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REVIEW ARTICLE

Nanoengineered particles for sustainable crop production: potentials and challenges

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Abstract

Nanoengineered nanoparticles have a significant impact on the morphological, physiology, biochemical, cytogenetic, and reproductive yields of agricultural crops. Metal and metal oxide nanoparticles like Ag, Au, Cu, Zn, Ti, Mg, Mn, Fe, Mo, etc. and ZnO, TiO_2, CuO, SiO_2, MgO, MnO, Fe_2O_3 or Fe_3O_4, etc. that found entry into agricultural land, alter the morphological, biochemical and physiological system of crop plants. And the impacts on these parameters vary based on the type of crop and nanoparticles, doses of nanoparticles and its exposure situation or duration, etc. These nanoparticles have application in agriculture as nanofertilizers, nanopesticides, nanoremediator, nanobiosensor, nanoformulation, phytostress-mediator, etc. The challenges of engineered metal and metal oxide nanoparticles pertaining to soil pollution, phytotoxicity, and safety issue for food chains (human and animal safety) need to be understood in detail. This review provides a general overview of the applications of nanoparticles, their potentials and challenges in agriculture for sustainable crop production.

Keywords Nanoengineered · Metal · Metal-oxide · Environment · Agriculture

Introduction

Agriculture is the primary need for any country to lead a better life. The presence of metal and metal oxide nanoparticles in agriculture soils has risen more in the past years. It is because of the increased production of a great number of nano-products by industries to meet the teeming world population. However, the accumulation of these engineered nanoparticles (ENPs) in plants, their translocation and their growth response are not clearly understood (Siddiqi and Husen 2016). These nanoparticles have a size ranging between 1 and 100 nm and disturb food chain system and impair the health of humans and animals. Metal nanoparticles like Ag, Au, Cu, Zn, Ti, Ce, Fe, Mg, Mn, and Mo are used as coating materials, antibacterial agents for biomedical applications, textile application, implants industry, personal care products, drug delivery, etc. Metal oxide nanoparticles such as TiO_2, ZnO, CuO, SiO_2, MnO, MgO, Fe_2O_3/Fe_3O_4 and GO have antibacterial, antifungal, and photocatalytic activities with self-cleaning properties (Fruth et al. 2021; Valenzuela et al. 2019). Superparamagnetic Fe_2O_3 nanoparticles, graphene, carbon nanotubes (CNTs) are utilized to treat heavy metals, pesticides, insecticides, microbes into water and wastewater as sorbent materials. Carbon nanotubes and ceramic nanoparticles have application in printed electronics inks. These ENPs directly or indirectly go into the agricultural land and improve or decrease the quality of crops, soil pH, plant growth, yield, and its nutritional value. Also due to the continuous accumulation of ENPs in different parts of crops, they can pose a significant impact on plant's physiological responses such as germination, anatomical changes, metabolism, cell growth and cytogenetic effects and yield (Kralova and Jampilek 2021; Sheikh Mohamed and Sakthi Kumar 2016; Shukla et al. 2016). Their presence in agricultural soils may improve or deteriorate the crop characteristics and its value. During the past few years, engineered nanoparticles have been used for crops as nanofertilizers, nanopesticide, nanoremediator, nanobiosensor, disease management, phytohormones,

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nanoformulation, phytostress-mediator, etc. (Mahakham et al. 2016). This paper attempts by narrative approach, to provide reviews on the various types of engineered metal and metal oxide nanoparticles, their agricultural usefulness in terms of crop improvement and the challenges and risks of the adoption of nanotechnology in crop production.

Types of engineered nanoparticles

Engineered nanoparticles are 1–100 nm in size and fabricated from bulk materials (> 500 nm). These nanoparticles have many common characteristics such as a larger surface area to volume ratio, electronic, optical, magnetic properties and high surface reactivity (Abbas et al. 2020). Engineered nanoparticles are classified into ceramic, polymeric, carbon-based, semiconductor and lipid-based nanoparticles (Table 1.) based on size, shape, morphology, physical and chemical properties (Khan et al. 2019; Ogunkunle et al. 2021).

i. Metal/metal oxide nanoparticles: Metal nanoparticles are synthesized by various procedures and classified into bottom-up approaches and top-down approaches (Jamkhande et al. 2019). Different metal nanoparticles have wide applications in our daily life and have gained market use worldwide. Among various metal nanoparticles, silver (Ag) nanoparticles have multifunctional properties for example bactericide, fungicide, antiviral, antioxidant and anti-inflammatory pest control for crop improvement because of its high surface area and a fraction of surface atoms (Cho et al. 2005; Kale et al. 2021). Ag nanoparticles are also used as coating materials for commercial applications on metals, textiles, paint, electrical, batteries, photography (Clarence Davies 2008). Ag nanoparticles of 1–100 nm in size have wide application in plant growth and development (Yan and Chen 2019) where the rate of seed germination (Shelar and Chavan 2015) with enhanced chlorophyll contents (Hatami and Ghorbanpour 2013) and yields (Sadak 2019) are significantly improved by the nanoparticles. Many reasons have been adduced as to why Ag nanoparticles have more applications as bactericide and fungicide. Ag nanoparticles break the cell wall of microorganism, damage cell membrane, accumulate in cell and release many free radicals which lead to cell death (Gupta et al. 2018). Ag ions block the respiratory enzymes of the microorganism and produce reactive oxygen species (ROS) is another reason for cell death (Aziz et al. 2015; Banerjee et al. 2010). **Gold (Au) nanoparticles** are exposed to the environment by consumer products such as electronic goods, cosmetics products, pharmaceuticals, textiles, and water treatment. These nanoparticles have applications in drug delivery, cell imaging, coating, and photodynamic therapy. **Copper (Cu) nanoparticles** are antimicrobial agents, that prevent the spoilage of food and enhance the shelf-life of food (Rai et al. 2018). Cu nanoparticles have antibacterial efficacy against *Escherichia coli* and *Staphylococcus aureus* which was reported earlier (Jia et al. 2012). Similarly, the fungicidal ability of Cu nanoparticles coated with chitosan was evaluated against *Alternaria solani* and *Fusarium oxysporum* for tomato plants (Saharan et al. 2015). **Fe nanoparticles** have metal-binding properties in various environmental conditions and are used for water purification as adsorbents (Kornarzyński et al. 2020). They also have the potential to enhance the germination capability of harvest plants (Alam et al. 2015). **Manganese (Mn) nanoparticles** are known to increase the photosynthetic activity of plants (Pradhan et al. 2014). **Nickel (Ni) nanoparticles** have unique magnetic properties, and are used as catalyst, manufacture of batteries, printing inks, textile applications and the adsorption of dyes. Ni nanoparticles are antimicrobial (Chaudhary et al. 2019), superparamagnetic materials (Li et al. 2012a), used in water splitting (Li et al. 2017), electrocatalyst (Fadil et al. 2014) and functionalized materials (McKeown et al. 2012). **Cerium (Ce) nanoparticles** have significant effects on agricultural crops (Ramírez-Olvera et al. 2018).

Metal oxide nanoparticles have several commercial and industrial products applications (Kaweeteerawat et al. 2015). ZnO-engineered NPs, Fe_2O_3-engineered NPs and NiO-engineered NPs are used as nano-fertilizer in

Table 1 Classification of engineered nanoparticles and their descriptions

Types	Description summary
Metal/metal oxide-based	These NPs are derived from metal or metal-oxide precursors
Carbon-based NPs	These are NPs derived from carbon atoms-carbon nanotubes, carbon quantum dots and fullerenes
Ceramic-based NPs	They are derived from inorganic solids of carbides, oxides, phosphates and carbonates
Polymeric-based NPs	They are organic-based NPs with nanocapsular or nanospheric shape
Semi-conductor NPs	They are derived from elements that are presence in group II-IV, III-V or IV-VI in the periodic table
Lipid-based NPs	These are NPs that are spheric in shape and consist of a solid core of lipids and soluble lipophilic molecules

Adapted from Khan et al. (2019), Ogunkunle et al. (2021)

agriculture to improve nutrient deficiency, regulate phytohormones and antioxidant action in agricultural crops (Rameshraddy et al. 2017; Rui et al. 2016). Cerium oxide nanoparticles (CeO_2) are used in sunscreens, catalysts, corrosion protection, polishing agents, microelectronics, and fuel additives. (Cassee et al. 2011). Because of the optical, thermal, and electrical features, these nanoparticles have been used for agricultural crops (Rajeshkumar and Naik 2018), especially in the enhancement of crop improvement (Cao et al. 2017; Yang et al. 2020).

ii. Semiconductor nanoparticles: They have wide band gaps and are placed in the periodic table of II-VI, III-V or IV-VI groups. They demonstrate properties between metals and non-metals properties and commonly used for electronics devices, photocatalysis, water splitting applications, photo-optics, etc. At this point, groups like III-V include GaN, GaP, InP, InAs, II-VI comprises ZnO, ZnS, CdS, CdSe, CdTe and IV consists of silicon and germanium. This activity of ZnO nanoparticles invited great attention in agricultural crops for pesticides, insecticides, fertilizer, herbicides, etc. Even ZnO nanosensors can detect the pesticides residue level, soil moisture and nutrients (Sabir et al. 2014). Titanium dioxide (TiO_2) nanoparticles, as photocatalyst and semiconductor materials, have great consideration in agriculture in the aspect of the plant sprouting and growth, deprivation of chemicals such as pesticides, finding and control of plant disease, plant protection, antibacterial activity (Wang et al. 2016).

iii. Lipid-based nanoparticles: Lipid-based nanoparticles are used as fungicides carrier such as carbendazim and tebuconazole for their slow release to reduce their toxicity level and prevent the plants from fungal disease (Campos et al. 2015). The essential oil from *Artemisia arborescens* L as pesticides formulated with solid lipid nanoparticles for regular treatment of soil (Lai et al. 2006). Solid lipid nanoparticles are also used in a controlled manner with the usage of herbicides atrazine and simazine to control the weeds in agricultural fields (De Oliveira et al. 2015).

iv. Ceramic nanoparticles: Ceramic nanoparticles such as clay and hydroxyapatite have been used in agricultural crops. Nano-clays loaded with different types of fertilizers such as nitrogen, phosphorus, and potassium have shown a slow release of nutrients (Sen et al. 2015). It has also been reported that nano-clays have the capacity of holding water as they possess a high absorbing ability to improve plants' productivity in dry lands. The studies on zeolite and kaolinite clays have shown the slow release of phosphatic fertilizer and the regulation of nutrient release from conventional fertilizer respectively (Bansiwal et al. 2006). Hydroxyapatite nanoparticles have been found to possess the potentials to be used as fertilizer for *Solanum lycopersicum* L when mixed with carboxymethylcellulose (CMC) which enhance plant metabolism and has role in plant growth (Marchiol et al. 2019).

v. Polymeric nanoparticles: Polymeric nanoparticles are used as nanocarriers for the target release of pesticides as growth promotors. This enhances the effective efficiency of agrochemicals such as slow release, enhances adhesion on the surface of roots and leaves and delays degradation of chemicals (Shakiba et al. 2020). The synthetic polymer mostly used as a nanocarrier is poly(lactic-co-glycolic acid) (PLGA) which is biocompatible and biodegradable. Alginate/chitosan polymer as a nano-carrier encapsulated with gibberellic acid was used as seeds priming of *Solanum lycopersicum* and demonstrated the potential to improve production in the plants (Pereira et al. 2019). Poly(lactide-co-glycolide)-b-poly(ethylene glycol) methyl ether (mPEG-PLGA) nanoparticles encapsulated with metolachlor was also used as pesticide delivery in plants (Tong et al. 2017).

vi. Carbon-based nanoparticles: This includes the structures such as graphene, fullerenes, carbon nanotubes, and carbon nanofibres which have various applications in semiconductor fields, electronics, and solar cells due to their multiple structures (Mathur 2016; Saleh 2020). Carbon-based nanomaterials penetrate the various types of cells and have the ability to improve the development of reactive oxygen species (Paramo et al. 2020; Zaytseva and Neumann 2016). A study on rice and *Cicer arietinum* plants has shown that carbon nanomaterials help to store the water content in the seeds and have the ability to translocate in upwards directions for the leaves (Nair et al. 2012). This may be because of the attachment of carbon nanotubes to the vascular bundles of the plants (Paramo et al. 2020).

Application of engineered nanoparticles in crop production

Crop production is a major sector of agriculture that needs fortification and improvement to meet the unrelenting demands for food by the teeming world population. It has been documented that the world population in 2013 was 7 billion and projected to achieve around 9.6 billion by 2050 and 10.9 billion by 2100 (United Nations 2013). Therefore, to obtain food security for this teeming world population, it is very important and expedient to increase food production and improve the quality of produced foods (FAO 2009). Nanotechnology, due to its ability to promote and improve the agricultural sector by increasing crop production, has been promoted as the rising technology to combat food security in recent times (Singh Sekhon 2014). Engineered nanoparticles (ENPs), due to their distinctive features like high surface area, particle and pore dimension and reactivity have been implemented in the process of improving crop production. In fact, it has been asserted that the interaction of nanoparticles with cells of plants always lead to the alteration of gene expressions as well as biological pathways that subsequently affect and promotes plant metabolism (Nair et al. 2010). The different applications of engineered metal/metal oxide nanoparticles in crop production viz-a-viz nanonutrition/nanofertilizer and nanopesticides are itemized in Table 2.

Use as nanonutrition/nanofertilizers

In the strive to achieve sustainable crop production in the post-Green Revolution era, serious issues of environmental and human health safety were reported due to dependency on agrochemicals in agriculture (Mishra and Singh 2015). One of the problems is the pollution of downstream surface/ground water as a large number of applied fertilizers are wasted and washed off through runoffs and other processes. These problems were overcome with the adoption and use of environmental-friendly bioformulations such as biofertilizers and biopesticides which is sustainable and proven to ensure biosafety. However, this exciting approach was confronted with the concerns of shelf-life, on-site stability and high-dose requirement of bioformulations (Mishra et al. 2017). In recent times, nanotechnological-based approaches in the use of nanoparticle-based formulations such as nanofertilizers and nanopesticides with superior properties over conventional bioformulations have been developed. Nanoparticles have been utilized successfully either as nano-carrier matrices or as nutrients (both micro- and macronutrients) due to their intrinsic ability to penetrate directly into cells of plants or promote micro- and macronutrients uptake by plant roots and enhance the growth and productivity of crops. This behavior of nanoparticles to effect enhanced growth has been reported to be greatly dependent on some intrinsic properties of nanoparticles such as the concentration, composition, both physical and chemical properties and surface charge (Bandala and Berli 2019; Lambreva et al. 2015; Ma et al. 2010).

An important aspect of the use of nanofertilizers is the sustained release of nutrients for crop plants as coated fertilizers with nanoparticles provide a slow release of nutrients to plants because of higher surface tension (Duhan et al. 2017; Santoso et al. 1995). Ombodi and Saigusa estimated 40–70%, of nitrogen, 80–90% of phosphate and 50–70% of potassium as applied fertilizers which are lost into the ecosystem causing pollution (Ombodi and Saigusa 2008). Therefore, nanocoating of nutrients, due to its stability minimizes the leaching of fertilizers from crop plants. Kottegoda et al. were used altered hydroxyapatite nanoparticles with urea and encapsulated in the soft wood of *Gliricidium sepium* as nano-fertilizer for a gradual release of nitrogen for 60 days (Kottegoda et al. 2011). Also, Zulfiqar et al. (2019) employed nano sulphur to coat urea fertilizer and utilized it as sustained-release sulphur nutrient in soil with low sulphur content. In addition, Corradini et al. (2010) have utilized biodegradable polymeric chitosan nanoparticles of less than 78 nm for a gradual release of NPK as manure to plant.

The use of nanoparticles, especially metal/metal oxide nanoparticles as foliar-applied nano-fertilizers has also been documented. Dhoke et al. (2013) reported the usage of metal oxide-engineered nanoparticles like TiO_2, FeO and ZnO as foliar nano-fertilizer sprays because of their ability to directly infiltrate leaf pores and influence the growth of crop plants, though there was threshold limit in this case. Delfani et al. reported that foliar function of Fe-Engineered NPs at a concentration of 500 mg/l to peas produced a significant increase of 47% in the number of pods per plant, 34% and 10% increase in Fe content and chlorophyll content of leaves, respectively, and 7% increase in weight of 1000-seeds (Delfani et al. 2014). The role of nanofertilizers in the agricultural sector is not only to achieving enhanced crop production but also help to improve crop resistance to abiotic stresses (Zulfiqar et al. 2019).

Use as nanopesticides

Plant protection is a major aspect of crop production that needs to be addressed in view of the menace that insect-pests wreck to food production. Hence, nanoparticles portend significant potential in the control of insect pest and pathogen-hosts in crop production. Nanoparticles with different characteristics have been reported for utilization as nanocarriers for encapsulating insecticides (de Oliveira et al. 2014). The process of nano-encapsulation has allowed adequate absorption of chemicals into crop plants because of the slow and sustained discharge of chemicals and proffer lasting and persistent results (Duhan et al. 2017; Scrinis and Lyons 2007).

For instance, carvacrol derived as a bioactive compound from thyme has been encapsulated with chitosan-engineered NPs and utilized as a bactericidal agent in crop production (Higueras et al. 2013; Keawchaoon and Yoksan 2011). Similarly, Zein Engineered NPs was used for the encapsulation of eugenol and curcumin and utilized as both insecticides, nematicide and bactericide (Gomez-Estaca et al. 2012; Zhang et al. 2014). Similarly, essential oil from garlic is insecticidal for *Tribolium castaneum* (red flour beetle) was encapsulated in polyethylene glycol-coated nanoparticles and the formulation was found efficienct compared to *T. castaneum* by 80% because of their sustained delivery of active principle from the nanoparticles (Yang et al. 2009). Entomotoxicity of several other nanoparticles have also been tested and confirmed. Debnath et al. (2010) showed the silica nanoparticles portend entomotoxicity in opposition to *Sitophilus oryzae* (rice weevils) with higher efficacy of about

Table 2 Selected applications of engineered nanoparticles in crop production

Application	Form of Engineered NPs	Application dose	Crop plant	Endpoint benefits	References
Nanofertilizers					
	Nano Fe_3O_4, 18.9–20.3 nm	30–60 mg/l	*Glycine max*	Increased chlorophyll content by 10% in greenhouse for 7 days	Ghafariyan et al. (2013)
	Metallic Mn, 20 nm	0.05–1 mg/l	*Vigna radiata*	Enhanced length of roots, shoot; promoted chlorophyll and carotenoid content	Pradhan et al. (2013)
	Nano-ZnO, 20 nm	1–200 mg/l	*Cicer arietinum*	Increased root length, shoot height, biomass and fruit starch plus glutelin content	Dhoke et al. (2011)
	Nano-calcite, 20–80 nm	160 mg/l	*Arachis hypogaea*	Increased ground biomass by 1.2 times, increased Ca content in both roots and stems and, increased soluble sugar and protein	Xiumei et al. (2005)
	Nano-apartite 16 nm –	21.8 mg/l	*Glycine max*	Increased ground biomass, growth rate and yield by 6.5-fold, 2.0-fold and 5.4-fold, respectively	Liu and Lal (2014)
	Nano-ZnO, 25 nm	NA	*Arachis hypogaea*	Yield was increased by 25–30%	Prasad et al. (2012)
Nanopesticides					
	Nano-TiO_2; 32 nm	NA	*Oryza sativa* & *Zea mays*	Applied as fungicides to reduce rice blast and maize southern leaf spot by 38% and 67%, respectively	Lu et al. (2006)
	Imidacloprid ($C_9H_{10}ClN_5O_2$); 30 nm	NA	*Oryza sativa*	Applied as insecticides with 95% effectiveness than conventional imidecloprid on Martianus-dermestoides insec	Guan et al. (2008)
	ZnO; 70–80 nm	NA	NA	Used as a fungicide to retard the growth of *Botrytis cinerea* and *Penicillium expansum* by 63–80% and 61–91%, respectively	He et al. (2011)
	Cu; 3–10 nm	NA	NA	Used as fungicides and activity was superior to bavistin (commercial fungicide) against *F. oxysporum*, *C. lunata*, *A.alternata*, and *P. destructiva*	Kanhed et al. (2014)
Nanosensor					
	Au; NA	NA	Not applicable	Utilized as biosensor for neurotoxic organophosphorus pesticides in the environment	Simonian et al. (2005)
	Cu; 100 nm	NA	Not applicable	Utilized as an electrical biosensor for fungal pathogen-*Sclerotinia sclerotiorum* in oilseed rape	Wang et al. (2010)

Table 2 (continued)

Application	Form of Engineered NPs	Application dose	Crop plant	Endpoint benefits	References
	Au-coated CNT; 30–60 nm	NA	Not applicable	Used as an electrical biosensor for Triazophos in vegetables and food sample	Li et al. (2012b)
	Ag; 50 nm	NA	Not applicable	Applied a monolayer film Raman detector to detect pesticides	Zhang (2013)

NA not available

90% than the bulk-sized silica. Scrinis and Lyons (2007) opined that the encapsulation of pesticides in nanoparticles offers adequate combination of chemical principle with crop plants which provides long-lasting effects.

Use in disease management

Engineered nanoparticles are also known for their potential to control plant diseases either used solely as applicant or carriers of conventional ingredients (Table 3). They have been reported as promising materials in plant disease management due to their inherent potential to increase effectiveness at little dose application and ensure human health safety to consumers (Bandala and Berli 2019; Srilatha 2011). Among such Engineered NPs that have been reported as effective against plant diseases, Cu hydroxide-engineered NPs have proven effective against fungal diseases caused by phytopathogens (Baker et al. 2005). Silver-engineered NPs have also been identified as effective with higher efficiency at low doses against fungi (Jo et al. 2009; Kim et al. 2008; Mishra et al. 2015). Potency and efficacy of Ag-engineered NPs are reported to be connected to the different forms and particle size of the engineered NPs, and the efficacy reduces as increases the size (Duhan et al. 2017). Similarly, chitosan-Cu has been utilized as a carrier agent for the encapsulation of saponin and $CuSO_4$ as antifungal material (Saharan et al. 2013). In Cucurbitaceae which are prone to powdery mildew disease, it has been found that nano-Ag at a concentration of 100 ppm was able to prevent the fungal hyphae growth in the plant family and prevent the germination of conidia (Lamsal et al. 2011). Nano silica has been utilized to confer resistance on maize plants against *Fusarium oxysporum* and *Aspergillus niger* because of better expression of phenolic compounds induced by the engineered NPs (Suriyaprabha et al. 2014).

Table 3 Some applications of engineered nanoparticles in viral disease management of crop plants

Application	Form of engineered NPs	Crop plants	Endpoint benefits	References
Nano-antiviral	Ag-NPs; 77 nm	*Vicia faba*	Decrease in concentration bean yellow mosaic virus, percentage of infection, and disease severity in the crop plant	Elbeshehy et al. (2015)
	Ag-NPs; 12 nm	*Solanum tuberosum*	Conferred resistance to potato virus infection in the crop plant	El-shazly et al. (2017)
	Au-NPs	*Hordeum vulgare*	Dissolved barley yellow mosaic viral particle in vitro in barley	Aref et al. (2012)
	Au-NPs; 31.67 nm	*Hordeum vulgare*	Destroyed gold barley yellow dwarf virus and eliminates virus infectivity hazards in barley	Alkubaisi and Aref (2017)
	TiO_2; 20 nm	*Nicotiana benthamiana*	Effectively limits viral infection and replication of Turnip mosaic virus	Hao et al. (2018)
	NiO; 20 nm	*Cucumis sativus*	Reduced disease severity and concentration of cucumber mosaic virus	Hamed Derbalah and Elsharkawy (2019)
	CeO_2-NPs; NA	*Nicotiana tabacum*	Reduced virus symptoms of tobacco mosaic virus	Eugene and Zholobak (2016)
	SiO_2-NPs; 100 nm	*Solanum lycopersicum*	Reduced disease severity and concentration of tomato yellow leaf curl virus	El-Sawy et al. (2018)

Viral infections in agriculture especially in the production of vegetables have been reported to be a great challenge (Lysenko et al. 2018). Metallic nanoparticles from Zn, Au, Ag, Si and Fe are studied candidates and considered antiviral agents due to their ability to intervene in one or more steps of viral replication, though the mechanisms are poorly understood (Lysenko et al. 2018; Vargas-Hernandez et al. 2020). Antiviral activity of SiO_2-Engineered NPs and ZnO-Engineered NPs have been reported against tobacco mosaic virus (TMV) in vitro by directly inactivating TMV through the interaction with envelope glycoproteins in *Nicotiana benthamiana* plants (Cai et al. 2019). Similarly, Cai et al. (2020) treated TMV with Fe_3O_4-engineered NPs and reported accumulation and fracture indicating interactions between the engineered NPs and TMV particles. Gold-engineered NPs have also been proven effective against barley yellow dwarf virus-PAV in barley as the engineered NPs and harmful for virus-like particles (Alkubaisi and Aref 2017).

Use as nanosensors

In agriculture, nanosensors have been recently introduced as useful tools for input efficiency (such as pesticides and fertilizers), and the detection of phytotoxicity, nutrient depletion/deficiency in soil and diseases in crop plants (Dubey and Mailapalli 2016). In fact, nanosensors have been reported as an important nanotechnological-breakthrough in the detection of plant viruses, nutrients level in soils as well as pathogens in crop plants (Brock et al. 2011). These nanosensors are produced mostly from two types of nanomaterials: (i) carbon nanotubes (single- or multi-walled), (ii) Metal-based nanoparticles (Al, Au, Zn) and metal oxide nanoparticles (ZnO, TiO_2, and Al_2O_3) (Khodakovskaya et al. 2012). In agriculture, the main nanosensors employed are the (i) bionanosensor and (ii) electrical nanosensors. The bionanosensor incorporates the sensitivity of biological organisms and nanoparticles into the sensor with the capacity to enhance sensitivity and minimize response-time (Dubey and Mailapalli 2016; Scott and Chen 2012). For instance, microcystins which are toxins produced by cyanobacteria have been detected effectively by several developed biosensors in recent times (Singh et al. 2012). The electrical-nanosensor is also an important device in agriculture that provides precise time-based information for efficient crop production and quality control of agricultural produce. For instance, in the detection of the level of the phenolic phytohormone-salicylic acid, Wang et al. (2010) developed an electrical nanosensor using nano-Au electrode that was modified with Cu-Engineered NPs to sense the electrocatalytic oxidation of salicyclic acid and detected the phytohormone levels in rape oilseed contaminated with *Sclerotina sclerotiorum*. Ogunkunle et al. (2021) also mentioned noble metal-engineered NPs like palladium and platinum biometallic alloys as a primary ingredient, due to their exceptional size and shape (Smith and Gambhir 2017) in the processing of electrochemical sensors.

Use as phytostress-suppresant

Responses to biotic and abiotic stresses in plants are measured by the increase in production levels of reactive oxygen species (e.g., O_2, H_2O_2 and OH) and induction of local and systemic defense responses (Cai et al. 2019). The defense system involves the antioxidants such as catalase (CAT), ascorbate peroxidase (APX), superoxide dismutase (SOD) and guiacol peroxidase (GPX) that help to counterbalance the effects of oxidants. Therefore, to overcome the impact of stressors on crop plants, the use of nanoparticles amongst several other strategies has been considered to support plant (Rajput et al. 2021) (Table 4). For instance, phytostress induced by pathogens can be suppressed by metal/metal oxide-engineered NPs by the interference of cellular redox homeostasis through induction or reduction of the occurrence of oxidative stress (Vargas-Hernandez et al. 2020). Such engineered metal oxide NPs reported to have the potential of repression of oxidative stress in crop plants are TiO_2, CeO_2, ZnO, CuO, Ag, NiO, Al_2O_3, $CoFe_2O_4$, Fe_3O_4, and Fe_2O_3 (Soares et al. 2018). Additionally, growth hormones (gibberellin, auxin, cytokinin, brassinosteroids, abscisic acid, and strigolactone) have also been reported to be induced by Engineered NPs as modulating defense responses to phytostress, either by abiotic or biotic agents (Hernández-Hernández et al. 2018; Rastogi et al. 2017). Copper nanoparticles mixed with chitosan polyvinyl alcohol hydrogels were tested on tomato plants in salt stress and found that the mixture overexpressed jasmonic acid (JA) gene in the crop plants (Hernández-Hernández et al. 2018). Similarly, Fe_2O_3 and TiO_2-engineered NPs were capable of to promote phytohormone quantities such as zeratin riboside, abscisic acid, and brassinoid in tobacco mosaic virus-infected tobacco (Hao et al. 2018). Similarly, stress induced by abiotic factors like heavy metals, salinity and drought have been ameliorated by various applications of engineered NPs (Table 4). Stresses induced by metals in crop plants have been alleviated by the applications of engineered NPs via both foliar and soil routes (Ogunkunke et al. 2022a, b). For instance, Cd stress in crop plants has been alleviated using nano-TiO_2 as phytostress suppressant via soil application, leading to reduced malonaldehyde (Ogunkunle et al. 2020a, b), and the foliar routes of application of nano-TiO_2 (Ogunkunle et al. 2020c) and nano-ceria (Ogunkunle et al. 2023) have also been proved effective in suppressing Cd stress in crop plants.

Salinity problems in agricultural soils have become a global phenomenon as there has been an increase in salt-affected soil worldwide (Islam et al. 2021). The stress induced can be detrimental to crop plants processes such

Table 4 Some application of engineered nanoparticles in the suppression of abiotic induced stress in crop plants

Abiotic stressor	Form of engineered NPs	Crop plants	Application method	Endpoint benefits	References
Heavy metals	Si	*Pisum sativum*	10 µM of Si-NPs via hydroponic growth medium	Si-NPs reduced Cr accumulation, and promoted synthesis of defense enzymes	Tripathi et al. (2015)
	Fe_3O_4	*Triticum aestivum*		NPs minimized the inhibitory of Pb, Cd and Cr, and improved superoxide dismutase and peroxidase	Konate et al. (2017)
	Fe	*Triticum aestivum*	0–20 mg/l in hydroponic growth medium	NPs reduced Cd accumulation, promoted plant growth, dry weight, and decreased activity of superoxide dismutase and peroxidase along	Rizwan et al. (2019)
	TiO_2	*Vigna unguiculata*	100 mg/kg via soil as a growth medium	NPs in combination of arbuscular mycorrhizal fungi reduced Cd uptake and translocation of Cd to above-ground biomass. Also improved stress tolerance of the crop	Ogunkunle et al. (2020a)
	ZnO	*Oryza sativa*	10–100 mg/l via hydroponic growth medium	NPs encouraged reduction in root and shoot accumulation of as in the seedlings	Yan et al. (2021)
	Fe_2O_3	*Oryza sativa*	0–100 mg/kg via soil medium	NPs restricted Cd transport in above-ground parts and improved fresh and dry biomass	Ahmed et al. (2021)
	SiO_2	*Glycine max*	NA	NPs lowered Hg accumulation in Root, and improved chlorophyll content	Li et al. (2020)
	TiO_2	*Zea mays*	0–250 mg/l via soil medium	NPs reduced Cd accumulation, and increased activities of antioxidant enzymes	Zhou et al. (2020)
	Se	*Oryza sativa*	5–20 mg/l via hydroponic growth medium	NPs lowered accumulation of Cd and Pb and improved yield	Hussain et al. (2020)
Salinity	Magnetite	*Triticum aestivum*		NPs improved chlorophylls, antioxidant enzymes and ameliorated polypeptides chains affected by salinity	El-Saber et al. (2021)
	SiO_2	*Glycine max*		NPs raised the level of leaf K^+ and biological antioxidant activities under salinity	Farhangi-Abriz and Torabian (2018)
	SiO_2	*Triticum aestivum*		NPs improved seed germination and growth under salinity	Mushtaq et al., (2019)
	Zn	*Brassica napus*		Detrimental impact of salinity was alleviated through the upregulation of the antioxidants and ionic control	Farouk and Al-Amri (2019)
	Cu	*Solnum lycopersicum*	Cu-Engineered NPs applied to the leaves mitigated salinity stress	Growth, ionic ration (Na^+/K^+), and levels of glutathione, polyphenols, and vitamin C contents were improved	Pérez-Labrada et al. (2019)

Table 4 (continued)

Abiotic stressor	Form of engineered NPs	Crop plants	Application method	Endpoint benefits	References
	Zeolite	*Solanum tuberosum*		Leaf relative H_2O content, leaf stomatal conductance, leaf photosynthetic rate and chlorophyll contents were enhanced	Mahmoud et al. (2019)
	SiO_2	*Musa acuminata*	Applied at concentrations of 0, 50, 100, and 150 mg/l	Application of SiO_2-NPs reduced MDA content and electrolyte leakage	Mahmoud et al. (2020)
	Fe	*Fragaria ananassa*	Application rates of 0, 0.08, and 0.8 ppm	Fe-NPs improved photosynthetic pigments and membrane stability index	Mozafari et al. (2018)
	TiO_2	*Zea mays*	Application rates of 40, 60, and 80 ppm	NPs enhanced K ion concentration, antioxidants; and decreased membrane electrolyte leakage and MDA content	Shah et al. (2021)
Drought	Si	*Crataegus laevigata*	Application rates of 0, 10, 50 and 100 mg/l	S-NPs improved the photosynthetic rate and stomatal conductance considerably	Ashkavand et al. (2015)
	TiO_2	*Linum usitatissimum*	Application rates of 0, 10, 100, and 500 mg/l,	TiO_2-NPs increased the carotenoids content and seed oil and protein contents, and ameliorated cell membrane damage, and ameliorated cell membrane damage	Aghdam et al. (2015)
	Fe	*Triticum aestivum*	Applied at the rate of 25, 50, and 100 mg/kg	NPs increased the chlorophyll a content up to 66% and eradicated the oxidative stress by switching antioxidative defense system	Adrees et al. (2020)
	ZnO	*Mangifera indica*	Applied at the rates of 50, 100, and 150 mg/l	NPs enhanced leaf NPK content, total carbohydrates, total sugars, and proline content; and SOD, POX, and CAT activities at 100 mg/l	Elsheery et al. (2020)
	Si	*Mangifera indica*	Applied at the rates of 150 and 300 mg/l	NPs enhanced leaf NPK content, total carbohydrates, total sugars, and proline content; and SOD, POX, and CAT activities at 150 mg/l	Elsheery et al. (2020)
	Zero-valent Cu	*Zea mays*	Applied at the rates of 3.333, 4.444 and 5.556 mg/l	Cu-NPs increased anthocyanin, chlorophyll, and carotenoid contents. Also improved drought stress tolerance by decreasing the oxidative stress via the enhancement of ROS scavenging antioxidant enzymes	Van Nguyen et al. (2021)
	ZnO	*Solanum melongena*	Application rates of 50 and 100 ppm	ZnO-NPs improved macro- and micronutrients' uptake and increased relative water content	Semida et al. (2021)

NA not available

as the physiological, biochemical, and molecular activities, thereby causing a reduction in crop productivity (Kumar et al. 2020). However, several attempts have been made to mitigate these salinity-induced stresses using nanoparticles as phytostress suppressants in crop production. Crop plants under salinity stress feasible to improve by the usage of nanoparticles either through foliar or soil route through the process of regulation of ion balance as Na^+ ion toxicity is reduced and K^+ ion uptake is promoted, thereby activating antioxidant defense system in the crop plant (Rajput et al. 2021). In addition, seed priming with engineered nanoparticles can also be utilized to ameliorate salinity stress. Seed primer of *Lupinus termis* with ZnO-Engineered NPs at 60 mg/l was able to ameliorate the detrimental effect of salinity stress induced by NaCl through increased pigmentation, osmoregulation, and improvement in stress-associated metabolites. Similarly, Ag-Engineered NPs were able to alleviate salinity stress in *Triticum aestivum* after seed priming (Mohamed et al. 2017). The major stress of the crop plants is drought and causes great loss in crop productivity if not checked or ameliorated by reducing leaf area, crop growth, carboxylation, and water potential in addition to causing crops' hormonal imbalance (Kumari et al. 2018). Some applications of engineered nanoparticles in the alleviation of drought-induced stresses in crop plants are presented in Table 4.

Use as nanoremediator

Contamination of water bodies, soil, and air by heavy metals from industrial activities, manufacturing, landfills and oil fields posed a grave threat to human well-being and ecosystem functionality. Since several decades ago, the discharge of metalloids and innumerable organic compounds from industrial and agricultural activities had resulted in a huge increase in contaminated land and water body (Gil-Díaz et al. 2019). Many of these metalloids are toxic, carcinogenic and can endangered human health, even at a very low dose (Baragaño et al. 2020). They are usually intractable to biochemical responses and therefore difficult to eliminate from the environments. As such, it is a global concern that requires ecofriendly remediating approaches. Application of nanomaterials for remediation connotes an innovative solution with a tendency to induce significant changes in the speciation of heavy metals. Indeed, there is increasing interest in pollution remediation by nanotechnological approach as it serves as an alternative approach to prevent, reduced, and treat environmental pollution (Corsi et al. 2018; Gil-Díaz et al. 2016; Xue et al. 2018). For example, previous works had revealed that nanoscale iron particles have been quite effective for environmental remediation. The advantage of nanoscale zero-valent iron (nZVI) appears to as an effective strategy for the contaminated soil remediation (Gil-Díaz et al. 2019), likely due to their high surface area to weight ratio, which permits higher reactivity rate than micron-scale ZVI when normalized to mass. Nanoscale zero-valent iron (nZVI) remediate typical polluted soil and water by significantly reducing the availability of both As and Hg (De et al. 2009; Gil-Díaz et al. 2016). It has also been ascertained to be highly effective in elimination of several contaminants, like chlorinated compounds, heavy metals and others (Xue et al. 2018).

The key benefits of using nanoremediator for agricultural soil and groundwater remediation, especially in urban cleaning, are reduction in cleanup time and cost accrue (Alazaiza et al. 2021). Unlike traditional methods, nanoremediator usually completely degrade some contaminants without the need for the disposal of polluted soil or water. However, the effects of nanoremediators on the environmental remain unclear and need more investigation to ascertain the environmental fate and toxicity of these nanoremediators. Due to its magnetic property and small size effect, nZVI has a problem of aggregating quickly, which extensively reduces its reactivity towards the contaminant. To provide a solution to this issue, nZVI is often coated with surface modifiers. It can also be bound with Rhamnolipid, a glycolipid anionic biosurfactants that is produced by numerous strains of *Pseudomonas aeruginosa*. Rhamnolipid has surface/interfacial activities and could be a promising alternative to stabilize NZVI. Moreover, if a nanoremediation is combined with a traditional method such as the use of microorganisms, they could generate a better result. For example, It has been found that when *Geobacter metallireducens* was bound with particulate ferrous oxide, it reduced 4-nitroacetophane, a highly toxic organic compound (Braunschweig et al. 2013).

Challenges/risks of nanotechnology in crop production

In the current trends, traditional farming and nutritional demands are changing rapidly in agricultural crops. New challenges require a new approach to innovate the latest technology. Engineered nanoparticles such as fertilizers, pesticides, remediators, sensors, phytohormones, formulation and stress-mediators are widely implemented to enhance plant growth, yield, soil improvement and minimize phytotoxicity. Since the global production of nanoparticles is daily increasing, so the challenges and risks on crop production are based on dose and toxic effects on germination, root growth, chlorophyll, chromosomal deviation, yield, etc. The nanotoxicity studies of various metals and metal oxide nanoparticles like carbon nanotubes (single or multiwall), Ag, ZnO, Fe has shown arrest in plant growth (Dimkpa et al. 2012; Ghosh et al. 2015). Phytotoxicity of metals and metal oxides nanoparticles are controlled by the size of the plant and plant species, size, concentration, and stability of engineered nanoparticles (Wang 1991; Wang and Freemark 1995). The toxicity of Ag nanoparticles in plants is because of their impact on the biochemical properties which stimulate free radical generation thereby inducing oxidative stress in plants (Nair et al. 2010)). Engineered nanoparticles interact with various cellular components and nucleic acids, causing chromosomal aberration, genomic changes and alter the cell signaling mechanism (Ray et al. 2012; Singh et al. 2017).

Soil pollution by metal and metal oxide nanoparticles is an emerging issue for food safety and threat for man and animals. Large concentrations of ENPs present in the soil enter through various agricultural activities and accumulate for long. A study indicated that the quantity of ENPs present in soil was far greater than water, air or other atmospheric components (Gottschalk et al. 2009). Usage of ENPs in soil has a negative impact on plant productivity, existing microorganism, soil enzymes activity because it generates free radicals that lead to lipid peroxidation and DNA damage (Thul and Sarangi 2015).

Safety issues along the food chain (human and animal safety)

Engineered nanoparticles are transmitted through several links to the food chain which is a great concern for safety issues. Toxicity of nanoparticles is based on the physical and chemical properties when exposed to biological systems. Nanoparticles are used for food, cosmetics, textiles, water treatment, coatings on materials, electronic devices, pharmaceutical and biomedical fields, etc. (Aslani et al. 2014; Exbrayat et al. 2015). And some possible ways of the transmission of nanoparticles into the food chain are inhalation through air, intake by water and food, absorption of nanoparticles through cosmetics products, and entry through the gills of aquatic animals (Maharramov et al. 2019). Ingested nanoparticles damage the cellular organ within the gastrointestinal tract (GIT) (Buzea et al. 2007). Though, nanoparticles are used to treat water and wastewater, it is difficult to estimate the release concentration of used nanoparticles to the environments. Accumulation of ENPs in tissues of crop plants changes their physiochemical features by altering the proteins, lipid, nucleic acid content and by generating hydroxyl radicals which has an impact on the food chain (Da Costa and Sharma 2015; Rajput et al. 2019a, 2019b).

Conclusion and future perspectives

The crop production sector in agriculture is always facing massive environmental pressure and climate change with consequential negative effects on soil fertility and its nutrients quality because of the continuous use of pesticides, herbicides, fertilizers and contamination by industrial chemicals and water effluents. Nanotechnology-based crop production is an emerging trend for the next-generation revolution and transformation in the agricultural system. This is a sustainable approach for better plant productivity than the conventional type and supports progress in overall crop production in the agricultural sector. It has the potential to promote input use efficiency, enhance nutrient management of soils, and encourage the genetic improvement of crop plants for food safety and security.

In the meantime, research on the applications of nanotechnology in agriculture, especially the application in crop production is less than a decade old. This actually necessitated the need for more studies on the unintended implications of the use of engineered nanoparticles on the environment, especially the negative effects that are genetically transferable to offspring in future generations or multigeneration. It is also important that further research be carried out to understand the implication of the adoption of engineered nanoparticles on plants in the wild to unravel their implications on plant biodiversity.

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