Agronanobiotechnology: Present and Prospect

Abhaya Kumar Sahu, Swikruti Sonali Kar, and Punam Kumari

1 Introduction

Nanoscience, nanoengineering and nanotechnology offer plenty of a multitude of possibilities altogether. They demonstrate a practical recourse in the agriculture and agri-foodstuff areas, by offering a novel and progress scoring. In this light, we would like to share some recent advances in nanotechnologies and NM structures that could aid in food supply chain management and precision agriculture. Nanotechnology's applications and advantages in agriculture have gotten a lot of attention, especially in the development of novel nanopesticides and nanofertilisers.

Because of insufficient natural gas and oil reserves, production cost intrusions such as chemical fertilisers and pesticides are predicted to rise at an unprecedented rate. Several state-of-the-art methods for enhancing precision farming techniques are now available due to advances in nanotechnology, allowing accurate control at the nanometre scale. Nanotechnology has many applications in agricultural equipment, including increasing the resistance of machines and agricultural tools to wear, corrosion and ultraviolet rays through the use of nanocoating; the supply by nanocoating of durable mechanical elements and by biosensors for mechanical applications and chemical weed management in intelligent machines. Manufacturing of nano-covers for axes is to prevent friction. Nanotechnology is being used in the manufacture of alternative fuels to minimise carbon emissions. Nanotechnology has also demonstrated its ability to change the genetic constitution of crop plants to help improve crops significantly (DeRosa et al. 2010). Pesticides and chemical fertilisers were widely used during the green revolution, resulting in a loss of soil biodiversity,

---

A. K. Sahu · S. S. Kar · P. Kumari (✉)
P. G. Department of Biosciences and Biotechnology, Fakir Mohan University, Balasore, Odisha, India
e-mail: punam.lifescience@gmail.com

F. Fernandez-Luqueno, J. K. Patra (eds.), *Agricultural and Environmental Nanotechnology*, Interdisciplinary Biotechnological Advances,
https://doi.org/10.1007/978-981-19-5454-2_2

groundwater pollution and resistance to pathogens and pests. The provision of pesticides for safety purposes is becoming increasingly important in nanotechnology (Duhan et al. 2017). Nanotechnology in agriculture aims to minimise plant defence constituent dosages, reduce loss of nutrients, locate pathogens of plants, monitor residue of pesticide and raise output. A nanopesticide is a recipe used to maximise the effect of plant protection products using NMs as an active component (Saratale et al. 2018).

Agrarian nanotechnology is one of the main targets that needs immediate consideration in developing new nanocomposites capable of carrying active ingredients such as nutrients, fertilisers and pesticides. Farming programmes that focus on climate, recovering soil infertility and creating a new drought-resistant crop are among the other accomplishments that remain to be achieved to spread sustainable agriculture practices around the world. Furthermore, environmental sustainability and green chemistry principles must be built into nanotechnologies from the beginning. Consequently, investments in the growth and effective implementation of advanced agricultural technologies are crucial to enhancing agriculture and the food processing sector. In addition, to minimise food losses and increase food security, it can improve agricultural production, storage and transport (Shafiee-Jood and Cai 2016). Through systematic interdisciplinary research and efficient knowledge transfer, advanced analytical techniques are thus made possible using various kinds of NMs, interfaces and devices and their properties (Anderson et al. 2016). Electrical, optical sensors or electromagnetic sensors and electrochemicals are among the nanotechnology capabilities currently available in the market. Advanced wastewater treatment systems are proposed for effective wastewater treatment to overcome the lack of water supplies and low rainfall. The excessive use of mineral fertilisers and pesticides causes huge pollution and severe health problems (Yu et al. 2017). This improves the release mechanism and targeted mineral and nanopesticidal supply which shows better activity with an excellent protection efficiency compared to conventional pesticides.

Nanotechnology applications are unpredictable in farming due to its reliance on various natural components such as weather, season, water, soil, and agriculture. Therefore, the detection, registration, manipulation and storage of reliable and accurate data for both biotic and abiotic components are essential to addressing quality and food demand issues while ensuring environmental sustainability (Chhipa 2017; Servin et al. 2015). NMs can be used in agriculture on a broad spectrum, as well as increasing crop production and improving soil quality.

1.1 What Is Nanotechnology?

Nanotechnology is an exciting interdisciplinary research area. The term ‘Nanotechnology’ was popularised by Bulovic et al. (2007) and Taniguchi et al. (1974). Nanotechnology is a field of study that aims to create ‘stuff’ on the scale of atoms and molecules, such as materials and computers. The diameter of a hydrogen atom is ten times that of a nanometre, which is one-billionth of a metre. A human hair is 80,000 nm in diameter on average. Ordinary physical and chemical laws may not apply at such scales. Between the nanoscale and the macroscale, materials' colour, weight, conductivity and reactivity, for example, can differ dramatically. However, just 6 times the mass of steel, carbon 'nanotubes' are 100 times more powerful. The scientist who coined the word nanotechnology, Eric Drexler, has issued a warning about the development of 'highly powerful, extremely dangerous technologies'. Nanotechnology has been lauded for its potential to increase energy efficiency, assist in environmental sanitisation and address significant health issues. It is believed that it can increase production efficiency substantially while lowering costs. Nanotechnology-based goods, according to an engineers, it would be smaller, cheaper, lighter and more durable, and would require less energy and raw materials to manufacture. Nanotechnology has had a major effect on a wide variety of businesses and everyday lives (Gruère et al. 2011; Scott and Chen 2013). NPs are described as particles with a diameter of 1–100 nm, according to the Environmental Protection Agency (EPA). This material is ideal for use in a variety of creative and novel applications that solve social needs and problems due to its small size and properties (Nakache et al. 2000). The future agriculture applications of nanotechnology and NMs, nutrition, disease resistance, delivery of genetic materials and formation of soil structure are discussed in the following sections. NPs have unique properties that enable them to be used in a variety of fields, including electronics, medicine, pharmaceuticals, engineering and agriculture. NPs are materials with a scale of fewer than 100 nm (Thomas et al. 2012).

1.2 What Are NPs?

NPs are a unique type of material having eccentric properties and a broad range of assortments. NPs are thought to serve as a linkage between atomic structures and material extent. Furthermore, because of their high surface-to-mass ratio and their tiny capacity, inorganic NPs have special properties. Gold (Au) and silver (Ag) NMs, among other metallic NPs types, have been developed, which have attracted a lot of attention due to their outstanding success in a number of scientific fields, as well as optics, biosensing and catalysis. Plant extracts are currently being used as inhibitors and blocking agents in the development of NPs, which may be preferable to bacterial synthesis because it eliminates the need for the complex method of culturing and maintaining the cell. Because of their superior catalytic, optical and electrical properties, NPs, especially Ag NPs, have found widespread use in opto-electronics, detection, diagnostics, antimicrobials, catalysis and therapeutics (Sivakumar et al. 2012). Exceptional free-radical hunting, obstruction of carbohydrate digestive enzymes (-Glucosidase and-Amylase), and a development in glucose absorption rate were used to demonstrate the anti-diabetic potential of AgNPs derived from *Tephrosia tinctoria* (Rajaram et al. 2015). Au and Ag NPs have recently been synthesised successfully by utilising the leaf and root extract of *Panax ginseng*, a medicinal herbal plant (Singh et al. 2016). Netala et al. (2016) demonstrated that NM toxicity risks are reduced when NMs are synthesised using biological processes, allowing for biological applications (e.g. agriculture, drug delivery and bio-sensing). Using nanotechnology in agriculture has numerous advantages when it comes to plant disease management and overall development. Micro/macronutrients and nanoformulations containing fertilisers, for example, have increased crop yield while also serving as a biological controlling agent against numerous plant infectious agents when combined and applied to crop development (Keswani et al. 2016). Some NPs, such as magnesium (Mg), titanium oxide (TiO), zinc oxide (ZnO), silicon (Si), and Ag NPs, play a role in indirectly suppressing plant infection by antioxidant/antimicrobial/heavy metal absorption (Rastogi et al. 2019). NPs were divided into biological NPs (as well as fullerenes) and inert NPs (Karthika et al. 2015). Inorganic NPs, such as noble metallic NPs, have recently received a lot of attention because they have a lot of applications in medicine. A general overview of NPs classification is as described below. The properties of Ag metal change drastically when it is decreased to a particle size of 1–100 nm and Ag-NPs are formed. When $AuCl_4$ or another Aurum salt (such as $AuCl_3$) is reduced in the attendance of catalysts or other reducing agents, Au-NPs are formed, resulting in a shift in the noble metal's basic properties on a scale of 1–100 nm. In solution, Au-NPs look burgundy to purplish. They come in a variety of shapes, including spherical rings, nanorods, decahedral, tetrahedral, sub-octahedral triangles, hexagonal, octahedral and icosahedral, among others (Alaqad and Saleh 2016). Ag and Au-NPs are the most widely studied. NPs is also made from metals such as Pb and Cu, non-metals such as Se and heavy metal oxides such as ZnO and SnO_2. Rajan et al. (2016) investigated the antibiotic efficacy of ZnO NPs and discovered that they are effective against pathogenic bacteria. The representative applications for different types of NMs are listed in Table 1.

1.3 Application of Nanotechnology in Agriculture

Natural or manufactured NMs are used in agriculture. Engineered nanomaterials (ENMs) are divided into three categories: combined, inorganic, and organic containing modified surface mud. There are also applications for salts, heavy metal oxides, nanotubes, heavy metals, fullerenes and black carbon. Micelles and liposomes in lipid-based NMs have a high degree of stability. Self-assembling molecules are often used to make protein-based NMs (Puri et al. 2009). The use of engineered natural microorganisms (ENMs) has been shown to improve plant germination and productivity (Servin and White 2016). Many trees are excellent for NM absorption and storage. The cell of plants' interactions with ENMs can guide changes in the expression of plant genes and related biological pathways that can impact plant production and growth. ENMs vary according to the stage of growth, phase and exposure time for various plant species (Panpatte et al. 2016). Applications in agriculture to improve efficiency are illustrated by many nanotechnology

Table 1 Different types of nanomaterials and their applications

Nanomaterials (NMs)	Constituent NPs	Applications	References
Nanofertilisers	Nano Fe/SiO_2	Enhanced maize and barley seedlings shoot length by approximately 20.8% and 8.25%, respectively	Zhao et al. (2017)
	ZnO, TiO_2, MWCNTs, FeO, $ZnFeC_4$-oxide and Hydroxyfullerness	Growth and production of crops with enhanced efficiency of many crop species including spinach, peanut, mungbean, soy, onion, wheat, tomato, wheat, mustard and potato	Shinde et al. (2020), Derbalah et al. (2018)
	Zinc/Boron, generated on the chitosan emulsion NPs by mounting $ZnSO_4$ and H_3BO_3	Enhanced consumption of zinc, chlorophyll elements and coffee's photosynthesis	Wang and Nguyen (2018)
	Nano-zinc and boron	Increase fruit yields and consistency, rises in pH on pomegranate (*Punica granatum*) juice without impacting the properties of any fruit attribute	Shehzad et al. (2018)
	TiO_2	Compared with plant control *Glycine max* L, a beneficial impact on the oil yield, seed and other elements	Rezaei et al. (2015)
	Nano Fe_3O_4	Increase the disponibility of iron and protein in plants, often used for chlorosis treatment	Siva and Benita (2016), Rui et al. (2016)
	TiO_2 and SiO_2	Minimised Cd toxicity and increased development by promoting the ability of anti-oxidants and preventing translocation of Cd in the *Oryza sativa* plant	Rizwan et al. (2019)
Nanopesticides	ZnO, CuO and Ag-NPs	Symptoms of soil-borne disease and *B. cinerea* in *Prunus domestica* fruits with the grey mold have been eliminated	Malandrakis et al. (2019)
	Ag-NPs	The development of *Xanthomonas axonopodis* pv. malvacearum and *Xanthomonas campestris* pv. campestris in vitro in *Vigna unguiculata* could be inhibited and there were no phytotoxicity	Vanti et al. (2019)

(continued)

Table 1 (continued)

Nanomaterials (NMs)	Constituent NPs	Applications	References
	ZnO	Interruption in *Callosobruchus maculate* larval and pupal growth and development	Malaikozhundan et al. (2017)
Nanofungicides	Al_2O_3 NPs	Treated effectively rot root *Fusarium* in *Solanum lycopersicum* tomato	Shenashen et al. (2017)
	Metallic NPs	Antibacterial and antifungal activity in plants	Slavin et al. (2017)
	AuNPs	Antifungal activity in *Candida albicans*	Aljabali et al. (2018)
	ZnO	Applied to plants in case of fungal phytopathogens, named *Penicillium expansum*, *Aspergillus niger*, *Fusarium oxysporum*, *Botrytis cinerea*, *Alternaria alternate*, etc.	Jamdagni et al. (2018)
	Chitosan/silver combination (Ag@CS NPs)	Efficacious to rice blast triggered by *Pyricularia oryzae*	Pham et al. (2018)
Nanoherbicides	Atrazine nanocapsulation	Reduced root and shoot growth in *B. pilosa* and reduced the operation of photo system II	Sousa et al. (2018)
	2,4-dichlorophenoxyacetic acid (2,4-D)	Rice husk waste was surface adsorbed with 2,4-D to serve as an herbicide nanocarrier. And they demonstrated reversible and improved sorption of 2,4-D which shows their uniqueness to be a strong carrier for herbicide encapsulation	Abigail et al. (2016)
Seed germination	ZnO	Enhanced rice germination and raises length of radical and plumule	Upadhyaya et al. (2017)
	Six metal oxide NPs binary mixtures (TiO_2, Fe_2O_3, CuO, NiO, Co_3O_4 and ZnO)	Improved *Brassica* seed germination	Ko et al. (2017)
	SiO_2	Boost the germination of the seed	Alsaeedi et al. (2018)

approaches. This included nanoformulation for crop protection, detecting nanobiosensor toxicity, genetic alteration of plants by nanodevices, effective diagnosis of disease and the advancement of agrochemicals. The gain of nanoarrays from genetic content and protein supplies in crop designing, drug supply, pathogen detection and environmental control that need to be monitored (McLoughlin 2011; Pandey et al. 2010; Mir et al. 2017). For resisting plant pathogens and for immersive agrochemicals nanofilms, nanofibrous pads and quantum dots (QDs) open up a new opportunity for agriculture and in other sectors. Crop germination and seedling growth were found to be unaffected by QDs at low concentrations. QDs may also be used to check identified physiological processes in plant root systems using live imaging (Das et al. 2015a, b). For their nanofertiliser properties, FeO, TiO_2, urea hydroxyapatite, ZnO, $nSiO_2$ NPs and carbon-based NPs have all been examined (Kottegoda et al. 2017; Subbaiah et al. 2016). Nano ZnO, SiO_2, FeO and TiO_2 are all examples of nanofertilisers. In the last ten years, there has been a comprehensive study of many NPs for metal oxides such as TiO_2, Al_2O_3, CeO_2, ZnO and FeO for agricultural processing. Both micronutrients and fertilisers were found to increase the condition of the soil at the nanoscale (Jose and Radhakrishnan 2018). The use of TiO_2 NPs in soya has shown that the content of nitrate reductase and the absorption of water and the antioxidant process are substantially increased (Kataria et al. 2019). Nano-encapsulated formulations of pesticides require low dosages of pesticides, and therefore human exposure, with limitable side effects, to make them safe to protect crops (Nuruzzaman et al. 2016). The mesoporous silica NPs (MSNPs) were suggested for chemicals and DNA transmission into the isolated plant cells (Yi et al. 2015). *Prunella vulgaris* callus proliferation was also boosted by Au-NPs and Ag-NPs, either singularly or in combination (Faizal et al. 2016). Colonisation and film growth can all be examined with nanofabricated vessels which simulate capillary activity as well as following the xylon-inhabiting bacteria's movement and recolonisation (Jose and Radhakrishnan 2018). The schematic representation of applications of nanotechnology is depicted in Fig. 1.

1.3.1 NMs in Nutrient Addition

The use of nanotechnology to provide nano-sized nutrients for crop production is known as nanonutrition (Mura et al. 2017). The researchers used both biotic and abiotic NPs. Inorganic sources such as salts are used to make the abiotic form of nutrients or NPs, but this is harmful since many of these are not biodegradable. We will make micronutrients and macronutrients more accessible to plants by using nanonutrition. Insect and pest defence using nanotechnology has been used on plants. Nanofertilisers can improve nutrient uptake and aid in the development of more intensive, sustainable agriculture. Weanlings have been given casein micelles as a source of nutrition. Since these particles are cleared in the stomach proteolytically, the animals of farming are not at risk (Day et al. 2015). Akbari and Wu (2016) suggest encapsulating and shedding hydrophobic and hydrophilic bioparticles of the harsh stomach world using canola proteins cruciferin as NPs. In addition, the volume of iron increased in sunflowers by the Fe_3O_4 coated EDTA NPs (Shahrekizad et al. 2015). The growth of peanuts is boosted by an increased supply of iron and iron

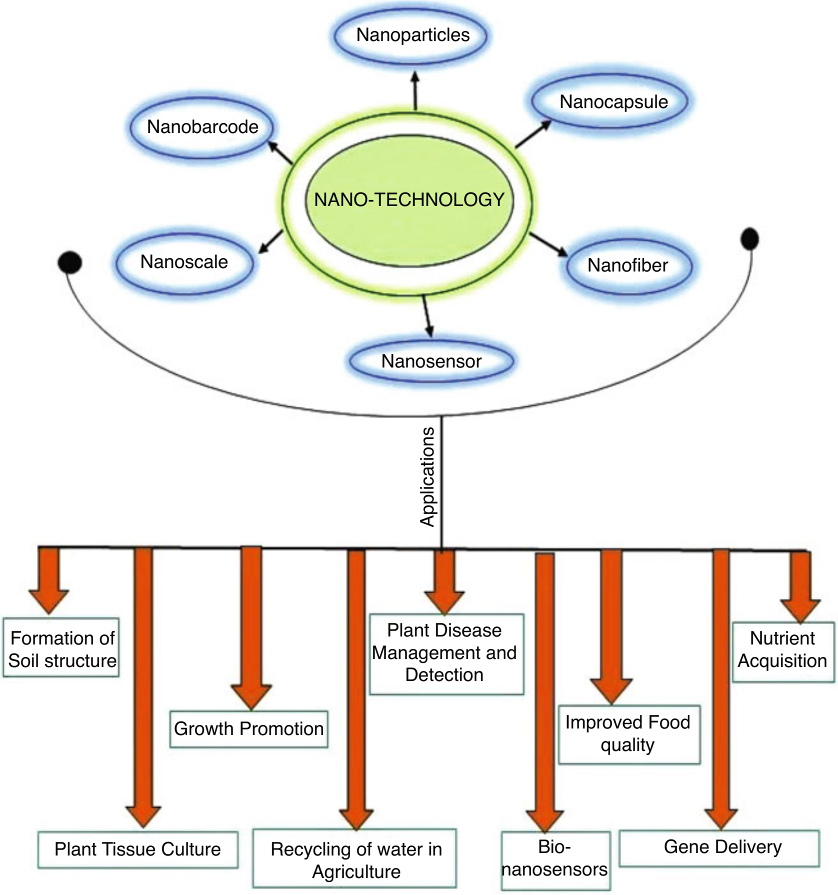

Fig. 1 Various types of nanotechnology applications are using in agriculture

oxide NPs (Rui et al. 2016). The implementation of Zinc-boron nanofertiliser prepared with $ZnSO_4$ loading chitosan NPs emulsion in coffee leaves enhanced Zn, N and P uptake, and improved chlorophyll content (Wang and Nguyen 2018). When exposed to different amounts of Cu-NP, the number of Cu^{+2} ions produced by Cu-NPs did not affect *Phaseolus radiatus* and *Triticum aestivum*. Saharan et al. (2015) demonstrated that CuO-NPs can be used in hydroponic environments, shifted and biotransformed by rice plants, but even Cu-NP is bioavailable. The casparian NPs will pass into the exodermis, epidermis and cortex of the root before reaching the endodermis. Tomatoes' early blight and *Fusarium* wilt may be treated as antifungal agents with Cu-chitosan NPs.

1.3.2 NPs Promote Plant Growth

Researchers worldwide have also researched this growing promotional behaviour of unique metal NPs (Salem et al. 2015). In *Brassica juncea* plants treated with iron sulphide (FeS) NPs, activate RuBisCo small subunit (rubisco S), RuBisCo big subunit (rubisco L), glutamine synthase (GS) and glutamate synthase (GltS). The mechanism by which FeS NPs have caused growth and yield increase is thought to be the carbon and nitrogen assimilation pathways that are activated at various growth stages. Rawat et al. (2017) announced that *Brassica juncea* 7-day seedlings exposed to Ag metal NPs have growth and antioxidant status (at 0, 25, 50, 100, 200 and 400 ppm). Ag NPs treatment improves the fresh weight, root and shoot length and vigour index of seedlings. The treated seedlings had a 32.6% increase in root length and a 13.3% increase in vigour index. ArgovitTM is an *Allium cepa* AgNP formulation. The concentration level for polyvinylpyrrolidone (PvP)–AgNP formulations tested is 10–17 times higher than those formerly announced and has not caused genotoxic or cytotoxic damage to *A. cepa*. (10–1666 g/mL completed formulations). Favour development without damaging roots or bulbs, in other words, low concentration (5 and 10 g/mL) (Francisco et al. 2020). The benefits of nanofertilisers are lower degradation of water bodies, less ground contamination, delayed and constant release of nutrients, an improvement in output yields, better photosynthesis (Mehrazar et al. 2015). Fe_2O_3-NPs rise the content of plant protein and iron to reduce chlorosis disease (Siva and Benita 2016). Hafeez et al. (2015) demonstrated that Copper (Cu-NP) improved wheat cultivar in the Millat-2011 crop and yield by growing chlorophyll content, leaf area and root dried weight and shoot dried weight. Yassen et al. (2017) reported that the SiO_2 nanofertiliser application rises cucumber growth and production by increasing the phosphorus and nitrogen content of the plant. Chitosan is a randomly dispersed polymer, connected to biodegradable and biocompatible N-acetyl-glucosamine units and β-(1,4)-D-glucosamine. Several examples show that chitosan NP application results in impressive plant growth. Nano chitosan-NPK 239 fertiliser enhances the growth and productivity of wheat plants grown in sandy soil (Abdel-Aziz et al. 2016). Chitosan–polymethacrylic acid (PMAA) NP in pea plants increases the build-up of starch at root ends. In addition, protein production such as legumin and vicilin was increased (Khalifa and Hasaneen 2018).

1.3.3 Management and Detection of NMs in a Plant Disease

Appreciating the mechanism of contamination and propagation, and then looking at modes by which this can be alleviated, is the most critical aspect of plant disease management. However, this was a problem until recently when we were able to investigate the intercommunicating use of nanofabrication between plant and disease agents to know better how microbes migrate. By nanomanufacturing the xylem system, we could better appreciate the mechanism of the microbes in the xylem system. Earlier, all such experiments would need tissue damage to produce a good picture of the process. Ag NPs in an investigation performed by Medda et al. (2015) showed an inhibitory influence on fungal germination and budding. In addition to the structural disruption, there have been changes in the sugar, lipid and protein content. *Ralstonia solanacearum* is one of the species affected by Ag (Aravinthan et al. 2015). Antibiotic use must be restricted and monitored, and procedures must be developed under which NPs can effectively prevent the spread of diseases (Huijskens et al. 2016). Studies indicate that heavy metal NPs can lysis negatively loaded membranes of bacteria because of their load (Gahlawat et al. 2016). Such a case was the splitting of the ß-lactam ring with certain microorganism. A ß-Lactam antibiotic containing NPs blocks the tendency of microbes to cleave (Kalita et al. 2016). The biocidal function of the membrane cell wall of bacteria has been established by hydrogels made from NPs such as qPDMAEMA (Xu et al. 2015). Cu-chitosan NP inhibited the growth of *Alternaria solani* and *Fusarium oxysporum* in tomatoes by 70.50 and 73.5%, respectively (Saharan et al. 2015). In the case of *Macrophomina phaseolina*, 25% of ball mouldings are more antifungal in the combination of nanotrifloxystrobin and 50% of tebuconazole (75 WG) fungicide than conventional fungicides (Kumar et al. 2015). Chitosan (CS) and Ag NPs (also called Ag@CS NPs) were antifungal activity in opposition to the rice explosion which was created by *Pyricularia Oryzae* (Pham et al. 2018). The antifungal and antiprotozoal activity of ZnO-NP with ciprofloxacin and ceftazidime were detected in *Aspergillus niger*, *Alternaria alternativeata*, *Penicillium expansum*, *F. oxysporum*, and *Bancroftian filaria*. The maximal antifungal efficacy was reached when 0.25 mg mL^{-1} ZnO-NPs were paired with 8 mg mL^{-1} ciprofloxacin and 32 mg mL^{-1} ceftazidime (Jamdagni et al. 2018). Anti-fungal experiments have been conducted utilising zinc oxide NPs (ZnO-NPs) with results indicating that ZnO-NPs have a significant ability to inhibit the growth of fungal infectious agents (Khan et al. 2019). Arciniegas-Grijalba et al. (2017) have been studied the antifungal impact of ZnO-NP on *Erythricium salmonicolor* pink coffee disease. Two categories of ZnO synthesised at several concentrations have been utilised to quantify inactivation of fungal mycelial formation. High Resolution Optical and Microscopic (HROM) and Transmission Electron Microscopy (TEM) were found to prevent growth and morphologic transformation such as dilution of hyphae fibres and fungal clumbing patterns at 9 mmol L^{-1} zinc acetate ($ZnC_4H_6O_4$). The CuNP-based settlement of *F. culmorum*, *F. équiseti* and *F. oxysporum* has decreased substantially, according to Bramhanwade et al. (2016); *Staphylococcus aureus*, *Escherichia coli* and *Proteus vulgaris* colonisation was studied by Mishra and Sharma (2017) who found that most of them were inhibited by *P. vulgaris* colonisation while *S. aureus* colonisation was least inhibited. Both of these have a minor inhalation effect on colonisation by Ag NPs *Staphylococcus aureus*, *Bacillus cereus*, *Listeria monocytogenes*, *Salmonella typhimurium* and *E. coli* (Patra and Baek 2017). The combined antimicrobial chemicals and Ag-NPs have had a greater inhibitory effect and are known for their antifungal property (Khan et al. 2019).

1.3.4 NPs in Management of Pests

Biopesticides have long been praised as a cleaner alternative to chemical pest control, offering a lower risk to humans and the environment. Natural materials are used in their production, such as animals, trees, bacteria and nematodes. Because of their efficacy, target precision, biodegradability, environmental protection and appropriateness of integrated pesticide control (IPM) programmes, biopesticides are gaining popularity. Biopesticides still account for just 2% of all plant protectants used worldwide, despite an upward trend in growth for the last two decades. Agriculture's use of biopesticides is perfectly matched with industry trends that encourage safe eating while still preserving the environment. Residue-free food is becoming increasingly popular among consumers. The most common insect pest control biopesticides are secondary metabolites, including tannins, polyphenols, glycosides, flavonoids and alkaloids. Examples are *Tagetes*, *Acorus*, *Gnidia*, *Argemone*, *Vitex*, *Ocimum*, *Chrysanthemum*, *Annona*, *Calotropis*, *Neem* and *Toddalia* (Singh et al. 2014). Siva and Kumar (2015) grew Ag NPs taken from *Aristolochia indica* leaf extract. Laboratory biosecurity against *Helicoverpa armigera* III instar larvae demonstrated a rise in the larvae efficacy of antifeedant with lower values of (Lethal Concentration) LC_{50} of 84.56 and 309.98 mg mL^{-1} compared with LC_{50} values of 127.49 and 766.54 mg mL^{-1} or crude aqueous extract. In environmentally safe way, silver and plum NPs are synthesised. *Sitophilus oryzae* pesticide operation with a 100% success rate (Sankar and Abideen 2015). Cotton leafworm larvae are completely eradicated when the CuO-NPs are used, such as *Spodoptera littorals* (Shaker et al. 2016). *Callosobruchus maculatus* larva and pupal development are delayed with *Bacillus thuringiensis* coated ZnO NPs. The Bt-ZnO NPs are effective nanopesticides against *C. maculatus*, according to the study (Malaikozhundan et al. 2017). The different types of nanoagrochemicals, along with their applications, are schematised in Fig. 2.

1.3.5 Nanomaterials Utilised in Plant Tissue Culture

Some of the techniques used to remove microbial infections from explants include somatic embryogenesis, callus induction, somaclonal variation, organogenesis, secondary metabolite and genetic transformation enhancement. These are just a few of the applications for NPs in plant tissue culture. It has been demonstrated that adding ZnO-NPs to the MS medium results in cultures being free of infection (Helaly et al. 2014). In a temporary immersion bioreactor method, Ag-NPs (Agrovit) seemed to have potential hermetic effects on the regeneration of *Vanilla planifolia* (Spinoso-Castillo et al. 2017). *Prunella vulgaris* callus proliferation was also improved by Au-NPs and Ag-NPs, either singly or in mix (Faizal et al. 2016). It has been demonstrated that incorporating Ag-NPs into tobacco can help to reduce the harm caused during protoplast isolation by cellulolytic enzymes (Bansod et al. 2015). It has been demonstrated that increasing the quantity of ZnO-NPs in the MS medium causes *Lilium ledebourii* to accumulate more special bioactive compounds (Chamani et al. 2015).

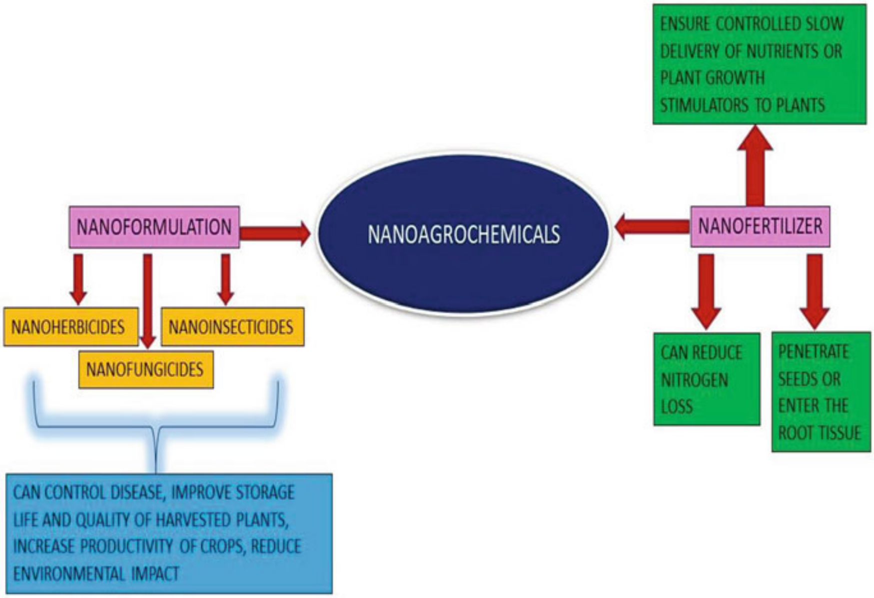

Fig. 2 Types of nanoagrochemicals application

1.3.6 Agricultural Nanotechnologies and Water Recycling

Water is one of the most important and critical elements in agriculture. In agriculture, it is a valuable and expensive commodity. However, the water used for irrigation in most agricultural communities comes from a polluted origin. This contagion could come from any type of waste disposed in the household or in the industry. These infections are detrimental to both the yield and the soil fertility (Fatta-Kassinos et al. 2011). Nanoporous materials, certain membranes and other NMs have recently been used in wastewater treatment as a result of recent nanotechnology implementation (Prasad and Thirugnanasanbandham 2019). The following are some of the approaches that can be used to improve the consistency and protection of water: (1) Biological hazard purification, (2) Pollutant removal and tracking, (3) Wireless nanosensors.

1.3.7 Agricultural Waste Recycling Applications for Nanotechnology

A broad community of researchers is investigating how green technologies can be used to solve current and potential problems. These items must be marketable, ideally and biodegradable. Agricultural waste (AW) can be used to produce green technology-based products (Sangeetha et al. 2017). Over time, the volume of farm waste has increased as a result of the increasing productivity of the agricultural sector. The majority of farm waste is made up of leaves, stems, empty fruit bunches and different plant materials. They contain a lot of lignocellulosic content (Abdul Khalil et al. 2012). Uses have been developed for nanocellulose of cellulosic material derived from industrial waste. In addition to nanocellulose, efforts were made to withdraw noble metals from plant waste for utilisation in medicine supply organisations (Mahal et al. 2013). Au-grape waste NPs are associated with breast cancer cells in humans and are soluble in vitro in cancer inspect (Krishnaswamy et al. 2014).

1.3.8 Nanobiosensor Act as a Biodetector in Soil and Plants

Nanobiosensors are made up of small, transducer-based materials which transmit signals to reconnaissance elements so that a single or multiplex analysed analyte can be detected. These include NMs, QDs, magnetic, carbonaceous and noble metals, signal transduction (electro-chemical, optical and magnetic) and recognition elements (antibodies, aptamers, proteins, and enzymes). Moreover, the recognition elements are further categorised into single analytes metalloids (nutrients, pesticides, soil humidity) and multiplex analytes metalloids (Pb, Hg, Ni, Cr, Cd, Cu, As). These are employed for use for deployment for nanosensor design (microfluidic, optofluidic and substrate/scaffold devices) which is shown in Fig. 3. Fictionalisation, immobilisation and miniaturisation are the intriguing features of nanobiosensors which integrate transduction system biological components into complex architecture to increase NMs' analytical performance (Arduin et al. 2016). The nanobiosensors have an on/off feature, detect analytes in parts per trillion (ppt) and limit the matrix analysed centred on nanoformulation (Antonacci et al. 2018).

The complementary content explains the most commonly used nanobiosensors, their sensing techniques and their use in soil and water systems analysis. Early application of the soil can help prevent adverse effects. Are there considerable health threats due to the concentration of highly toxic metal ions in arable soil and plants beyond thresholds? They are studied using chemical optical sensors that employ electromagnetic radiation as a means of identifying the binding of them with organic immobilised colour in the sample (Gruber et al. 2017). Two popular optical sensors for heavy metal ions in fluvial water or fluorescent soil and superficial dispersal of Raman are improved (SERS) which are designed with biological macromolecules/reduced metal oxides. The use of lightweight nanosensor designs for consumption or commercial use of metal ion detection may be better combined with micro-fluid or paper chip strategy (Ullah et al. 2018).

Urea (most widely used fertiliser for the yield of crops), nitrate, nitrite and urease cause eutrophication and have environmental effects and contaminants in water (Delgadillo-Vargas et al. 2016; Mura et al. 2015). Based on microfluid impedimetric and colorimetric assessments, the detection of these infections in soil and water is done using nanobiosensors. After all, precise and efficient nitrogen compound detection using nanobiosensors offers a spatial and temporal variance in the field of nutrients, allowing for the tracking of their concentration, fertiliser analysis, and

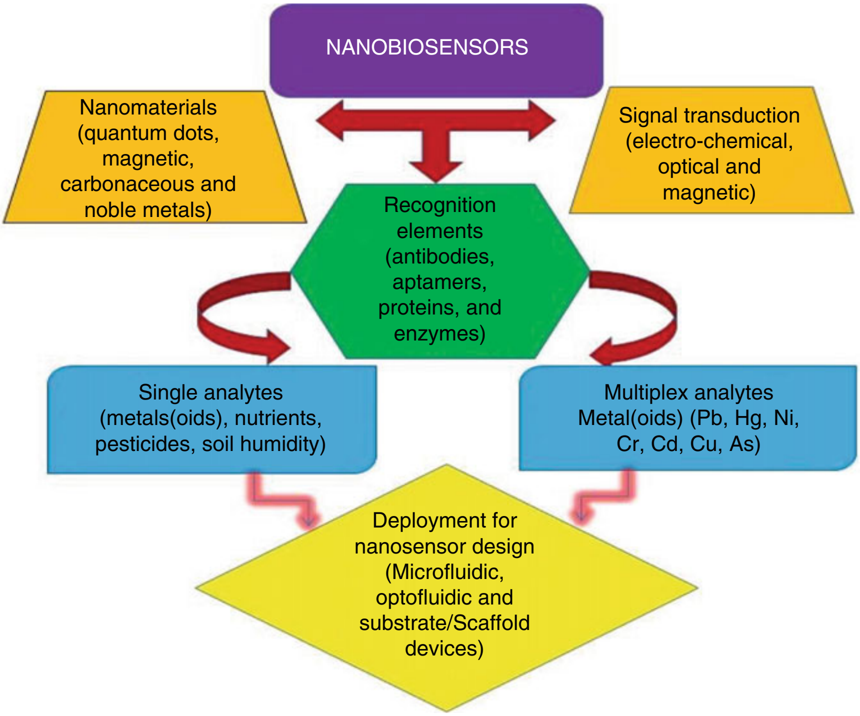

Fig. 3 Types and applications of nanobiosensors

application in smart farming. To calculate the soil's humidity level, nanostructured particles with improved functions such as rapid reaction, sensitivity, stability and the potential to be used repeatedly. Two examples of ceramic-based nanobiosensors with a wide range of sensitivity and reaction include limitable electrodes and graphene oxide (rGO) films for AgPd. By transporting ions and graphene oxide concentration, these sensors take advantage of the attributes of NM and ceramic materials. In inclusion, the NM-based soil quantification biosensor is used for soil analysis in infant stages, and the water solutions for complete organic matter, sodium chloride, organic carbon, residual nitrates and phosphates are restricted only to in vitro conditions (Antonacci et al. 2018). Nanotechnology, known as artificial intelligence technologies and next-generation sensors, has been utilised in robotic nose cones (e-noses). They are widely used in yield field to follow producing methods and plant diseases evaluation, infestation by insects or toxins in soil and water. Although the use of nanotechnologies leads to a new age of intelligent agriculture and minimises associated danger, the widespread use of agricultural and food goods based on NMs and nanosensors that have become less likely to remain in motion has posed concerns about the environment and the health of human beings.

A recent two-year study has shown a useful impact on a microbial and enzymatic community when low levels of nCuO and nZnO (10 mg kg^{-1}) were used (Joko et al. 2017). Denitrification (11-fold increase of NO_3 concentration) was significantly inhibited by another study, and lower levels of nCuO (10 and 100 mg kg^{-1}) would not have a repressive outcome (Zhao et al. 2017). Microbial biomass countervailing results and comfortability of NPs are mostly dictated by the number of NPs applied in the soil. The Ag NPs were found to only harm the activity of microbials by adding a higher dose of Ag to the crop field (Rahmatpour et al. 2017; He et al. 2018). An analytical sensing unit is a biosensor designed exclusively for the evaluation and readability of biological interactions using electromechanical elucidation and transduction. Nanobiosensors containing biofertilisers, including *B. subtilis*, *Pseudomonas fluorescens*, *Rhizobium* sp., *Paenibacillus elgii*, *Azospirillum* sp., and *Azotobacter* sp. encourage crop plant growth under in vitro conditions (Shukla et al. 2015). Enzyme-based electrochemical biosensors were created by mixing enzymatic response and electrochemical methodologies (Vimala et al. 2016). Acetylcholinesterase (AChE) amperometry biosensors are used to detect pesticides and prevent AChE. Xiong et al. (2018) conducted a short report on the advances and issues of organophosphorus pesticide detection in enzyme-functional nanostructure biosensor. A dependable, sensitive, time-saving approach for electrochemical biosensors reduces pre-treatment steps and can be paired with other analytical techniques (Bakirhan et al. 2018). Coal nanotubes (CNTs), which have a particular combination of chemical, electrical, physical and operative properties, can act as scaffolds for the immobilisation of biomolecules on their surfaces, making them suitable for transmitting signals relevant to the study of analytes, biomarkers of disease, or metabolites (Tîlmaciu and Morris 2015). The responsive device of silicon nanofilms (SiNWs) formed by self-assembling (vapour–liquid–solid mechanism) and consistent with the silicon reduction and integration technology of Complementary metal–oxide–semiconductor (CMOS) systems is designed to provide easy and low-cost bacterial sensor supporting hanging bacteria and improving bacterial sensitivities (Borgne et al. 2017). Several fertilisers, herbicides and pesticides may be traced and used in real-time, as well as insecticides, heavy metals, organic contaminants and pathogens (Kumar et al. 2015). Increased pesticide use for various agricultural activities has helped to create breaking sensors to investigate the distinctive chemical and the physical characteristics for pesticide residue detection of NMs. Thus, ‘nanosensors’ are developed for traceability and detection of physicochemical characteristics in otherwise difficult locations and can have higher accuracy, lower limit recognition, selectivity, speed and portability over traditional techniques of identification (Fraceto et al. 2016).

1.3.9 Nanofertilisers Role in Agriculture

Nanofertiliser is a fertiliser made of nanosized molecules coated in a biosensor-coated polymer that releases the particle once the soil is needed. Montreal is the first company to manufacture nanofertilisers successfully. The fertiliser was created by inventing a process for using bacterial enzymes to disassemble the corresponding salts into nanometres. In India, for the first time in the world, a biosynthesis process for producing nanofertiliser was developed for the maintenance of soil-nutrient equilibrium. A nanoparticulate with polymer layer (working as a biosensor) can be used. Types of nanofertiliser are as followed. (a) Nanoporous zeolite, (b) Zinc nanofertilisers, (c) Nanoherbicides, (d) Nanopesticides, (e) Carbon nanotubes, (f) Nanoaptamers and (g) Boron nanofertiliser.

In contrast to chemical fertilisation, nanofertilisers seem to be more convenient. Nanocoating and technologies can assist in several ways to minimise costs and improve efficiency in the form. Soil accumulation, moisture absorption and carbon accumulation are also improved. The word nanotechnology often raises some health and environmental threats and issues. When it comes to danger and protection, only certain places would be pertinent. Initial NM experiments have caused significant risks to health and adverse consequences, even though tissue disruption in the human body affects all essential species.

1.4 Nanopesticides Role in Agriculture

The use of biopesticides is restricted due to their low and environmentally reliant efficacy in the fight against harmful effects of traditional pesticides. Nanopesticides should overcome these disadvantages. Sluggish degradation and controlled release of active substances from suitable NMs will ensure effective pest management for a long period (Chhipa 2017). As a result, nanopesticides are critical for the efficient and healthy management of a variety of pests, and they can help to minimise the use of traditional chemicals and the related environmental risks. To increase their effectiveness, nanopesticides are significantly more effective than traditional pesticides (Kah et al. 2019). Because AI solubility is improved by NPs, the environmental effects are considered to be smaller than conventional insecticides (Kah and Hofmann 2014).

Nanopesticides are not used so much as frequently as regular pesticides. They save money. Their output and lower costs of input by reducing waste and labour often increase pesticide productivity and seed quality. After all, for many reasons, nanopesticides (Ragaei and Sabry 2014) can cause health problems, including those reported by the EPA, the USA as follows:

1. Owing to their incredibly small size, dermal absorption of nanopesticides can pass through cell membranes.
2. By inhaling, they fully go into the lungs and pass to the brain via the blood–brain barrier.
3. The longevity and reactive capacity of certain NMs pose environmental issues and

4. The lack of awareness to quantify the exposure of the atmosphere in engineered NMs.

The findings are reassuring in terms of the staggered extraction of bioactive compounds from numerous crop pests and are valuable instruments for future activities to monitor agricultural pesticides. In recent years, nanosilica has been shown to be effective against insect pests in grain-based outcomes (Gamal 2018). Hashem et al. (2018) have illustrated the red beetle oil (*Tribolium castaneum*) as being of increased strength and stability and concluded that nanoemulsions would mitigate the use of possibly hazardous artificial pesticides to combat insect pests. Weeds are increasingly threatened by urban cultural agriculture. Most nanoherbicides have biodegradable polymers and herbicides' efficacy can be strengthened. Atrazine is depicted by Poly (*ε-caprolactone*), for instance, because of its good physicochemical properties, improved bioavailability and biocompatibility (Abigail and Chidambaram 2017). An analysis of atrazine Foliar's involvement in nanoformulation (*Brassica juncea* L. *Czern.*) plant showed an herbicide-specific interaction through to the leaves' vascular tissues (Bombo et al. 2019). This resulted in a good ability to maintain low herbicide activity concentrations and greatly increase herbicide performance. Similarly, the sleek amaranth (*Amaranthus viridis* L.) was more popular than the hairy beggarticks (*Bidens pilosa* L.) (Sousa et al. 2018). Nanoformulations are thus generated as effective nanoherbicides for treating weeds as depicted in Fig. 4. Herbicides encapsulated in poly (*ε-caprolactone*) are less toxic to *Pseudokirchneriella subcapitata* and *Prochilodus lineatus* than herbicides alone, but they are more toxic to *Daphnia* species (De Andrade et al. 2019). Stringent approaches to risk analysis of nanoparts can be used to characterise the positive forms of molecular and cellular nanopesticides focused on these threats and other studies of NPs (Pandey et al. 2018; Diez-Ortiz et al. 2015; Tiwari et al. 2020).

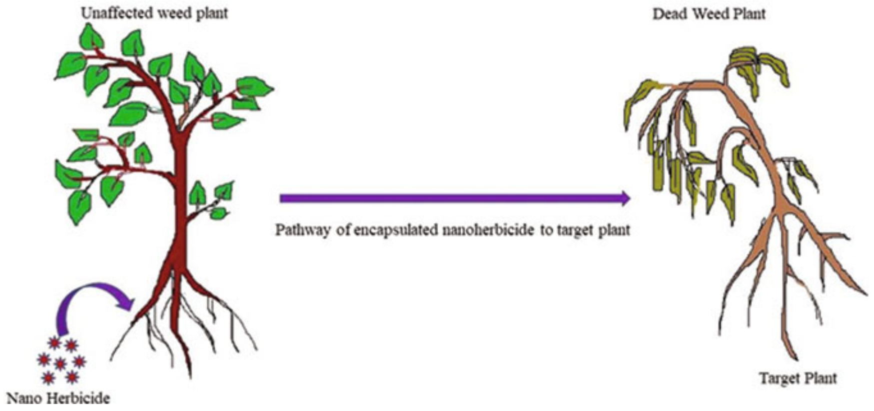

Fig. 4 Effects of nanoherbicides on weed plants

2 NPs-Mediated Gene Delivery

The plant cell wall, which renders genetic manipulation even more elusive in plants than in animal cells, is another major impediment to replacing plants with new and improved traits. Gene of interest transfer in plants can manifest in many ways, along with agrobacterium-mediated transformation, electroporation and biolistic particle transfer (Rivera et al. 2012). While efficient in a variety of plants, these methods possess disadvantages such as reduced plant species productivity, irreversible damage to target tissues and other issues. Tissue culture requires regeneration, which is labour-intensive, as well as the unwelcomed alien genome (Joldersma and Liu 2018). It has a wider range of agricultural research applications, including the use of nanocides to treat plant diseases, enzymatic nanobioprocessing to generate energy from AW, and as a possible gene carrier. NPs, nanofibres and nanocapsules are among the instruments available for gene manipulation (Wang et al. 2016). Methods of gene transmission mediated by NPs have many advantages for transgenic plant development, including passive biomolecule delivery to plants, which is beneficial because it is a minimally invasive, species-independent process, and it allows for plants that have been genetically altered in vivo (Cunningham et al. 2018). Kámán-Tóth et al. (2018) recently developed *Agrobacterium tumefaciens* electroporation which was performed on a direct overnight-grown culture plate and also found to be easy and efficient, minimising the probability of cell injury during the processing of *A. tumefaciens* cells, reducing the number of washing measures and removing the need for a shaking incubator. The observational study of centrophenoxine on *T. aestivum* L. is remarkable, a drug-derived compound that selectively stimulates auxin synthesis and removes the highly corrosive product 2,4-D (Ismagul et al. 2018). By combining the cotton worm's *chitinase* gene with cells bombarded on maize cells, Osman et al. (2015) were able to establish an insecticide-resistant maize plant that was resistant to *Sesamia cretica*, the corn borer. The potential for transformation using biolistic approaches is limitless. A reporter gene, egfp was found in a seasonal liana, *Tripterygium wilfordii* delivered by particle delivery system (PDS)/ 1000 and had been modified often with hygromycin. The size of the particles, the amount of plasmid DNA used, the helium strain used, and the distance from the cell at which the particles are bombarded are all factors in obtaining high-efficiency (19.17%) transformants (Zhou et al. 2018). They have a higher surface-area-to-volume ratio due to their small size. NP-mediated carrier systems are one of the most significant uses, and due to their unique optical properties, they are still the most popular route for delivering biomolecules, particularly genes, into the host (Karimi et al. 2016). In *alfalfa* plants, Amani et al. (2018) used positively charged polyamidoamine (hPAMAM dendrimer) NMs in combination with transgenic using ultrasound and identified them as genetically transformed plant cells using the *GUS* reporter gene.

3 NPs Identified Environmental Pollutants and Remedy Nanotechnology

On our developed planet, responsive identification and successful elimination of a growing array of chronic and evolving environmental contaminants face significant challenges (Liu et al. 2011). Onsite installations can include sensors, diagnostic and remediation instruments that allow close monitoring of environmental factors. As a result, plant growth and safety, as well as agricultural production, are improved and agrochemicals are decreased in precision agricultural terms. NMs are versatile products in general environmental contamination, identification and remediation techniques. Environmental contamination is one of the world's biggest issues (Das et al. 2015a, b). It is possible that chemical compounds of either natural or anthropogenic origin have polluted the soil and groundwater in sufficient quantities to pose a significant health or climate risk (Thomé et al. 2015). In nanotechnology, these environmental issues relating to soil and water conservation are seen as potentially sustainable solutions. New cost-efficient ways of eliminating soil contaminants like heavy metal/metalloids, dyes and organic pollutants can be contributed by a technique based on nanotechnology, as well as for the treatment of sewage and wastewater. Heavy metal ions and organic molecules have also been removed using metal oxide NPs. Due to its redox cycle, ion exchange, high contaminant affinity and magnetism, iron oxides have already been frequently used as potential adsorbents in the atmospheric. One of the iron oxides (Fe_2O_3), Magnetite (Fe_3O_4), is used for the adsorption of pollutants (Adeleye et al. 2016). Magnetic oxides can be removed via aqueous phase easily after extracting the pollutants, which renders the cleaning process more economical. Bimetallic nanostructures, that is, Pd/Fe, Ag-Fe and Ni-Fe, have finally been formed to solve NP agglomerations with carboxymethyl cellulose, polymers and surfactants stabilised. And hence, these structures have been studied for their right to eliminate and dissolve heavy metals, dyes and halogenated compounds effectively (Li et al. 2016). Heavy metals, especially plumes (Pb^{2+}) and Cd^{2+}, can be irradiated using (Al_2O_3/TiO_2) nanocomposite with brittle Ti silicate (Das et al. 2015a, b).

4 NPs-Mediated Improved Food Quality and Safety

4.1 Nanoemulsions

Nanoemulsions are composed primarily of three main ingredients: a surfactant/emulsifying agent, as well as water and oil. The emulsifier is crucial because it helps not only to bind the ingredients together but also to prevent them from sticking together and reduces the amount of surface energy (interface tension) between the oil and water phases per unit area and also helps the oil and water phases mix better. However, repulsive electrostatic interactions and steric obstacles help to stabilise the nanoemulsion. Nanoemulsions have grown in popularity in recent years as a result of their wide range of applications in various industries. Because of their wide surface area, nanosized emulsions have a major advantage in terms of bioavailability. They can also serve as protective barriers for bioactive materials encapsulated in aqueous media and help lipophilic compounds dissolve better. Nanoemulsions can be divided into three categories: (1) Oil-in-water emulsions (O/W) are a form of an emulsion that combines oil and water, (2) W/O emulsions (water-in-oil) and (3) Nanoemulsions that are bi-continuous. An oregano oil-based nanoemulsion will adequately protect lettuce from *E. coli*, *Salmonella typhimurium* and *Listeria monocytogenes*, according to research (Bhargava et al. 2015). Landry et al. (2015) used carvacrol nanoemulsion to demonstrate the protection of broccoli and radish seed. Mung bean and alfalfa seeds were also protected from the food pathogenic microbes. *E. coli* and *S. typhimurium* are belong to coliform type of bacteria (Landry et al. 2014). In another study on plums, a lemongrass oil-based nanoemulsion was found to protect against *E. coli* and *S. typhimurium* (Kim et al. 2013). A lemongrass nanoemulsion-enhanced sodium alginate film was found to inhibit *E. coli* in one study while also expanding the apple's self-life (Prakash et al. 2018). Biofilm formation is inhibited by a variety of simple oil-based nanoemulsions. Quatrin et al. (2017) demonstrated that *Eucalyptus globulus* essential oil nanoemulsion has been shown to have antifungal properties. It was discovered that essential oil extracted from *Citrus medica* L. var. sarcodactylis supplemented with nanoemulsions were effective against *Staphylococcus aureus* biofilm. Cumin oil nanoemulsion had a similar inhibitory effect on *E. coli* biofilm production and *S. aureus* (Amrutha et al. 2017). When compared to their free form, the anti-biofilm behaviour of essential oils was found to be improved in nanoemulsions (Lou et al. 2017). Two of the primary goals of using nanoemulsions in the food industry are encirclement and distribution of a biologically active substance. In the food industry, nanoemulsions can be used to replace foods with low water solubility, such as-carotene (Gupta et al. 2016). Many experiments have shown that nanoemulsions facilitate the absorption of many encapsulated food supplements. A nanoemulsion of curcumin, in comparison to curcumin in its free form, was simple and fast to absorb (Gupta et al. 2016).

4.2 Nanosensors-Mediated Food Safety

A sensor is a compound device that can react qualitatively or quantitatively to a target. Tiny inorganic molecules, gases, or biomolecules may all be considered physical parameters such as protein; DNA or even full cells may be the target. A biosensor is two different structures comprising a biological substance called a receptor as well as another transducer array. The certain biochemical product inherent resemblance to a generic individual can be a receptor inside a biosensor. The biosensors can be divided, focusing upon the number of atoms utilised, into (a) biosensors based on enzymes, (b) biosensors based on an antibody (immunosensors), (c) aptameric biosensors (aptasensors), (d) peptide-dependent biosensors, (e) natural biosensor premised on receptors and (f) gene-related biosensors (genosensors). In anticipation of health issues, especially in third-world countries, detecting water or food is becoming essential for controlling contaminants. Regrettably, effluent outflow into the atmosphere is currently unregulated. Nanosensors, which range from small molecules to large molecules, open up a modern perspective of pathogen observation and recognition such as poisons, therapeutics and vaccines, heavy metals, biologically active viruses, fungi and bacteria, and organic and volatile compounds. The studies and feedback from scientists all over the world have been extremely beneficial in the diagnosis, nutritional screening and toxin-free ecosystem. Several biosensing techniques to examine the specific physical and chemical properties of NMs have been established, and their ability has improved in both the laboratory and field with the addition of excellent stable receptors of high affinity. The following section recaptures the various forms of pollutants found using different nanotechnologies.

4.2.1 Chemical Contaminant Nanosensors

Synthetic contaminants and substance contamination in the wild is one of the major food and environmental problems in the world. Pesticides, herbicides and insecticides are sources of heavy metal contaminants through industrial anabolic practices, because of unsustainable cultivation and medical overuse of antibiotics and medicines (FAO 2016). Aldehydes, for example, are used as nanosensors (Duan et al. 2019) Biphenyls, hydrazine (Teymoori et al. 2018), hydroquinone (Ren et al. 2018), phenols and derivatives of organic toxic compounds (Ren et al. 2018; Wang et al. 2018; Jigyasa and Rajput 2018), chloropropane (Fang et al. 2019) and 2,4,6-trinitrotoluene (Malik et al. 2019).

4.2.2 Biological Contaminant Nanosensors

Infections of living organisms include disease-causing species like bacteria, viruses and fungi found in raw fruits, vegetables and meat. These pathogens may enter nutrition with drinkable water by faecal pollution, soil contamination, or pests. Bad handling practices can allow these to reach even canned or packaged foods. Numerous factors have been described for combating pathogenic bacteria via its enterotoxins, and they are now being used to detect bacteria as small as single cells. *Salmonella* sp. (Zou et al. 2019), *Escherichia* sp. (Kaur et al. 2017) and *Pseudomonas* sp. (Kaur et al. 2017) are the most common pathogens (Hu et al. 2019).

5 NMs Impact on Soil/Plant System

5.1 *Impact of Soil Organic NMs*

In modern agriculture, the use of nanotechnology may also have important implications for soil organic matter (SOM) dynamics. However, these impacts can vary according to the quality of the SOM because they can either be hydrophilic or hydrophobic and, because of their biochemical variations, their decomposition in the soil is distinct (Grillo et al. 2015). According to latest research, the mechanics of SOMs are impacted differently depending upon soil properties, test conditions and ENM dosage utilised for the investigations (Rahmatpour et al. 2017; Schlich and Hund-Rinke 2015; Shi et al. 2018). The use of low dose Ag NPs has no major influence on the nature of SOM (Rahmatpour et al. 2017).

Instead, the stabilisation of SOM by the combination of humic molecules using covalent bonds helped other kinds of metal oxides, including TiO_2 NPs, too (Nuzzo et al. 2016). Because of their HS-complexity, Simonin et al. (2015) showed that TiO_2 NPs have no effect on microbial SOM dynamics in most cases; however, they can reduce SOMs by improving their stability. The use of ZnO NPs has reduced the efficiency of littered biodegradation of organic carbon by upto 13% as microbial activities have decreased (Rashid et al. 2017b). Another study found that using Fe_2O_3 NPs reduced CO_2 emissions by upto 30%, demonstrating that the use of nanomaterials in the soil causes fewer SOM to break down (Rashid et al. 2017a). The NMs will protect the environment by releasing CO_2 into the atmosphere through organic emissions, which will help to reduce global warming. Higher CuO concentrations have been linked to lower SOM content in paddy soils, according to Shi et al. (2018).

5.2 *Impact of Nanomaterials on Soil Microbes*

In comparison to organic NPs, inorganic NPs (silver and metal oxides) have high toxicity, fullerenes and carbon nanotubes since the microbial activity and NP exposure and function vary greatly depending on their type (Rajput et al. 2018; Simonin and Richaume 2015). Gram^{-}ve bacteria, since their cell wall composition is distinct, are also less susceptible to ENM than Gram^{+}ve bacteria (McKee and Filser 2016). The NPs on carbon-based substances were severely affected in C and N cycles by the efficient genes and pathway microbial soil community (Archaea, Bacteria and Eukarya), but S and P cycles are less vulnerable (Wu et al. 2020).

Another analysis found that the soils in microsome were exposed for over 60-days to various doses of the TiO_2 and ZnO NPs, suggesting the reduction of MBC and a negative effect on induced substrate respiration, demonstrating lower microbial activity. In the meantime, the bacterial soil population changed and diversity decreased as a result of these enzymatic NMs (Ge et al. 2011). Similarly, the number of MBC, heterotrophic bacteria and fungi units forming ZnO and Fe_2O_3 NPs has decreased significantly (Rashid et al. 2017a, b). Tong et al. (2016) record marginal effect on MBC and their enzyme activity of C60 NMs of various particle sizes.

Now many NPs (ZnO, Ag, TiO_2, Al_2O_3, CuO, etc.) have a detrimental effect on soil bacterial diversity, as per findings, while Si, Fe, Au, Pb and Ag_2S have either no effect or maybe just mild impact on NP studies (Suresh 2013; Simonin and Richaume 2015; Rajput et al. 2020). Since these consequences are not inherently harmful and may be nonspecific, it is important to take into account the dosage, scale, form and characteristics of NPs and the soil when examining these particles' reactions with regard to the soil ecosystem.

Microbes in the soil can be negatively affected by nanomaterials. The hazard of NPs affects their structure, dosage, concentration and nature, as well as humidity in the soil (Peng et al. 2020; Chen et al. 2019). When NMs reach a certain concentration, they can prevent the growth of certain soil microbes. This has a significant effect on the microbial biomass and population (Kang et al. 2019; Peng et al. 2020). Biogenic NMs have currently been found to be less harmful to soil microbials than their chemically synthesised counterparts and, as a result, they've been promoted as a way to combat intoxication of NPs in soils (Ottoni et al. 2020; Mishra et al. 2020). Given the paucity of data pertaining to biogenic NMs in soils, more research is needed to fully understand their potential.

5.3 Plants Containing NMs

5.3.1 Mechanism for Uptake and Translocation

The pre-optimised application of NPs enhances the germination, stand establishment, growing and development of seeds in several plant species. In addition, NPs convey tolerance to environmental stresses in trees because of the utterance of genes that are resistant to stress (Van Aken 2015) and proteins (Giraldo et al. 2014). The below lines addressed the absorption as well as translocation. NMs in the plant system also define their effect on plant morphology and physiology.

Via a complex chain of events, NPs entering the xylem (vessel), stele and eventually reaching the leaves infiltrate the root epidermis into its cell membrane and cell wall (Tripathi et al. 2017). NPs are integrated into the root zone of plants through apoplastic and/or symplastic pathways and mediated by endocytosis, pore formation, carrier proteins, and plasmodesmata are depicted in Fig. 5. Designed NPs are carried out by numerous lateral root hairs from soil to plant vascular system. The NPs along with water and food particles are transferred to the capillary vascular system of the roots. The NPs are also uptaken by leaves through its different foliar entry by cuticle, stomata, hydathodes, lenticels, wounds and root entry by root tips,

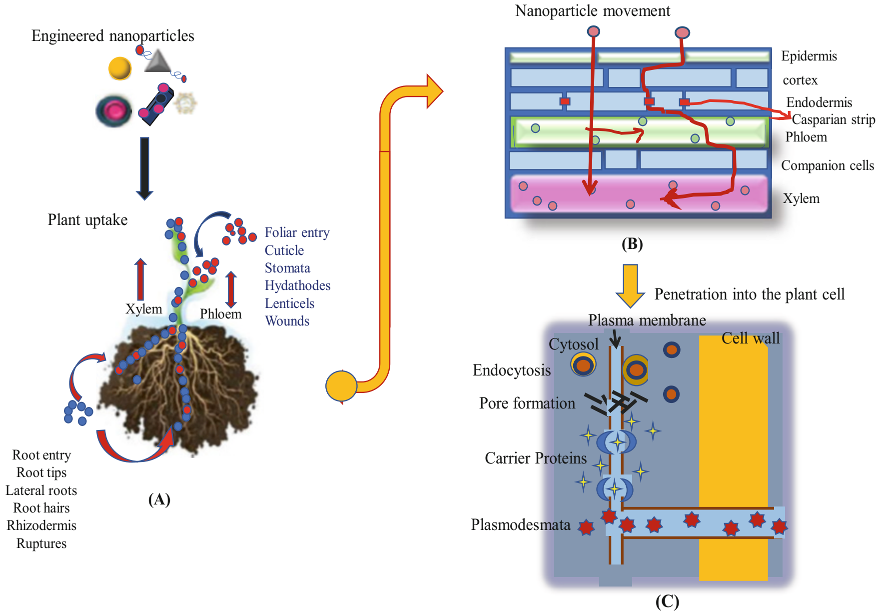

Fig. 5 NPs' uptake and translocation in vascular plants. (**a**) Translocation in whole plant via root to leaves. (**b**) Translocation in tissue by apoplastic and symplastic. (**c**) Transportation in cellular level through plasma membrane

lateral roots, root hairs, rhizodermis and ruptures (Fig. 5a). The NPs penetrate the plant cell; they can be transferred from one cell to another via apoplastic or symplast via plasmodesmata (Fig. 5b). By confining to the carrying proteins, new pores from NMs enter the plant cell via ion channels, aquaporin and endocytosis (Fig. 5c) (Kurepa et al. 2010). NPs entering a cell wall rely on the cell wall's pore size, and smaller NPs quickly move via the cellular wall (Fleischer et al. 1999). Larger NPs, on the other hand, penetrate the stomata and hydathodes (Hossain et al. 2016). NPs are transported utilising pores of the stomata when the particles are 40 nm or larger. Rather than a vascular bundle, these NPs are constructed in storms and are transferred through the phloem to various sections (Tripathi et al. 2017). The NPs join seed coating via parenchymatic intercellular spaces. After all, the fullerene NPs stormed energy pathways and electron transportation (Hossain et al. 2016). The utilisation of NPs has improved the regulation of several genes, such as genes related to stresses and waterways (Tripathi et al. 2017). The *NtLRX1*, *NNtPIP1* and *CycB* genes, which are answerable for transfer of water, cell and cell division task, respectively, were upgraded with the use of MWCNTs (Khodakovskaya et al. 2012). However, at elevated concentrations, technologies can be disruptive. For example, CeO_2 NPs (2000 and 4000 mg) aquaporins regulate the entrance of NPs into the seed coat.

5.3.2 NM Influence on Plants

When NMs have interacted with plants, a variety of morphological modifications occur in plants, based on their concentration and existence (Siddiqui et al. 2015). Consequently, NMs have a beneficial or phytotoxic effect on plants (Siddiqui et al. 2015; Aslani et al. 2014).

Germination, biomass, sheet volume and root elongation are the primary effects of NP toxicity on plant physiological characteristics. NPs can reduce germs, lengthen plants and stimulate the demise of plants (Yang et al. 2017). NPs can reduce germs, photosynthetic rate (Barhoumi et al. 2015), plant growth hormone (Rui et al. 2016) and also cause slow development, changes of sub-cellular metabolism, oxidation to cell membranes (Noori et al. 2020), chromosomal anomalies (Raskar and Laware 2014), water translocation disruption (Martínez-Fernández et al. 2016), alteration of gene transcription pattern (García-Sánchez et al. 2015), and finally, stimulate the demise of plants (Yang et al. 2017). Plant cells and NPs communicate to augment plant gene interpretation and relevant biological routes which then affect plant proliferation and efficiency (Moreno-Olivas et al. 2014). The contacts between plants and NPs can lead to improved plant growth and development expression as well as biological pathways (Moreno-Olivas et al. 2014). They had documented compromising the use of NPs of TiO_2 genomic DNA. Transcriptomic research has shown that the toxicity of NPs disturbed the link between gene regulation upwards and downwards in higher seedlings (Landa et al. 2015). Exposure of the individual wall-mounted carbon nanotubes to *SLR1* and *RTCS* genes in maize was controlled.

5.3.3 NPs Act as Defensing Molecules

The plants species are confronted to metal NPs induce oxidative disruption that leads to the development and activation of the reactive oxygen species (ROS) and antioxidant defence system (Rico et al. 2015). Ascorbate peroxidase (APX), superoxide dismutase (SOD), catalase (CAT), glutathione reductase (GR), guaiacol peroxidase (GPX), and other enzymes and non-enzymatic antioxidants such as glutathione (GSH), ascorbates (ASC), thiols(-SH-) and phenolics furnish antioxidant defensive strategy (Rico et al. 2015; Singh and Lee 2016). The catalysis of superoxide dismutase is used to disperse anion superoxide into hydrogen peroxide (Rico et al. 2015). ROS and hydrogen peroxides have the potential to be used in oxide dismutation. Consequently, these generated ROS radicles can serve as a signalling molecule in activating the plant antioxidant system to decontaminate the free radicles since the application of TiO_2 NPs can trigger photocytotoxicity owing to ROS development (Yin et al. 2012). H_2O_2 to H_2O is reduced by the APX produced by NM ROS (Rico et al. 2015). Plants produced a potential oxidative stress antioxidant attributable to NPs (Wei and Wang 2013). CAT induced in nFe_3O_4, $nCeO_2$, $nMnO_2$ and nAu causes GPX, while $nCeO_2$, and nPt complement SOD. SOD stimulates antioxidant enzymes (Tripathi et al. 2017). In spinach, the application of nTiO_2 raised SOD, CAT, APX and GPX. Song et al. (2012) have also documented improved GPX, SOD, and CAT activities. The use of low concentrations (200 mg mL^{-1}), TiO_2, of NPs improved the peroxidase (POD), CAT, SOD, chlorophyll, and malondialdehyde (MDA) of the superoxide by eliminating the ROS and TiO_2 NPs-caused cell membrane disturbance at high concentrations (500 mg mL^{-1}).

5.4 Formation of Soil Structure

The Earth's ecological balance is also most important, and the chemical and biological melting of rocks generates soil, which is a valuable nonrenewable component. The nucleus of a diverse microflora is soil (bacteria, fungi and actinomycetes). It comprises both advantageous and adverse microbes and accounts for approximately up to 75–90% of the biomass in soil. NPs penetrate the natural world by many processes, including the use of NPs, the disposal of nano-related products and urban water smudges that produce NPs (Tolaymat et al. 2017). NPs are both locally produced and engineered in the soil world. In situ, NPs are soil colloids; small and granular fragments which aren't in the nanoscale range play an important role in soil transformation due to cation changes and particle alignment. In addition, weathering allows the creation of NPs, as well as of amorphous rocks, such as Fe and mineral oxides, as a result of soil erosion. The most important man-made sources of NPs are metal oxides (ZnO, CuO, SiO_2) and metal (Zn, Fe, Al, Ag, Ni, Si) (fullerene). Metal NPs, for instance, have been frequently employed and investigated by numerous investigators in connection to microbial diversity and its activities in soil (You et al. 2017).

6 Future Prospects of Nanotechnology

In this part, we have seen the different fields of application of nanotechnology. Nanotechnology may be used in precision agriculture; waste reduction and contamination; improving the use of services such as water, fertilisers and pesticides; and many more. With the advancement of years and new knowledge is incorporated into the world of nanotechnology, the fields where NMs can be used in agriculture can be extended further. The scope of use of the current materials will be improved over the years. The above limitations should then be addressed. As these issues remain unanswered, this technology is being impaired in the agribusiness.

The fields for the use of nanotechnology in the agro-industry are the following:

1. Terms of planning supply systems to be used in fertilisers, pesticides and herbicides application.

2. Nanosensors, which can be used in smart farming through efficient use of water, fertilisers, nutrients, herbicides, etc.
3. Biopolymers in the nanoscale that may be used for disinfecting and neutralising heavy metals and pollutants.
4. To meet the need for a stable and improved efficiency, researchers must examine the synthesis of improved NMs in the areas of configuration, interface chemistry scale and posology, human and environmental aspects.
5. Foodstuffs should be packaged and stored in a smarter way to strengthen their shelf life and product consistency.

In many areas, nanotechnology is in its prime stage; seeing all this modern advancement, it makes clear that it has a wide spectrum, and there will be objections and disapproval towards any new technology in this area, overcoming all of its myths and ethics in its own right. This invention would aid generations of foodstuffs and not just one. Instead of knowing the advantages and efficiency of technology, we are mindful that few activities are at risk. Nanotechnologies in agriculture provide traditional agricultural methods with new resources such as nanofertilisers, nanopesticides and nanosensors.

7 Constraints

Although nanotechnology may be the solution to many of these problems in agriculture to date, more study is also required to solve public and policymakers' questions about the human, ecology and environmental impact of such materials.

Some of the major issues affecting the use of nanotechnology in the farming manufacturing industry are as follows:

- Interactions between non-targets: these NPs can also interfere with non-target cells or surfaces. For example, if NPs are used to treat non-target organisms or even other compounds as an antimicrobial agent, particles may be used in certain cases, with unintentional results (Chaudhary 2017).
- Effects on the air and humans: While there is continuing analysis into the manufacture of new NPs in different sectors, there is insufficient study of the effects of NPs on humans and the climate. However, Mukhopadhyay (2014) said nanotechnology is the way forward because of its enormous ability to be used by the farming sector.
- Cost effect: While this technology is innovative, it is not a cost-effective approach that all farming nations can adopt. Government and Industry sectors have inadequate funding that could restrict the use of this technology. There is also limited funding needed for research in this area.
- Rising awareness: There is a lack of awareness of the application among the general public and policymakers, as well as information on the protection and positive effects of using this programme.

- Regulations concerning ethics: As this is a modern agri-industry medium, legislation must be developed to ensure the observance of all safety protocols and the proper labelling of NM products. Any of the above constraints will prohibit or hinder the use of this technology in the agro-industry.

References

Abdel-Aziz HMM, Hasaneen MNA, Omer AM (2016) Nano chitosan-NPK fertilizer enhances the growth and productivity of wheat plants grown in sandy soil. Span J Agric Res 14:e0902

Abdul Khalil HPS, Bhat AH, Ireana Yusra AF (2012) Green composites from sustainable cellulose nanofibrils: a review. Carbohydr Polym 87:963–979

Abigail EA, Chidambaram R (2017) Nanotechnology in herbicide resistance. Nanostructured materials: fabrication to applications. IntechOpen, Rijeka, pp 207–212

Abigail MEA, Melvin Samuel S, Chidambaram R (2016) Application of rice husk nano-sorbents containing 2,4-dichlorophenoxyacetic acid herbicide to control weeds and reduce leaching from soil. J Taiwan Inst Chem Eng 63:318–326

Adeleye AS, Conway JR, Garner K, Huang Y, Su Y, Keller AA (2016) Engineered nanomaterials for water treatment and remediation: costs, benefits, and applicability. Chem Eng J 286:640–662

Akbari A, Wu J (2016) Cruciferin coating improves the stability of chitosan nanoparticles at low pH. J Mater Chem B 4(29):4988–5001

Alaqad K, Saleh TA (2016) Gold and silver nanoparticles: synthesis methods, characterization routes and applications towards drugs. J Environ Anal Toxicol 6(384):2161–0525

Aljabali AA, Akkam Y, Al Zoubi MS, Al-Batayneh KM, Al-Trad B, Abo Alrob O, Alkilany AM, Benamara M, Evans DJ (2018) Synthesis of gold nanoparticles using leaf extract of *Ziziphus zizyphus* and their antimicrobial activity. Nano 3:174

Alsaeedi A, El-Ramady H, Alshaal T, El-Garawani M, Elhawat N, Al-Otaibi A (2018) Exogenous nanosilica improves germination and growth of cucumber by maintaining K^+/Na^+ ratio under elevated Na^+ stress. Plant Physiol Biochem 125:164–171

Amani A, Zare N, Asadi A et al (2018) Ultrasound-enhanced gene delivery to alfalfa cells by hPAMAM dendrimer nanoparticles. Turk J Biol 42(1):63–75

Amrutha B, Sundar K, Shetty PH (2017) Spice oil nanoemulsions: potential natural inhibitors against pathogenic *E. coli* and *Salmonella* spp. from fresh fruits and vegetables. LWT- Food Sci Technol 79:52–159

Anderson JA, Gipmans M, Hurst S, Layton R, Nehra N, Pickett J, Tripathi L (2016) Emerging agricultural biotechnologies for sustainable agriculture and food security. J Agric Food Chem 64(2):383–393

Antonacci A, Arduini F, Moscone D, Palleschi G, Scognamiglio V (2018) Nanostructured (bio) sensors for smart agriculture. TrAC Trends Anal Chem 98:95–103

Aravinthan A, Govarthanan M, Selvam K, Praburaman L, Selvankumar T, Balamurugan R, Kim JH (2015) Sunroot mediated synthesis and characterization of silver nanoparticles and evaluation of its antibacterial and rat splenocyte cytotoxic effects. Int J Nanomedicine 10:1977–1983

Arciniegas-Grijalba PA, Patiño-Portela MC, Mosquera-Sánchez LP, Guerrero-Vargas JA, Rodríguez-Páez JE (2017) ZnO nanoparticles (ZnO-NPs) and their antifungal activity against coffee fungus Erythricium salmonicolor. Appl Nanosci 7(5):225–241

Arduin F, Cinti S, Scognamiglio V, Moscone D (2016) Nanomaterials in electrochemical biosensors for pesticide detection: advances and challenges in food analysis. Microchim Acta 183(7):2063–2083

Aslani F, Bagheri S, Muhd Julkapli N, Juraimi AS, Hashemi FS, Baghdadi A (2014) Effects of engineered nanomaterials on plants growth: an overview. Sci World J 2014:641759

Bakirhan NK, Uslu B, Ozkan SA (2018) Chapter 5: The detection of pesticide in foods using electrochemical sensors. In: Food safety and preservation, modern biological approaches to improving consumer health. Academic, London, pp 91–141

Bansod S, Bawskar M, Rai M (2015) *In vitro* effect of biogenic silver nanoparticles on sterilisation of tobacco leaf explants and for higher yield of protoplasts. IET Nanobiotechnol 9:239–245

Barhoumi L, Oukarroum A, Taher LB, Smiri LS, Abdelmelek H, Dewez D (2015) Effects of superparamagnetic iron oxide nanoparticles on photosynthesis and growth of the aquatic plant *Lemna gibba*. Arch Environ Contam Toxicol 68(3):510–520

Bhargava K, Conti DS, da Rocha SR, Zhang Y (2015) Application of an oregano oil nanoemulsion to the control of foodborne bacteria on fresh lettuce. Food Microbiol 47:69–73

Bombo AB, Pereira AES, Lusa MG, de Medeiros Oliveira E, de Oliveira JL, Campus EVR, Mayer JLS (2019) A mechanistic view of interactions of a nanoherbicide with target organism. J Agric Food Chem 67(16):4453–4462

Borgne BL, Salaun AC, Pichon L, Jolivet-Gougeon A, Martin S, Roge R, Sagazan O (2017) Silicon nanowires based resistors for bacteria detection. PRO 496:1–4

Bramhanwade K, Shende S, Bonde S, Gade A, Rai M (2016) Fungicidal activity of Cu nanoparticles against *Fusarium* causing crop diseases. Environ Chem Lett 14(2):229–235

Bulovic V, Mandell A, Perlman A (2007) U.S. Patent No. 7,157,750. Washington, DC: U.S. Patent and Trademark Office

Chamani E, Ghalehtaki SK, Mohebodini M, Ghanbri A (2015) Iran J Genet Plant Breed 4:11–19

Chaudhary M (2017) Nanotechnology: resource management for sustainable agriculture. Ind Res J Genet Biotechnol 9:310–313

Chen M, Sun Y, Liang J, Zeng GL, Tang L, Song B (2019) Understanding the influence of carbon nanomaterials on microbial communities. Environ Int 126:690–698

Chhipa H (2017) Nanofertilizers and nanopesticides for agriculture. Environ Chem Lett 15(1): 15–22

Cunningham FJ, Goh NS, Demirer GS et al (2018) Nanoparticle-mediated delivery towards advancing plant genetic engineering. Trends Biotechnol 36(9):882–897

Das S, Sen B, Debnath N (2015a) Recent trends in nanomaterials applications in environmental monitoring and remediation. Environ Sci Pollut Res 22(23):18333–18344

Das S, Wolfson BP, Tetard L, Tharkur J, Bazata J, Santra S (2015b) Effect of N-acetyl cysteine coated CdS: Mn/ZnS quantum dots on seed germination and seedling growth of snow pea (*Pisum sativum* L.): imaging and spectroscopic studies. Environ Sci Nano 2(2):203–212

Day L, Williams RPW, Otter D, Augustin MA (2015) Casein polymorphism heterogeneity influences casein micelle size in milk of individual cows. J Dairy Sci 98(6):3633–3644

De Andrade LL, Santo Pereira ADE, Fraceto LF, Dos Reis Martinez CB (2019) Can atrazine loaded nanocapsules reduce the toxic effects of this herbicide on the fish *Prochilodus lineatus*? A multibiomarker approach. Sci Total Environ 663:548–559

Delgadillo-Vargas O, Garcia-Ruiz R, Forero-Álvarez J (2016) Fertilising techniques and nutrient balances in the agriculture industrialization transition: the case of sugarcane in the Cauca river valley (Colombia), 1943–2010. Agric Ecosyst Environ 218:150–162

Derbalah A, Shenashen M, Hamza A, Mohamed A, El Safty S (2018) Antifungal activity of fabricated mesoporous silica nanoparticles against early blight of tomato. Egypt J Basic Appl Sci 5:145–150

DeRosa MC, Monreal C, Schnitzer M, Walsh R, Sultan Y (2010) Nanotechnology in fertilizers. Nat Nanotechnol 5(2):91

Diez-Ortiz M, Lahive E, George S, Ter Schure A, Van Gestel CA, Jurkschat K, Spurgeon DJ (2015) Short-term soil bioassays may not reveal the full toxicity potential for nanomaterials; bioavailability and toxicity of silver ions ($AgNO_3$) and silver nanoparticles to earthworm *Eisenia fetida* in long-term aged soils. Environ Pollut 203:191–198

Duan H, Deng W, Gan Z, Li D, Li D (2019) SERS-based chip for discrimination of formaldehyde and acetaldehyde in aqueous solution using silver reduction. Microchim Acta 186(3):1–11

Duhan JS, Kumar R, Kumar N, Kaur P, Nehra K, Duhan S (2017) Nanotechnology: the new perspective in precision agriculture. Biotechnol Rep 15:11–23

Faizal H, Abbasi BH, Ahmad N, Ali M (2016) Integrated nanoscale silicon sensors using top-down fabrication. Appl Biochem Biotechnol 180:1076–1092

Fang M, Zhou L, Zhang H, Liu L, Gong ZY (2019) A molecularly imprinted polymers/carbon dots-grafted paper sensor for 3-monochloropropane-1,2-diol determination. Food Chem 274:156–161

FAO (2016) The FAO action plan on antimicrobial resistance 2016–2020. Food and Agriculture Organization of the United Nations, p 25

Fatta-Kassinos D, Kalavrouziotis I, Koukoulakis P, Vasquez M (2011) The risks associated with wastewater reuse and xenobiotics in the agroecological environment. Sci Total Environ 409: 3555–3563

Fleischer A, O'Neill MA, Ehwald R (1999) The pore size of non-graminaceous plant cell walls is rapidly decreased by borate ester cross-linking of the pectic polysaccharide Rhamnogalacturonan. Plant Physiol 121(3):829–838

Fraceto LF, Grillo R, de Medeiros GA, Scognamiglio V, Rea G, Bartolucci C (2016) Nanotechnology in agriculture: which innovation potential does it have? Front Environ Sci 4:20

Francisco AD, Pereira ML, Maia KC, Silva WC, Leite AC, Vasconcelos TL, Nascimento RS, Grasseschi D (2020) Fe_3O_4 nanoparticles as surfactant carriers for enhanced oil recovery and scale prevention. ACS Appl Nano Mater 3(6):5762–5772

Gahlawat G, Shikha S, Chaddha BS, Chaudhuri SR, Mayilraj S, Choudhury AR (2016) Microbial glycolipoprotein-capped silver nanoparticles as emerging antibacterial agents against cholera. Microb Cell Factories 15:25

Gamal MMZ (2018) Nano-particles: a recent approach for controlling stored grain insect pests. Acad J Agric Res 6(5):88–94

García-Sánchez S, Bernales I, Cristobal S (2015) Early response to nanoparticles in the *Arabidopsis* transcriptome compromises plant defence and root-hair development through salicylic acid signalling. BMC Genomics 16(1):1–17

Ge Y, Schimel JP, Holden PA (2011) Evidence for negative effects of TiO_2 and ZnO nanoparticles on soil bacterial communities. Environ Sci Technol 45(4):1659–1664

Giraldo JP, Landry MP, Faltermeier SM, McNicholas TP, Iverson NM, Boghossian AA, Strano MS (2014) Plant nanobionics approach to augment photosynthesis and biochemical sensing. Nat Mater 13(4):400–408

Grillo R, Rosa AH, Fraceto LF (2015) Engineered nanoparticles and organic matter: a review of the state-of-the-art. Chemosphere 119:608–619

Gruber P, Marques MP, Szita N, Mayr T (2017) Integration and application of optical chemical sensors in microbioreactors. Lab Chip 17(16):2693–2712

Gruère G, Narrod C, Abbott L (2011) Agricultural, food, and water nanotechnologies for the poor. International Food Policy Research Institute, Washington

Gupta A, Eral HB, Hatton TA, Doyle PS (2016) Nanoemulsions: formation, properties and applications. Soft Matter 12(11):2826–2284

Hafeez A, Razzaq A, Mahmood T, Jhanzab HM (2015) Potential of copper nanoparticles to increase growth and yield of wheat. J Nanosci Adv Technol 1:6–11

Hashem AS, Awadalla SS, Zayed GM, Maggi F, Benelli G (2018) *Pimpinella anisum* essential oil nanoemulsions against *Tribolium castaneum*—insecticidal activity and mode of action. Environ Sci Pollut Res 25(19):18802–18812

He K, Zeng Z, Chen A, Zeng G, Xiao R, Xu P, Huang Z, Shi J, Hu L, Chen G (2018) Advancement of Ag–graphene based nanocomposites: an overview of synthesis and its applications. Small 14(32):1800871

Helaly MN, El-Metwally MA, El-Hoseiny H, Omar SA, El-Sheery NI (2014) Effect of nanoparticles on biological contamination of *'in vitro'* cultures and organogenic regeneration of banana. Aust J Crop Sci 8(4):612

Hossain Z, Mustafa G, Sakata K, Komatsu S (2016) Insights into the proteomic response of soybean towards Al_2O_3, ZnO, and Ag nanoparticles stress. J Hazard Mater 304:291–305

Hu W, Wan L, Jian Y, Ren C, Jin K, Su X, Wu W (2019) Electronic noses: from advanced materials to sensors aided with data processing. Adv Mater Technol 4(2):1800488

Huijskens E, Smit L, Rossen J, Heederik D, Koopmans M (2016) Evaluation of patients with community-acquired pneumonia caused by zoonotic pathogens in an area with a high density of animal farms. Zoonoses Public Health 63:160–166

Ismagul A, Yang N, Maltseva E et al (2018) A biolistic method for high throughput production of transgenic wheat plants with single gene insertions. BMC Plant Biol 18(1):135

Jamdagni P, Rana JS, Khatri P, Nehra K (2018) Comparative account of antifungal activity of green and chemically synthesized zinc oxide nanoparticles in combination with agricultural fungicides. Int J Nano Dimen 9:198–208

Jigyasa A, Rajput JK (2018) Bio-polyphenols promoted green synthesis of silver nanoparticles for facile and ultra-sensitive colorimetric detection of melamine in milk. Biosens Bioelectron 120: 153–159

Joko Y, Sasaki R, Shintani K (2017) Dynamic encapsulation of corannulene molecules into a single-walled carbon nanotube. Phys Chem Chem Phys 19:27704–27715

Joldersma D, Liu Z (2018) Plant genetics enters the nano age? J Integr Plant Biol 60(6):446–447

Jose A, Radhakrishnan EK (2018) Applications of nanomaterials in agriculture and food industry. Green Sustainable Adv Mater Appl 2:343–375

Kah M, Hofmann T (2014) Nanopesticide research: current trends and future priorities. Environ Int 63:224–235

Kah M, Tufenkji N, White JC (2019) Nano-enabled strategies to enhance crop nutrition and protection. Nat Nanotechnol 14(6):532–540

Kalita S, Kandimalla R, Sharma KK, Kataki AC, Deka M, Kotoky J (2016) Amoxicillin functionalized gold nanoparticles reverts MRSA resistance. Mater Sci Eng C 61:720–727

Kámán-Tóth E, Pogány M, Dankó T et al (2018) A simplified and efficient *Agrobacterium tumefaciens* electroporation method. 3Biotech 8(3):148

Kang HJ, Lee SH, Lim TG, Park HD (2019) Effect of inoculum concentration on methanogenesis by direct interspecies electron transfer: performance and microbial community composition. Bioresour Technol 291:121881

Karimi M, Ghasemi A, Zangabad PS et al (2016) Smart micro/nanoparticles in stimulus-responsive drug/gene delivery systems. Chem Soc Rev 45(5):1457–1501

Karthika D, Vadakkan K, Ashwini R, Shyamala A, Hemapriya J, Vijayanand S (2015) Prodigiosin mediated biosynthesis of silver nanoparticles (AgNPs) and evaluation of its antibacterial efficacy. Int J Curr Microbiol App Sci 4(11):868–874

Kataria S, Jain M, Rastogi A, Živčák M, Brestic M, Liu S, Tripathi DK (2019) Role of nanoparticles on photosynthesis: avenues and applications. In: Nanomaterials in plants, algae and microorganisms. Springer, Cham, pp 103–127

Kaur H, Shorie M, Sharma M, Ganguli AK, Sabherwal P (2017) Bridged rebar graphene functionalized aptasensor for pathogenic *E. coli* O78:K80:H11 detection. Biosens Bioelectron 98:486–493

Keswani C, Sarma BK, Singh HB (2016) Synthesis of policy support, quality control, and regulatory management of biopesticides in sustainable agriculture. In: Singh HB, Sarma BK, Kumar N, Keswani C (eds) Agriculturally important microorganisms: commercialization and regulatory requirements in Asia. Springer, Singapore, pp 3–12

Khalifa NS, Hasaneen MN (2018) The effect of chitosan–PMAA–NPK nanofertilizer on *Pisum sativum* plants. 3Biotech 8:193–205

Khan MR, Rizvi TF, Ahamad F (2019) Effect of nanoparticles on phytopathogens. In: Ghobanpour M, Wani SH (eds) Advances in phytonanotechnology: from synthesis to application. Elsevier, London, p 466

Khodakovskaya MV, De Silva K, Biris AS, Dervishi E, Villagarcia H (2012) Carbon nanotubes induce growth enhancement of tobacco cells. ACS Nano 6(3):2128–2135

Kim IH, Lee H, Kim JE, Song KB, Lee YS, Chung DS, Min SC (2013) Plum coatings of lemongrass oil-incorporating carnauba wax-based nanoemulsion. J Food Sci 78:E1551–E1559

Ko KS, Koh DC, Kong IC (2017) Evaluation of the effects of nanoparticle mixtures on Brassica seed germination and bacterial bioluminescence activity based on the theory of probability. Nano 7:344–354

Kottegoda N, Sandaruwan C, Priyadarshana G, Siriwardhana A, Rathnayake UA, Berugoda Arachchige DM, Amaratunga GA (2017) Urea-hydroxyapatite nanohybrids for slow release of nitrogen. ACS Nano 11(2):1214–1221

Krishnaswamy K, Vali H, Orsat V (2014) Value-adding to grape waste: green synthesis of gold nanoparticles. J Food Eng 142:210–220

Kumar P, Kim KH, Deep A (2015) Recent advancements in sensing techniques based on functional materials for organophosphate pesticides. Biosens Bioelectron 70:469–481

Kurepa J, Paunesku T, Vogt S, Arora H, Rabatic BM, Lu J, Wanzer MB, Woloschak GE, Smalle JA (2010) Uptake and distribution of ultrasmall anatase TiO2 Alizarin red S nanoconjugates in Arabidopsis thaliana. Nano Lett 10:2296–2302

Landa P, Prerostova S, Petrova S, Knirsch V, Vankova R, Vanek T (2015) The transcriptomic response of *Arabidopsis thaliana* to zinc oxide: a comparison of the impact of nanoparticle, bulk, and ionic zinc. Environ Sci Technol 49(24):14537–14545

Landry KS, Chang Y, McClements DJ, McLandsborough L (2014) Effectiveness of a novel spontaneous carvacrol nanoemulsion against *Salmonella enterica* Enteritidis and *Escherichia coli* O157: H7 on contaminated mung bean and alfalfa seeds. Int J Food Microbiol 187:15–21

Landry KS, Micheli S, McClements DJ, McLandsborough L (2015) Effectiveness of a spontaneous carvacrol nanoemulsion against *Salmonella enterica* Enteritidis and *Escherichia coli* O157: H7 on contaminated broccoli and radish seeds. Food Microbiol 51:10–17

Li Q, Chen X, Zhuang J, Chen X (2016) Decontaminating soil organic pollutants with manufactured nanoparticles. Environ Sci Pollut Res 23(12):11533–11548

Liu X, Wang R, Xia Y, He Y, Zhang T (2011) LiCl-modified mesoporous silica SBA-16 thick film resistors as humidity sensor. Sens Lett 9(2):698–702

Lou Z, Chen J, Yu F, Wang H, Kou X, Ma C, Zhu S (2017) The antioxidant, antibacterial, antibiofilm activity of essential oil from *Citrus medica* L. var. sarcodactylis and its nanoemulsion. LWT- Food Sci Technol 80:371–377

Mahal A, Khullar P, Kumar H, Kaur G, Singh N, Jelokhani-Niaraki M, Bakshi MS (2013) Green chemistry of zein protein toward the synthesis of bioconjugated nanoparticles: understanding unfolding, fusogenic behavior, and hemolysis. ACS Sustain Chem Eng 1:627–639

Malaikozhundan B, Vaseeharan B, Vijayakumar S, Thangaraj MP (2017) *Bacillus thuringiensis* coated zinc oxide nanoparticle and its biopesticidal effects on the pulse beetle, Callosobruchus maculatus. J Photochem Photobiol B Biol 174:306–314

Malandrakis AA, Kavroulakis N, Chrysikopoulos CV (2019) Use of copper, silver and zinc nanoparticles against foliar and soil-borne plant pathogens. Sci Total Environ 670:292–299

Malik M, Padhye P, Poddar P (2019) Down conversion luminescence-based nanosensor for labelfree detection of explosives. ACS Omega 4:4259–4268

Martínez-Fernández D, Barroso D, Komárek M (2016) Root water transport of *Helianthus annuus* L. under iron oxide nanoparticle exposure. Environ Sci Pollut Res 23(2):1732–1741

McKee MS, Filser J (2016) Impacts of metal-based engineered nanomaterials on soil communities. Environ Sci Nano 3(3):506–533

McLoughlin KS (2011) Microarrays for pathogen detection and analysis. Brief Funct Genomics 10(6):342–353

Medda S, Hajra A, Dey U, Bose P, Mondal NK (2015) Biosynthesis of silver nanoparticles from *Aloe vera* leaf extract and antifungal activity against *Rhizopus* sp and *Aspergillus* sp. Appl Nanosci 5:875–880

Mehrazar E, Rahaie M, Rahaie S (2015) Application of nanoparticles for pesticides, herbicides, fertilisers and animals feed management. Int J Nanopart 8(1):1–19

Mir SA, Shah MA, Mir MM, Iqbal U (2017) New horizons of nanotechnology in agriculture and food processing industry. In: Integrating biologically-inspired nanotechnology into medical practice. Springer, Cham, pp 230–258

Mishra VL, Sharma R (2017) Green synthesis of nanoparticles and their antibacterial activity against pathogenic bacteria. Int J Pharm Sci Res 90:24

Mishra S, Yang X, Singh HB (2020) Evidence for positive response of soil bacterial community structure and functions to biosynthesized silver nanoparticles: an approach to conquer nanotoxicity? J Environ Manag 253:109584

Moreno-Olivas F, Gant VU, Johnson KL, Peralta-Videa JR, Gardea-Torresdey JL (2014) Random amplified polymorphic DNA reveals that TiO_2 nanoparticles are genotoxic to *Cucurbita pepo*. J Zheijang Univ Sci A 15(8):618–623

Mukhopadhyay SS (2014) Nanotechnology in agriculture: prospects and constraints. Nanotechnol Sci Appl 7:63

Mura S, Greppi G, Roggero PP, Musu E, Pittalis D, Carletti A, Irudayaraj J (2015) Functionalized gold nanoparticles for the detection of nitrates in water. Int J Environ Sci Technol 12(3): 1021–1028

Mura S, Chianella I, Greppi GF (2017) Nanotechnology in agriculture and food sciences. Georgofili 12(2):169–209

Nakache E, Poulain N, Candau F, Orecchioni AM, Irache JM (2000) Biopolymer and polymer nanoparticles and their biomedical applications. In: Handbook of nanostructured materials and nanotechnology. Springer, Cham, pp 577–635

Netala VR, Kotakadi VS, Bobbu P, Gaddam SA, Tartte V (2016) Endophytic fungal isolate mediated biosynthesis of silver nanoparticles and their free radical scavenging activity and antimicrobial studies. 3Biotech 6(2):132

Noori A, Donnelly T, Colbert J, Cai W, Newman LA, White JC (2020) Exposure of tomato (*Lycopersicon esculentum*) to silver nanoparticles and silver nitrate: physiological and molecular response. Int J Phytoremediation 22(1):40–51

Nuruzzaman MD, Rahman MM, Liu Y, Naidu R (2016) Nanoencapsulation, nano-guard for pesticides: a new window for safe application. J Agric Food Chem 64(7):1447–1483

Nuzzo A, Madonna E, Mazzei P, Spaccini R, Piccolo A (2016) *In situ* photo-polymerization of soil organic matter by heterogeneous nano-TiO_2 and biomimetic metal-porphyrin catalysts. Biol Fertil Soils 52(4):585–593

Osman GH, Aseem SK, Alreedy RM et al (2015) Development of insect resistant maize plants expressing a chitinase gene from the cotton leaf worm, *Spodoptera littoralis*. Sci Rep 5:18067

Ottoni CA, Neto ML, Léo P, Ortolan BD, Barbieri E, De Souza AO (2020) Environmental impact of biogenic silver nanoparticles in soil and aquatic organisms. Chemosphere 239:124698

Pandey RR, Saini KK, Dhayal M (2010) Using nano-arrayed structures in sol-gel derived Mn^{2+} doped TiO_2 for high sensitivity urea biosensor. J Biosens Bioelectron 1:101

Pandey S, Giri K, Kumar R, Mishra G, Rishi RR (2018) Nanopesticides: opportunities in crop protection and associated environmental risks. Proc Natl Acad Sci 88(4):1287–1308

Panpatte DG, Jhala YK, Shelat HN, Vyas RV (2016) Nanoparticles: the next generation technology for sustainable agriculture. In: Microbial inoculants in sustainable agricultural productivity. Springer, Cham, pp 289–300

Patra JK, Baek K-H (2017) Antibacterial activity and synergistic antibacterial potential of biosynthesized silver nanoparticles against food borne pathogenic bacteria along with its anticandidal and antioxidant effects. Front Microbiol 8:167

Peng Z, Liu X, Zhang W, Zeng Z, Liu Z, Zhang C, Yuan X (2020) Advances in the application, toxicity and degradation of carbon nanomaterials in environment: a review. Environ Int 134: 105298

Pham DC, Nguyen TH, Ngoc UTH, Le NTT, Tran TV, Nguyen DH (2018) Preparation, characterization and antifungal properties of chitosan-silver nanoparticles synergize fungicide against *Pyricularia oryzae*. J Nanosci Nanotechnol 18:1–7

Prakash A, Baskaran R, Paramasivam N, Vadivel V (2018) Essential oil based nanoemulsions to improve the microbial quality of minimally processed fruits and vegetables: a review. Food Res Int 111:509–523

Prasad R, Thirugnanasanbandham K (2019) Advances research on nanotechnology for water technology. Springer, Cham

Puri A, Loomis K, Smith B, Lee JH, Yavlovich A, Heldman E, Blumenthal R (2009) Lipid-based nanoparticles as pharmaceutical drug carriers: from concepts to clinic. Crit Rev Therap Drug Carrier Syst 26(6):523

Quatrin PM, Verdi CM, de Souza ME, de Godoi SN, Klein B, Gundel A, Santos RCV (2017) Antimicrobial and antibiofilm activities of nanoemulsions containing *Eucalyptus globulus* oil against *Pseudomonas aeruginosa* and *Candida* spp. Microb Pathog 112:230–242

Ragaei M, Sabry A (2014) Nanotechnology for insect pest control. Int J Sci Environ Technol 3: 528–545

Rahmatpour S, Shirvani M, Mosaddeghi MR, Nourbakhsh F, Bazarganipour M (2017) Dose–response effects of silver nanoparticles and silver nitrate on microbial and enzyme activities in calcareous soils. Geoderma 285:313–322

Rajan A, Cherian E, Baskar G (2016) Biosynthesis of zinc oxide nanoparticles using *Aspergillus fumigatus* JCF and its antibacterial activity. Int J Mod Sci Technol 1:52–57

Rajaram K, Aiswarya DC, Sureshkumar P (2015) Green synthesis of silver nanoparticle using *Tephrosia tinctoria* and its antidiabetic activity. Mater Lett 138:251–254

Rajput VD, Minkina T, Sushkova S, Tsitsuashvili V, Mandzhieva S, Gorovtsov A, Nevidomskyaya D, Gromakova N (2018) Effect of nanoparticles on crops and soil microbial communities. J Soils Sediments 6:2179–2187

Rajput V, Minkina T, Sushkova S, Behal A, Maksimov A, Blicharska E, Barsova N (2020) ZnO and CuO nanoparticles: a threat to soil organisms, plants, and human health. Environ Geochem Health 42(1):147–158

Rashid MI, Shahzad T, Shahid M, Imran M, Dhavamani J, Ismail IM, Almeelbi T (2017a) Toxicity of iron oxide nanoparticles to grass litter decomposition in a sandy soil. Sci Rep 7(1):1–11

Rashid MI, Shahzad T, Shahid M, Ismail IM, Shah GM, Almeelbi T (2017b) Zinc oxide nanoparticles affect carbon and nitrogen mineralization of *Phoenix dactylifera* leaf litter in a sandy soil. J Hazard Mater 324:298–305

Raskar SV, Laware SL (2014) Effect of zinc oxide nanoparticles on cytology and seed germination in onion. Int J Curr Microbiol App Sci 3(2):467–473

Rastogi A, Tripathi DK, Yadav S, Chauhan DK, Živčák M, Ghorbanpour M, El-Sheery NI, Brestic M (2019) Application of silicon nanoparticles in agriculture. 3Biotech 9(3):90

Rawat M, Nayan R, Negi B, Zaidi MGH, Arora S (2017) Physio-biochemical basis of iron-sulfide nanoparticle induced growth and seed yield enhancement in *B. juncea*. Plant Physiol Biochem 118:274–284

Ren X, Cheshari EC, Qi J, Li X (2018) Silver microspheres coated with a molecularly imprinted polymer as a SERS substrate for sensitive detection of bisphenol A. Microchim Acta 185(4):1–8

Rezaei F, Moaveni P, Mozafari H (2015) Effect of different concentrations and time of nano TiO_2 spraying on quantitative and qualitative yield of soybean (*Glycine max* L.) at Shahr-e-Qods. Iran Biol Forum 7:957–964

Rico CM, Peralta-Videa JR, Gardea-Torresdey JL (2015) Chemistry, biochemistry of nanoparticles, and their role in antioxidant defense system in plants. In: Nanotechnology and plant sciences. Springer, Cham, pp 1–17

Rivera AL, Gomez-Lim M, Fernandez F et al (2012) Physical methods for genetic plant transformation. Phys Life Rev 9(3):308–334

Rizwan M, Ali S, Ur Rehman MZ, Malik S, Adrees M, Qayyum MF, Alamri SA, Alyemeni MN, Ahmad P (2019) Effect of foliar applications of silicon and titanium dioxide nanoparticles on growth, oxidative stress, and cadmium accumulation by rice (*Oryza sativa*). Acta Physiol Plant 41:35

Rui M, Ma C, Hao Y, Guo J, Rui Y, Tang X, Zhu S (2016) Iron oxide nanoparticles as a potential iron fertilizer for peanut (*Arachis hypogaea*). Front Plant Sci 7:815

Saharan V, Sharma G, Yadav M, Choudhary MK, Sharma SS, Pal A, Raliya R, Biswas P (2015) Synthesis and in vitro antifungal efficacy of Cu–chitosan nanoparticles against pathogenic fungi of tomato. Int J Biol Macromol 75:346–353

Salem NM, Albanna LS, Awwad AM, Ibrahim QM, Abdeen AO (2015) Green synthesis of nano-sized sulfur and its effect on plant growth. J Agric Sci 8(1):188

Sangeetha J, Thangadurai D, Hospet R, Purushotham P, Manowade KR, Mujeeb MA, Mundaragi AC, Jogaiah S, David M, Thimmappa SC, Prasad R, Harish ER (2017) Production of bionanomaterials from agricultural wastes. In: Nanotechnology. Springer, Cham, pp 33–58

Sankar MV, Abideen S (2015) Pesticidal effect of green synthesized silver and lead nanoparticles using *Avicennia marina* against grain storage pest *Sitophilus oryzae*. Int J Nanomater Biostruct 5 (3):32–39

Saratale RG, Saratale GD, Shin HS, Jacob JM, Pugazhendhi A, Bhaisare M, Kumar G (2018) New insights on the green synthesis of metallic nanoparticles using plant and waste biomaterials: current knowledge, their agricultural and environmental applications. Environ Sci Pollut Res 25(11):10164–10183

Schlich K, Hund-Rinke K (2015) Influence of soil properties on the effect of silver nanomaterials on microbial activity in five soils. Environ Pollut 196:321–330

Scott N, Chen H (2013) Nanoscale science and engineering for agriculture and food systems. Ind Biotechnol 9(1):17–18

Servin AD, White JC (2016) Nanotechnology in agriculture: next steps for understanding engineered nanoparticle exposure and risk. NanoImpact 1:9–12

Servin A, Elmer W, Mukherjee A, De la Torre-Roche R, Hamdi H, White JC, Dimkpa C (2015) A review of the use of engineered nanomaterials to suppress plant disease and enhance crop yield. J Nanopart Res 17(2):1–21

Shafiee-Jood M, Cai X (2016) Reducing food loss and waste to enhance food security and environmental sustainability. Environ Sci Technol 50(16):8432–8443

Shahrekizad M, Ahangara AG, Mirb N (2015) EDTA-coated Fe_3O_4 nanoparticles: a novel bio-compatible fertilizer for improving agronomic traits of sunflower (*Helianthus annuus*). J Nanostruct 5:117–127

Shaker AM, Zaki AH, Abdel-Rahim EF, Khedr MH (2016) Novel CuO nanoparticles for pest management and pesticides photodegradation. Adv Environ Biol 10:274–283

Shehzad A, Qureshi M, Jabeen S, Ahmad R, Alabdalall AH, Aljafary MA, Al-Suhaimi E (2018) Synthesis, characterization and antibacterial activity of silver nanoparticles using *Rhazya stricta*. PeerJ 6:e6086

Shenashen M, Derbalah A, Hamza A, Mohamed A, El Safty S (2017) Antifungal activity of fabricated mesoporous alumina nanoparticles against root rot disease of tomato caused by *Fusarium oxysporum*. Pest Manag Sci 73:1121–1126

Shi J, Ye J, Fang H, Zhang S, Xu C (2018) Effects of copper oxide nanoparticles on paddy soil properties and components. Nano 8(10):839

Shinde S, Paralikar P, Ingle AP, Rai M (2020) Promotion of seed germination and seedling growth of *Zea mays* by magnesium hydroxide nanoparticles synthesized by the filtrate from *Aspergillus niger*. Arab J Chem 13:3172–3182

Shukla S, Kumar R, Mishra R, Pandey A, Pathak A, Zaidi MGH, Srivastava SK, Dikshit A (2015) Prediction and validation of gold nanoparticles (GNPs) on plant growth promoting rhizobacteria (PGPR): a step toward development of nano-biofertilizers. Nanotechnol Rev 4(5):439–448

Siddiqui MH, Al-Whaibi MH, Firoz M, Al-Khaishany MY (2015) Role of nanoparticles in plants. In: Nanotechnology and plant sciences. Springer, Cham, pp 19–35

Simonin M, Richaume A (2015) Impact of engineered nanoparticles on the activity, abundance, and diversity of soil microbial communities: a review. Environ Sci Pollut Res 22(18):13710–13723

Simonin M, Guyonnet JP, Martins JM, Ginot M, Richaume A (2015) Influence of soil properties on the toxicity of TiO_2 nanoparticles on carbon mineralization and bacterial abundance. J Hazard Mater 283:529–535

Singh J, Lee BK (2016) Influence of nano-TiO_2 particles on the bioaccumulation of Cd in soybean plants (*Glycine max*): a possible mechanism for the removal of Cd from the contaminated soil. J Environ Manag 170:88–96

Singh P, Jayaramaiah RH, Sarate P, Thulasiram HV, Kulkarni MJ, Giri AP (2014) Insecticidal potential of defense metabolites from *Ocimum kilim* and *scharicum* against *Helicoverpa armigera*. PLoS One 9(8):e104377

Singh P, Kim YJ, Wang C, Mathiyalagan R, Yang DC (2016) The development of a green approach for the biosynthesis of silver and gold nanoparticles by using *Panax ginseng* root extract, and their biological applications. Artif Cells Nanomed Biotechnol 44(4):1150–1157

Siva GV, Benita LFJ (2016) Iron oxide nanoparticles promotes agronomic traits of ginger (*Zingiber officinale* Rosc.). Int J Adv Res Biol Sci 3:230–237

Siva C, Kumar MS (2015) Pesticidal activity of eco-friendly synthesized silver nanoparticles using *Aristolochia indica* extract against *Helicoverpa armigera* Hubner (Lepidoptera: Noctuidae). Int J Adv Sci Tech Res 2:197–226

Sivakumar P, Devi CN, Renganathan S (2012) Synthesis of silver nanoparticles using *Lantana camara* fruit extract and its effect on pathogens. Asian J Pharm Clin Res 5:97–101

Slavin YN, Asnis J, Häfeli UO, Bach H (2017) Metal nanoparticles: Understanding the mechanisms behind antibacterial activity. J Nanobiotechnol 15:65

Song G, Gao Y, Wu H, Hou W, Zhang C, Ma H (2012) Physiological effect of anatase TiO_2 nanoparticles on *Lemna minor*. Environ Toxicol Chem 9:2147–2152

Sousa GF, Gomes DG, Campos EV, Oliveira JL, Fraceto LF, Stolf-Moreira R, Oliveira HC (2018) Post-emergence herbicidal activity of nanoatrazine against susceptible weeds. Front Environ Sci 6:12

Spinoso-Castillo JL, Chavez-Santoscoy RA, Bogdanchikova N, Perez-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 129:195–207

Subbaiah LV, Prasad TN, Krishna TG, Sudhakar P, Reddy BR, Pradeep T (2016) Novel effects of nanoparticulate delivery of zinc on growth, productivity, and zinc biofortification in maize (*Zea mays* L.). J Agric Food Chem 64(19):3778–3788

Suresh S (2013) Synthesis, structural and dielectric properties of zinc sulfide nanoparticles. Int J Phys Sci 8(21):1121–1127

Taniguchi N, Arakawa C, Kobayashi T (1974) On the basic concept of nanotechnology. In: Proceedings of the international conference on production engineering, pp 18–23

Teymoori N, Raoof JB, Khalilzadeh MA, Ojani R (2018) An electrochemical sensor based on CuO nanoparticle for simultaneous determination of hydrazine and bisphenol a. J Iran Chem Soc 15: 2271–2279

Thomas R, Jasim B, Mathew J, Radhakrishnan EK (2012) Extracellular synthesis of silver nanoparticles by endophytic *Bordetella* sp. isolated from *Piper nigrum* and its antibacterial activity analysis. Nano Biomed Eng 4(4):183–187

Thomé A, Reddy KR, Reginatto C, Cecchin I (2015) Review of nanotechnology for soil and groundwater remediation: Brazilian perspectives. Water Air Soil Pollut 226(4):1–20

Tîlmaciu C, Morris MC (2015) Carbon nanotube biosensors. Front Chem 3:59

Tiwari E, Mondal M, Singh N, Khandelwal N, Monikh FA, Darbha GK (2020) Effect of the irrigation water type and other environmental parameters on CeO_2 nanopesticide–clay colloid interactions. Environ Sci: Processes Impacts 22(1):84–94

Tolaymat T, El Badawy A, Genaidy A, Abdelraheem W, Sequeira R (2017) Analysis of metallic and metal oxide nanomaterial environmental emissions. J Clean Prod 143:401–412

Tong ZH, Bischoff M, Nies LF, Carroll NJ, Applegate B, Turco RF (2016) Influence of fullerene (C 60) on soil bacterial communities: aqueous aggregate size and solvent co-introduction effects. Sci Rep 6(1):1–9

Tripathi DK, Singh S, Singh S, Pandey R, Singh VP, Sharma NC, Chauhan DK (2017) An overview on manufactured nanoparticles in plants: uptake, translocation, accumulation and phytotoxicity. Plant Physiol Biochem 110:2–12

Ullah N, Mansha M, Khan I, Qurashi A (2018) Nanomaterial-based optical chemical sensors for the detection of heavy metals in water: recent advances and challenges. TrAC Trends Anal Chem 100:155–166

Upadhyaya H, Roy H, Shome S, Tewari S, Bhattacharya MK, Panda SK (2017) Physiological impact of zinc nanoparticle on germination of rice (*Oryza sativa* L) seed. J Plant Sci Phytopathol 1:62–70

Van Aken B (2015) Gene expression changes in plants and microorganisms exposed to nanomaterials. Curr Opin Biotechnol 33:206–219

Vanti GL, Nargund VB, Basavesha KN, Vanarchi R, Kurjogi M, Mulla SI, Tubaki S, Patil RR (2019) Synthesis of *Gossypium hirsutum*-derived silver nanoparticles and their antibacterial efficacy against plant pathogens. Appl Organomet Chem 33:e4630

Vimala V, Clarke SK, Urvinder Kaur S (2016) Pesticides detection using acetylcholinesterase Nanobiosensor. Biosens J 5:133

Wang SL, Nguyen AD (2018) Effects of Zn/B nanofertilizer on biophysical characteristics and growth of coffee seedlings in a greenhouse. Res Chem Intermed 44:4889–4901

Wang P, Lombi E, Zhao FJ et al (2016) Nanotechnology: a new opportunity in plant sciences. Trends Plant Sci 21(8):699–712

Wang Y, Yue Q, Tao L, Zhang C, Li CZ (2018) Fluorometric determination of hydroquinone by using blue emitting N/S/P-codoped carbon dots. Microchim Acta 185(12):1–9

Wei H, Wang E (2013) Nanomaterials with enzyme-like characteristics (nanozymes): next-generation artificial enzymes. Chem Soc Rev 42(14):6060–6093

Wu F, You Y, Werner D, Jiao S, Hu J, Zhang X, Wang X (2020) Carbon nanomaterials affect carbon cycle-related functions of the soil microbial community and the coupling of nutrient cycles. J Hazard Mater 390:122144

Xiong S, Deng Y, Zhou Y, Gong D, Xu Y, Yang L, Chen H, Chen L, Song T, Luo A, Deng X, Zhang C, Jiang Z (2018) Current progress in biosensors for organophosphorus pesticides based on enzyme functionalized nanostructures: a review. Anal Methods 46:5468–5479

Xu LQ, Li NN, Chen JC, Fu GD, Kang E-T (2015) Quaternized poly (2-(dimethylamino) ethyl methacrylate)-grafted agarose copolymers for multipurpose antibacterial applications. RSC Adv 5:61742–61751

Yang X, Pan H, Wang P, Zhao FJ (2017) Particle-specific toxicity and bioavailability of cerium oxide (CeO_2) nanoparticles to *Arabidopsis thaliana*. J Hazard Mater 322:292–300

Yassen A, Abdallah E, Gaballah M, Zaghloul S (2017) Role of silicon dioxide nano fertilizer in mitigating salt stress on growth, yield and chemical composition of cucumber (*Cucumis sativus* L.). Int J Agric Res 12:130–135

Yi Z, Hussain HI, Feng C, Sun D, She F, Rookes JE, Kong L (2015) Functionalized mesoporous silica nanoparticles with redox-responsive short-chain gatekeepers for agrochemical delivery. ACS Appl Mater Interfaces 7(18):9937–9946

Yin L, Colman BP, McGill BM, Wright JP, Bernhardt ES (2012) Effects of silver nanoparticle exposure on germination and early growth of eleven wetland plants. PLoS One 7(10):e47674

You T, Liu D, Chen J, Yang Z, Dou R, Gao X, Wang L (2017) Effects of metal oxide nanoparticles on soil enzyme activities and bacterial communities in two different soil types. J Soils Sediments 18:2179–2187

Yu Q, Shi Y, Tang H, Yang P, Xie A, Liu B, Wu W (2017) eFarm: a tool for better observing agricultural land systems. Sensors 17(3):453

Zhao L, Huang Y, Adeleye AS, Keller AA (2017) Metabolomics reveals $Cu(OH)_2$ nanopesticide-activated anti-oxidative pathways and decreased beneficial antioxidants in spinach leaves. Environ Sci Technol 51:10184–10194

Zhou J, Zhang Y, Hu T et al (2018) Functional characterization of squalene epoxidase genes in the medicinal plant *Tripterygium wilfordii*. Int J Biol Macromol 120:203–212

Zou D, Jin L, Wu B, Hu L, Chen X, Huang G, Zhang J (2019) Rapid detection of *Salmonella* in milk by biofunctionalised magnetic nanoparticle cluster sensor based on nuclear magnetic resonance. Int Dairy J 91:82–88