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REVIEW ARTICLE

Nanotechnological interventions for plant health improvement and sustainable agriculture

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Abstract

Agriculture is the source of food for both humans and animals. With the growing population demands, agricultural production needs to be scaled up where nanotechnology can play a significant role. The use of nanotechnology in agriculture can manage plant disease and growth for better and quality output. Therefore, this review focuses on the use of various nanoparticles for detection of nutrients and contaminants, nanosensors for monitoring the environmental stresses and crop conditions as well as the use of nanotechnology for plant pathogen detection and crop protection. In addition, the delivery of plant growth regulators and agrichemicals like nanopesticides and nanofertilizers to the plants along with the delivery of DNA for targeted genetic engineering and production of genetically modified (GM) crops are discussed briefly. Further, the future concerns regarding the use of nanoparticles and their possible toxicity, impact on the agriculture and ecosystem needs to be assessed along with the assessment of the nanoparticles and GM crops on the environment and human health.

Keywords Nanotechnology · Disease detection · Nanopesticides · Nanofertilizers · Nanosensors · Plant health · Sustainable agriculture

Introduction

Nanotechnology has a great scope to address various issues prevalent in the agricultural sector. The management of energy and resources as well as problems related to overuse of pesticides and fertilizers and their impact can be resolved by the proper utilization of nanotechnology in the plant disease and growth management (Chen and Yada 2011; Ditta 2012; Parisi et al. 2015). The increasing demand for agricultural commodities and recent technologies for better and higher yields can be met by optimizing agricultural practices and the introduction of nanoscale materials in agriculture (Gogos et al. 2012; He et al. 2019). Nanotechnology may be utilized for the modernization of the agricultural sector for sustained and income-generating occupation. This can be achieved by maximizing the agricultural outputs for crop yields by minimizing the cost of the inputs of various fertilizers and monitoring environmental conditions (Servin et al. 2015; Fraceto et al. 2016). Recently, the emphasis on the use of nanomaterials has increased because of their potential for seed germination and growth. These particles can control the release of agrichemicals and minimize nutrient loss during fertilization. Besides this, their application in agriculture

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will boost the quality and production of food globally and in an environmentally friendly manner by protecting and solving soil and water problems (Biswal et al. 2012; Ditta 2012; Khot et al. 2012; Sonkaria et al. 2012; Prasad et al. 2014; Sekhon 2014).

Nanomaterials (NMs) have become an integral part of nanoparticles (NPs) for monitoring and stimulating the plant growth because of their inherent unique chemical, electrical mechanical and thermal properties. The use of multi-walled carbon nanotubes (MWCNTs) has been observed to significantly increase the germination and vegetative biomass of tomato seeds (Khodakovskaya et al. 2009). For instance, the use of C-based nanotubes along with the NPs of other elements/compounds such as Au, SiO_2, ZnO, and TiO_2 has increased the uptake of elements and nutrients ultimately leading to better growth of plants (Khot et al. 2012). The utilization of nanopesticides reveals the concern for its possible toxicity. However, its use controls the release and delivery of herbicides as per the soil condition and thus reduces the required quantity of herbicides for weed removal (Gruère et al. 2011). Also, the nanoparticles may have a pesticidal side effect on pathogenic fungi. Further, it is observed that silver NPs inhibit the germination of conidia of *Raffaelea* and prevent the death of oak trees (Nair et al. 2010).

Therefore, the knowledge of nanoparticles and their potential applications in plant disease management is crucial for the researchers as well as the general public to address the problems in agriculture and increase the productivity to meet the increasing demands of the huge population. This review will briefly discuss different nanoparticles for the monitoring the plant growth, plant pathogen detection, delivery of agrichemicals, plant growth regulators and DNA for the betterment of crops and their productivity.

Nanotechnology for monitoring plant growth

Nanoparticles for detection of nutrients and contaminants

The use of various nanoparticles (NPs) can be employed for the regulation of plant disease and growth by various modes as depicted in Fig. 1. Besides this, the detection of contaminants like heavy metals is very crucial for monitoring proper plant growth. The separation of heavy metal from aqueous medium using C-based nanomaterials becomes difficult after the adsorption process. However, the magnetic metal/metal oxide nanocomposites' use can simply the heavy metals separation by the application of a magnetic field. The nanocomposite of multi-walled carbon nanotubes (MWCNTs) coupled with ferrous ferric oxide (Fe_3O_4), i.e. MWCNT/nano-Fe_3O_4 has greater adsorption capacity for Cr^{3+} in comparison to pristine MWCNT or activated carbon in an aqueous solution (Gupta et al. 2011a). However, the amount of Cr^{3+} adsorbed is dependent on factors like pH, wet time, and the mixing rate of the solution. Besides this, the nanocomposite can also be used in packaging material of column-based filtration. Similarly, the nanocomposite of multiwalled carbon nanotubes with alumina (Al_2O_3), MWCNT/Al_2O_3, has an enhanced removal capability for Pb^{2+} (Gupta et al. 2011b). In addition, titanium dioxide (TiO_2) is very efficient in nanocomposites for the detection and removal of heavy metals. The removal of several heavy metals by TiO_2 involves the surface complexation mechanisms, while graphite oxide (GO) removes heavy metals through electrostatic interaction. The formation of TiO_2-based flower-like structures on GO nanosheets further ease the process for removal of heavy metals like cadmium, lead and zinc (Lee and Yang 2012).

As all toxic heavy metals do not exist in elemental forms (for example, As and Cr are present in oxidized anion forms), so the use of C-based nanomaterials is very effective in the removal of these toxic forms by sorption. The nanotubes and nanosheets containing iron oxide are found to be effective in removing arsenate and arsenite using positively charged iron particles for electrostatic interaction (Mishra and Ramaprabhu 2010; Veličković et al. 2012; Yu et al. 2015). Arsenite and arsenate have been removed by GO with iron oxide surface groups, respectively, up to 54.18 mg/g and 26.76 mg/g (Yu et al. 2015), with similar values of 53.15 and 39.08 mg/g for MWCNT coated with iron oxide nanoparticles (Mishra and Ramaprabhu 2010). The chromate (Cr(VI)) anions are removed using various nanomaterial adsorbents, however, their removal mechanism is unclear due to a variety of nanocomposites tested (Pillay et al. 2009; Dinda et al. 2013; Gu et al. 2013; Kumar and Rajesh 2013). In this light, pristine (non-functionalized MWCNT) can absorb most of Cr(VI) present in traces in an aqueous solution (Pillay et al. 2009; Gu et al. 2013). Furthermore, GO with liquid cation Aliquat-336 show effective sorption and total removal of toxic chromium from tannery effluent as well as wastewater (Kumar and Rajesh 2013).

The utilization of zero-valent iron nanoparticles (nZVI) with compost from organic wastes has been investigated for its potential for decontamination in soils (Fajardo et al. 2015). The metals treated with nZVI via immobilization can prevent its transport to the groundwater through different layers of soil (Crane and Scott 2012). However, the immobilization of metals by nZVI in soils has only been tested in "in vitro" conditions till date. The immobilization of Pb and Zn in nZVI-treated soils has been demonstrated through leachate analysis (Gil-Díaz et al. 2014b). Some positive results for mobilizing arsenic (Gil-Díaz et al. 2014a), antimony (Dorjee et al. 2014) besides other metals/metalloids in contaminated soils have been obtained. Though the long-term

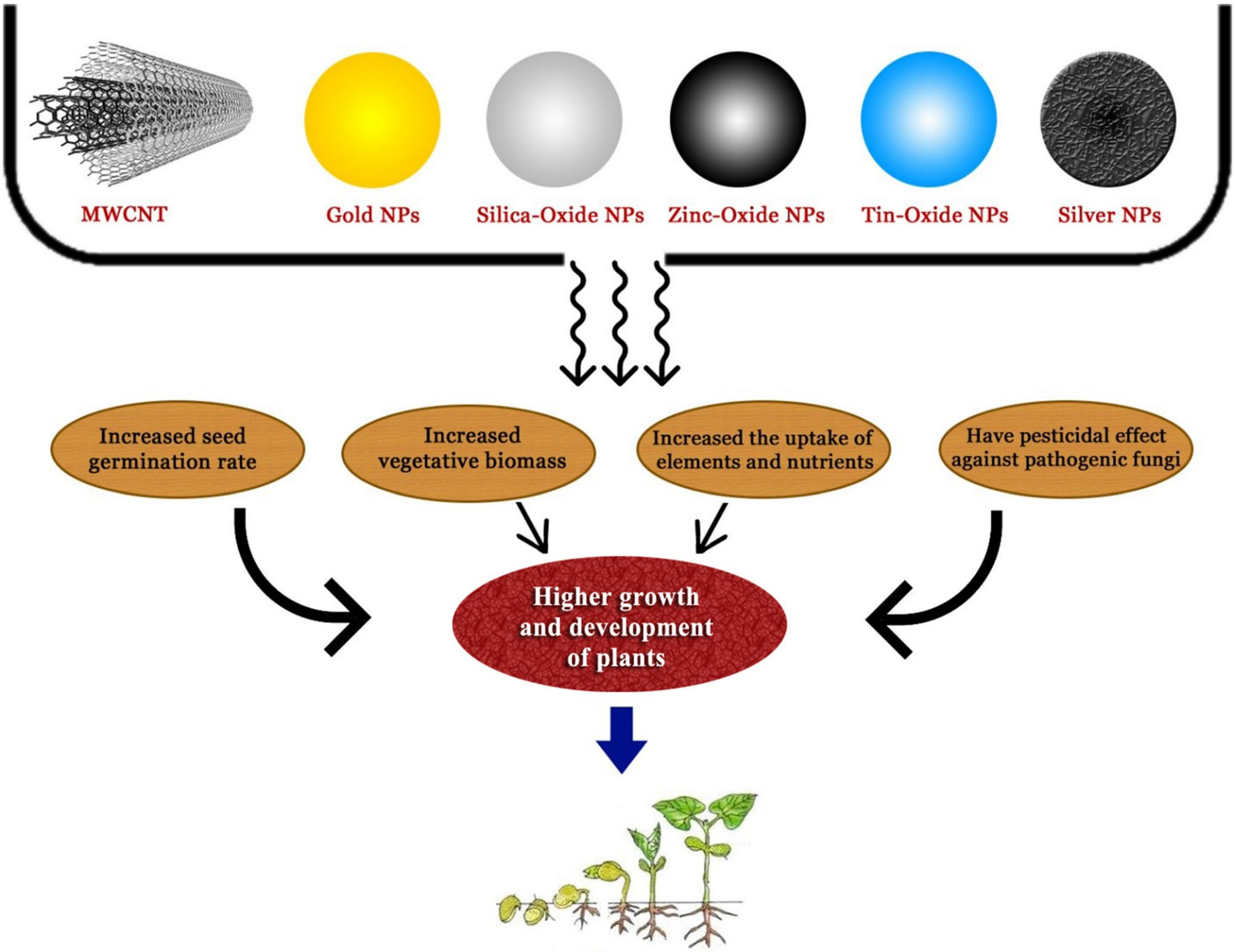

Fig. 1 Application of various nanoparticles (NPs) for the regulation of plant disease and growth by increased seed germination, vegetative biomass, uptake of elements and nutrients along with the management of pathogenic fungi

fate of nZVI in terms of environmental toxicity is a matter of concern, the nanoparticles can easily enter the food chain and cause bioaccumulation as well as spread other non-target pollutants in the soil (Masciangioli and Zhang 2003). Therefore, an in-depth understanding of the behaviour of nanomaterials is crucial to manage and control its toxicity.

Nanosensors for monitoring the environmental stresses and crop conditions

The idea of imaging sensors has been explored to monitor the plants under greenhouse during growth (Parsons et al. 2009). However, the process of assessing the ornamental quality is difficult, as only subjective references could be utilized. The feedforward artificial neural network (ANN) has been used to segregate the images, however, the prediction models in itself cannot achieve high accuracy because of low systematic improvement and robustness. The two important developments in the field of nanotechnology are biosensor and metal oxide-based semiconducting nanowires/nanotubes for plant monitoring. These assist in the exploration of nanoscale-based devices and sensors using different transducers (electric, optical, electrochemical and magnetic) as well as for in vivo detection (Liu 2008; Xia et al. 2010). In addition to this, wireless sensor technology (WST) in speciality crops has added new facets to the earlier communications system. The development of wireless sensor networking (WSN) technology has reduced the cost and power consumption and aided data processing using multifunctional sensor nodes. Besides, WSN helps in connecting to other sensors and access to data with external users. The applications of WST for monitoring crops along with some other applications are listed in Table 1.

WSN is one of the best inventions of the twenty-first century. Unlike radio-frequency identification (RFID) system devices which lack cooperative capabilities, WSN allows

Table 1 Wireless sensing technology (WST) applications in speciality crops

Sensor type	Applications	References
Wireless sensor networking (WSN)	WSN configurations for regulating vineyards	Burrell et al. (2004)
WSN	Management of heat up and potential frost damage in wine production	Beckwith et al. (2004)
WSN	Remote sensing network based on ZigBee	Morais et al. (2008)
WSN	Pest and phytophthora control in a potato field	Baggio (2005)
WSN	Management of distributed greenhouse	Gonda and Cugnasca (2006)
WSN	Regulation of environmental conditions in greenhouses with melon and cabbage	Yoo et al. (2007)
WSN	Real-time measurement of substrate water, temperature, electrical conductivity, photosynthetic radiation and leaf wetness	Lea-Cox et al. (2007)
WSN	ZigBee-based system for monitoring greenhouses	Zhou et al. (2007)
WSN	Temperature and humidity measurement of greenhouse horticulture	van Tuijl et al. (2007)
Radio-frequency identification (RFID)	Imaging and environmental sensing in greenhouses	Yang et al. (2008)
Wireless sensor node	Greenhouse monitoring	Wang et al. (2007)
Wireless sensor node	Measurement of soil parameters (electrical conductivity, humidity, salinity and temperature) in precision horticulture;	López et al. (2009)
WSN	Monitoring refrigerated storage chamber	Ruiz-Garcia et al. (2008)

communication among different network topologies and multihop. A multihop network is dynamically self-organized, where the nodes establish and maintain mesh connectivity among them. Further, motes (a small single unit of nodes) operate on various models to establish networks. These can also collect data on temperature and humidity (Ruiz-Garcia et al. 2009). RFID was initially developed for identification but later exploration in other facets led to the invention of various RFID-based wireless sensors. RFID is commercially active and semi-passive tags capable of collecting data information related to temperature (Amador et al. 2009; Jedermann et al. 2009). Besides this, some semi-passive tags coupled with sensors are under trial for monitoring moisture (Abad et al. 2009), vibration (Todd et al. 2009), light (Cho et al. 2005; Abad et al. 2009), pH (Steinberg and Steinberg 2009) as well as the amount of gases like acetaldehyde or ethylene (Vergara et al. 2007). These tags can also detect microbial contamination in food products and alert us with the food-borne pathogens in the supply chain (Wentworth 2003). These wireless sensor devices can be installed even in places without cable facility, such as in large fields (Morais et al. 2008) or can be embedded within the implements, that can match the readings to the true in situ crop properties (Ruiz-Garcia et al. 2009).

Nanotechnology for plant pathogen detection and crop protection

Pathogens infecting the plants are among the major factors responsible for reducing agricultural produce. Several emerging plant infectious diseases besides the old ones pose a threat to sustainable food supply (Roberts et al. 2006; Savary et al. 2012). Usually, the symptoms are visible on plant parts (leaves, stems and fruits) after infections (López et al. 2003; Al-Hiary et al. 2011). These symptoms help in the disease diagnosis, however, the early detection of pathogens is not possible as the plant infections are symptomless at the initial stages of infection. So, there is an immense need for prior detection of pathogens to control the proliferation of the diseases and monitor the plant health. This will also aid in the prevention of developing other new diseases, especially quarantine pathogens in case of cross-border issues (Vincelli and Tisserat 2008; Miller et al. 2009). For this purpose, several methods for diagnosing plant diseases like DNA-based methods and immunoassays (López et al. 2003), polymerase chain reaction (PCR)-assisted technique of DNA hybridization (Gutiérrez-Aguirre et al. 2009; Yvon et al. 2009), as well as other immunoassays namely enzyme-linked immunosorbent assay (ELISA), ELISA-based tissue print or direct dot-blot immunoassay (DTBIA) have been employed for the detection of pathogens (Nolasco et al. 2002). These molecular methods are robust but do have some limitations, especially when the few pathogens are present in plant parts or vectors during the early stages of infection. To overcome these limitations, biosensors based on antibodies and DNA play a significant role in the detection of plant pathogens (Sadanandom and Napier 2010; Singh et al. 2013). Some of the biosensors for detection of plant pathogens are shown in Table 2.

Nanotechnology for delivery of agrichemicals

Nanotechnology has an immense potential to develop an agricultural sector in such a manner that its environmental impacts are minimal with the use of resources and proper management of the use of various agrichemicals (Chen

Table 2 Biosensors for detection of the plant pathogen. Source: Khater et al. (2017)

Type of biosensor	Detection methods	Detecting plant pathogen
Antibody-based	Electrochemical/Enzyme label	*Cucumber mosaic virus*
	Electrochemical/AuNPs tag	*Pantoea stewartii sbusp. stewartii*
	Electrochemical/label-free	*Maize chlorotic mottle virus, Plum pox virus, Prunus necrotic ringspot virus*
	Optical/AuNPs tag	*Pantoea stewartii subsp. Stewartii, Potato virus x,*
	Optical/fluorescent tag	*Acidovorax avenae subsp., Citrulli, Chilli vein-banding mottle virus. Melon yellow spot virus, Pantoea stewartii sbusp., Stewartii, Watermelon silver mottle virus*
	Optical/label free	*Cymbidium mosaic virus, Odontoglossum ringspot virus*
DNA-based	Electrochemical/label-free	*Plum pox virus*, sugarcane white leaf disease, *Trichoderma harzianum*
	Optical/AuNPs tags	*Acidovorax avenae* subsp. *Citrulli*, Banana bunchy top virus, *Pseudomonas syringae*
	Optical/magnetic tag	*Botrytis cinereal*
	Optical/fluorescent tag	*Banana streak virus*
	Optical/luminescent tag	*Banana bunchy top virus*

and Yada 2011; Ditta 2012; Parisi et al. 2015). Figure 2 depicts the lipid, polymer, clay and porous inorganic-based nanomaterials for the delivery of agrichemicals (nanopesticides and nanofertilizers) to the plants through application in soil.

Nanopesticide

Nanotechnology is growing with promising "nanopesticides" for plant protection and management (Gogos et al. 2012; Khot et al. 2012; Kah et al. 2013). The "nanopesticide"

Fig. 2 The lipid, polymer, clay and porous inorganic-based nanomaterials for the delivery of agrichemicals (nanopesticides and nanofertilizers) to the plants through application in soil

consists of nanosized engineered structures having pesticidal properties (Bergeson 2010; Kookana et al. 2014). These nanosized particles are beneficial due to their unique properties like higher solubility, mobility and durability. In addition, they are designed for targeted release to avoid the harmful effects of chemicals and the development of resistance among pests (Sasson et al. 2007; Kah and Hofmann 2014). Nanocarriers are efficient in delivering agrichemicals including plant growth regulators (PGRs) to the specific target. The applications of nanomaterials for the detection of pesticide residues are enlisted in Table 3. Various mechanisms from the encapsulation of polymers to the use of bond interactions are utilized for long storage and controlled release of these nanoparticles (Pandey et al. 2003; Jordan et al. 2005; Kumar et al. 2014). Recently, Liang et al. (2017) reported bioinspired mussel avermectin NPs [P (St-MAA)-Av-Cat] which showed strong adhesion to plant leaves that can further reduce the loss and possible contamination of soils due to pesticide residues. It further exhibited excellent retention of avermectin with better storage stability and sustained release. In addition to this, Kumar et al. (2019) have developed a green, rapid, and cost-effective probe for detecting Mn(II) ions based on colorimetric measurements. For this, B-AgNPs were prepared by heating AgNPs with the extract from Bhilwa nuts. Then Mn(II) ions were used for the aggregation of B-AgNPs that leads to the colour change from yellowish-brown to dark red and also causes red shift (from 404 to 432 nm) in the surface plasmon resonance (SPR) peak. This colorimetric probe could be efficiently used for the detection of Mn(II) ions in water for field applications.

The polymeric nanospheres and nanocapsules along with nanogels and nanofibers are developed for efficient and controlled release of pesticides (Anton et al. 2008; Bhagat et al. 2013; Brunel et al. 2013; Xiang et al. 2013). Furthermore, the complex nano-based formulations like solid lipid nanoparticles (NPs), inorganic NPs coupled with organic active ingredients and coated liposomes are more efficient for the delivery of pesticides. The examples of organic active ingredients are mesoporous silica and calcium carbonate used as carriers for the controlled release of pesticides. The TiO_2-based nanoparticles (TiO_2 NPs) are utilized to decrease the residual impact on plants and soil by photocatalyzing the released organic ingredients (Bang et al. 2009; Qian et al. 2011; Ao et al. 2012; Kang et al. 2012; Nguyen et al. 2012a, b; Song et al. 2012a, b). It is estimated that about 2 million tons of pesticides are used per year worldwide. Among this, most (around 45%) is used in Europe, 25% in the USA and the remaining 25% in other parts of the world (De et al. 2014). Therefore, proper management of pesticides is essential because they can lead to resistance among pests and pathogens, impact on soil biodiversity by killing useful microbes and can cause biomagnification of pesticides along with destroying natural pollinator like birds (Tilman et al. 2002). Furthermore, the use of nanoparticles assisted with a gene or DNA-based transfer techniques in plants for developing insects and pest-resistant varieties as well as the

Table 3 Application of nanomaterials for the detection of pesticide residues

Pesticide/herbicide	Sensing material	Type of sensor	References
2,4,5-Trichlorophenoxy acetic acid	Poly-*O*-toluidine zirconium (IV) phosphate nanocomposite	Electrochemical	Khan and Akhtar (2011)
Fenitrothion in water samples	Nano-TiO_2/nafion composite	Electrochemical	Kumaravel and Chandrasekaran (2011)
Melamine in milk samples	18-crown-6 ether functionalized Au nanoparticles	Optical	Kuang et al. (2011)
Organochlorine and organophosphorus pesticides in cabbage	Amino-functionalized nanocomposite with tetraethylenepentamine	Chromatography	Zhao et al. (2011)
Methyl parathion in water samples	Nano-ZrO_2/graphite/paraffin	Electrochemical	Parham and Rahbar (2010)
Methyl parathion in vegetables (cabbage, spinach, lettuce)	Nano-Au/nafion composite	Electrochemical	Kang et al. (2010)
Methyl parathion, chlorpyrifos	Nano-sized polyaniline matrix with SWCNT, single-stranded DNA and enzyme	Electrochemical	Viswanathan et al. (2009)
Fenamithion and acetamiprid in water samples	Cd-tellurium quantum dots with *p*-sulfonatocalix(4)arene	Luminescence	Qu et al. (2009)
Parathion in water samples	Nano-ZrO_2/Au composite	Electrochemical	Wang and Li (2008)
Dichlorvos and paraoxon in drinking water samples	Acetylcholinesterase and pyranine immobilized on nano-sized liposomes	Optical nanobiosensor	Vamvakaki and Chaniotakis (2007)
Parathion in vegetables	Nano-TiO_2 on the glassy carbon electrode	Electrochemical	Li et al. (2006)
Pirimicarb in vegetables	Molecular imprinted nanopolymers	Piezoelectric	Sun and Fung (2006)

use of nanomaterial for developing various biosensors are trends that can modernize the agricultural sector (Rai and Ingle 2012).

Nanofertilizer

In the same manner, as nanopesticides, the nanofertilizers have a significant role to enhance the agricultural produce by supplying sufficient nutrients to the plants for their optimum growth and also modifying the conventional fertilization system (Liu and Lal 2015). The nanocoatings applied on the surface of fertilizers can adhere to plant parts more efficiently because of increased surface tension (Ghormade et al. 2011; Yang et al. 2012). Therefore, nanomaterial-based fertilizers, e.g. nutrient-augmented zeolites (Malekian et al. 2011; Zwingmann et al. 2011) enhances the efficiency of plants for the uptake of nutrients and thereby reducing the adverse effects of conventional fertilization system (Liu and Lal 2015). Khalifa and Hasaneen (2018) used chitosan (CS)-based fertilizer for the slow release. The CS–PMAA–NPK NP complex was from CS nanoparticles by polymerizing methacrylic acid (PMAA) for the entrapment of nitrogen, phosphorus and potassium (NPK) nanoparticles (NP). The impact of CS–PMAA–NPK NP complex was evaluated on the garden pea at different concentrations. The results showed reduced root elongation with the accumulation of starch at its tip in a dose-dependent manner. The mitotic cell division was also induced along with upregulation of some proteins like convicilin, vicilin and legumin β. However, the genotoxic effect was observed on the DNA at all the concentrations used, therefore, negative effects could be observed on plants and environment by this carrier with its accumulation in the agricultural fields.

Nanotechnology for delivery of plant growth regulators (PGRs)

Plant growth regulators (PGRs) are plant hormones that play an essential role in agriculture for increasing productivity and quality of crops (E1-Otmani et al. 2000; Rademacher 2015). PGRs can be either natural or synthetic compounds and mainly include auxin, gibberellins, cytokinins, and ethylene (Pereira et al. 2017). In 2014, the global market for agricultural inputs accounted for around 2.5% from these compounds (Rademacher 2015). Chitosan nanoparticles-based release system has been used for the controlled release of nitric oxide (Oliveira et al. 2016), whereas micro-particulates were used for the controlled release of brassinosteroid hormones (Quiñones et al. 2010) and naphthalene acetic acid (Tao et al. 2012). However, the major obstacles in the use of PGRs are their degradation when exposed to environmental factors like heat and light. To overcome these difficulties, the nanoscale materials are employed to increase the stability as well as to reduce their adverse environmental impacts (Campos et al. 2014; Rossi et al. 2014; Grillo et al. 2016). Various nanocarrier systems based on chitosan (CS) have been used for crop protection as well as for gene delivery (Kashyap et al. 2015).

Nanotechnology for delivery of DNA (targeted genetic engineering)

Nanotechnology has a significant role in producing transgenic plants through genetic engineering that have been proven to be an immense asset for the agriculture sector as well as for the pharmaceutical industry (Cunningham et al. 2018; Fachel et al. 2019). Most of the herbicide-tolerant plants, e.g. soy and cotton plants in the US are produced by modifying the gene using genetic engineering (Fernandez-Cornejo and Caswell 2006). The major aspect of transgenic plants is their potential to produce recombinant and therapeutic proteins of pharmaceutical importance, as they are safer medium compared to animal-based (yeast or bacterial) expression systems (Daniell 2006; Verma and Daniell 2007). The use of a suitable binary vector with *Agrobacterium* is an appropriate method to produce transgenic plants. *Arabidopsis thaliana* and *Nicotiana tabacum* are model systems for the genetic transformation of the nucleus and chloroplast of cells, as they are efficient for delivery of DNA and recovery of transformants. Furthermore, flowers immersed in liquid *Agrobacterium* culture by the floral dip method obtain a stable nuclear transformation of *Arabidopsis* germline cells (Clough and Bent 1998).

Salinity or salt stress poses a major concern for crop productivity. It is stress due to the combined effect of elevated osmotic and ionic stress in the soil (Flowers et al. 2014; Song and Wang 2014; Zhang et al. 2014). Plants have inbuilt mechanisms to counter these abiotic stresses through the accumulation of compatible solutes (Chen and Murata 2002). Compatible solutes are highly soluble in water and non-toxic low-molecular-weight compounds. Their concentration increases significantly in the cytosol in response to the saline environment, thereby decreasing the detrimental effects of salinity (Koyro et al. 2013; Zhang et al. 2014). One of the compatible solutes found in plants and animals (especially in marine invertebrates, bacteria and mammals) is glycine betaine (GB) (Chen and Murata 2011). The use of gene technology to transfer GB or genes related to GB has developed tolerance against various environmental stresses (Sakamoto and Murata 2000; Chen and Murata 2008). For example, GB has been applied in the case of non-GB synthesizing plants, tomato (Wyn Jones and Storey 1981). Potassium, on the other hand, balances membrane potential, activates enzymes and regulates the osmotic pressure and controls the stomal movement of cells (Chérel 2004). Besides this, it also acts as an activator of many biochemical processes like photosynthesis and signalling agent for linking plant adaptive responses to the environment (Römheld and Kirkby 2010; Anschütz et al. 2014). Therefore, using targeted gene delivery, genetically modified (GM) crops with specific stress resistance can be developed to withstand the adverse environmental conditions and thus enhance agricultural production. The GM crops are among the fastest adopted commodities in the agricultural biotechnology industry. However, there is a need for precise and sensitive detection methods of genetically modified organisms (GMOs) in GM crops before they are released commercially. Furthermore, an appropriate regulatory framework should be set up to assess the environmental and health-related risks associated with the use of GM crops (Kamle et al. 2017).

Conclusion and future perspectives

The application of nanomaterials in agriculture raises various socio-economic concerns due to their potential to contaminate food, cause phytotoxicity and ultimately impact the ecosystem (Chaudhry and Castle 2011). The impact of nanomaterials in agriculture and their health outcomes have been reviewed by Bouwmeester et al. (2009) and Kahru and Dubourguier (2010). However, the "toxicokinetics and toxicodynamics" of nanomaterials still needs in-depth research (Bouwmeester et al. 2009; Bergeson 2010). Nair et al. (2010) pointed out the effects of the nanomaterials on various agricultural produce as well as the alternative methods of cropping systems if nanomaterials are not degraded quickly. However, in a nutshell, future concern still lies in better understanding of their toxicity mechanisms in biological systems, exposure outcomes and proper control measures. Therefore, future research should be focused on understanding nanomaterials' toxicity, their impact on the ecosystem and suitable methods for sustainable agricultural production along with the proper assessment of the impact of GM crops on the environment and human health.

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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