food Chem 66(11):2589–2597. https://doi.org/10.1021/acs.jafc.7b04904

Yanık F, Vardar F (2015) Toxic Effects of Aluminum Oxide (Al2O3) Nanoparticles on root growth and development in Triticum aestivum. Water, Air, Soil Pollut 226(9):296. https://doi.org/10.1007/s11270-015-2566-4

Yaqoob AA, Ahmad H, Parveen T, Ahmad A, Oves M, Ismail IMI, Qari HA, Umar K, Mohamad Ibrahim MN (2020) Recent advances in metal decorated nanomaterials and their various biological applications: a review. Front Chem 8:341. https://doi.org/10.3389/fchem.2020.00341

Yoon SJ, Kwak JI, Lee WM, Holden PA, An YJ (2014) Zinc oxide nanoparticles delay soybean development: a standard soil microcosm study. Ecotoxicol Environ Saf 100:131–137. https://doi.org/10.1016/j.ecoenv.2013.10.014

Youssef MS, Elamawi RM (2020) Evaluation of phytotoxicity, cytotoxicity, and genotoxicity of ZnO nanoparticles in Vicia faba. Environ Sci Pollut Res 27(16):18972–18984. https://doi.org/10.1007/s11356-018-3250-1

Yuan L, Richardson CJ, Ho M, Willis CW, Colman BP, Wiesner MR (2018) Stress responses of aquatic plants to silver nanoparticles. Environ Sci Technol 52(5):2558–2565. https://doi.org/10.1021/acs.est.7b05837

Yusefi-Tanha E, Fallah S, Rostamnejadi A, Pokhrel LR (2020) Particle size and concentration dependent toxicity of copper oxide nanoparticles (CuONPs) on seed yield and antioxidant defense system in soil grown soybean (Glycine max cv. Kowsar). Sci Total Environ 715:136994. https://doi.org/10.1016/j.scitotenv.2020.136994

Zafar H, Ali A, Ali JS, Haq IU, Zia M (2016) Effect of ZnO nanoparticles on Brassica nigra seedlings and stem explants: growth dynamics and antioxidative response:7. https://doi.org/10.3389/fpls.2016.00535

Zafar H, Ali A, Zia M (2017) CuO nanoparticles inhibited root growth from Brassica nigra seedlings but induced root from stem and leaf explants. Appl Biochem Biotechnol 181(1):365–378. https://doi.org/10.1007/s12010-016-2217-2

Zafar H, Aziz T, Khan B, Mannan A, Rehman RU, Zia M (2020) CuO and ZnO Nanoparticle application in synthetic soil modulates morphology, nutritional contents, and metal analysis of Brassica nigra. ACS Omega 5(23):13566–13577. https://doi.org/10.1021/acsomega.0c00030

Zhang, P., Ma, Y., Liu, S., Wang, G., Zhang, J., He, X., Zhang, J., Rui, Y., Zhang, Z., 2017. Phytotoxicity, uptake and transformation of nano-CeO(2) in sand cultured romaine lettuce. Environmental pollution (Barking, Essex : 1987) 220(Pt B), 1400-1408. https://doi.org/10.1016/j.envpol.2016.10.094.

Zhang Z, Ke M, Qu Q, Peijnenburg W, Lu T, Zhang Q, Ye Y, Xu P, Du B, Sun L, Qian H (2018) Impact of copper nanoparticles and ionic copper exposure on wheat (Triticum aestivum L.) root morphology and antioxidant response. Environ Pollut (Barking, Essex : 1987) 239:689–697. https://doi.org/10.1016/j.envpol.2018.04.066

Zhao X, Liu Y, Jiao C, Dai W, Song Z, Li T, He X, Yang F, Zhang Z, Ma Y (2021) Effects of surface modification on toxicity of CeO2 nanoparticles to lettuce. NanoImpact 24:100364. https://doi.org/10.1016/j.impact.2021.100364

Zia-ur-Rehman M, Qayyum MF, Akmal F, Maqsood MA, Rizwan M, Waqar M, Azhar M (2018) Chapter 7 - Recent progress of nanotoxicology in plants. In: Tripathi DK, Ahmad P, Sharma S, Chauhan DK, Dubey NK (eds) Nanomaterials in plants, algae, and microorganisms. Academic Press, pp 143–174. https://doi.org/10.1016/B978-0-12-811487-2.00007-4

Zuverza-Mena N, Armendariz R, Peralta-Videa JR, Gardea-Torresdey JL (2016) Effects of silver nanoparticles on radish sprouts: root growth reduction and modifications in the nutritional value. Front Plant Sci 7:90. https://doi.org/10.3389/fpls.2016.00090