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Nanobiotechnology for agricultural sustainability, and food and environmental safety

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ORIGINAL ARTICLE

Abstract

Agricultural development has become a requisite to meet the food security of an increasing world population under changing climate for eliminating poverty and hunger. Recently, scientists recognized that human wellness and healthy life are going to face challenges in the near future because of the vulnerability of agriculture and natural resources. It is due to imbalance and unnecessary use of synthetic agricultural inputs in traditional farming systems. Therefore, improved agricultural technology has to ensure, in traditional farming, safe agricultural produce and bringing down of environmental pollution. Recently, nanotechnology (NT) has been recognized as a promising next-generation technology in the field of agriculture. As an environment-friendly and economically viable tool, the potentiality of nanomaterials (NMs), such as nanosensors, nanopesticides, nanofertilizers, nanocarriers, nanochips, and nano-packaging, has shown great prospect in improving safe agricultural productivity and upholding of environmental safety. Because the use of NMs decreases imbalance and unconscious utilization of synthetic fertilizers and pesticides, this minimizes the loss of nutrients and lead to improved agricultural productivity thru the smooth distribution of fertilizers and pesticides, and also improving water and nutrient efficiency. The current review concentrates on the utilization of NT for agricultural sustainability and environmental safety.

Keywords: agriculture, sustainability, nanotechnology, food, environmental safety

Introduction

The world population is rising and has anticipated to grow to 8.6 billion by mid-2030, 10 billion by mid-2050, and 11.2 billion by 2100; as a result, agricultural productivity should be boosted by 50% as compared to 2013 (Islam and Karim, 2019; United Nations, 2017). It is a well-known fact that agriculture has always been a key and steady sector that ensures raw materials for food and feed industries, where the success of each sector primarily depends on their accomplishments and activities (Food and Agricultural Organization of United Nations (FAO), 2017). However, the limitations of these sectors are the utilization of traditional techniques that are not sound environmentally and also not safe for human health (Goodrich-Schneider *et al.*, 2006; Singh and Singh, 2017). For example, in traditional farming, particularly in developing countries, farmers have little knowledge about the excessive and imbalanced use of synthetic fertilizers and pesticides. As a result, in order to get high productivity, generally they use high doses of fertilizers and pesticides, because they are not aware of the negative effects of the imbalance of agricultural inputs which are not good for human health and also not safe for the environment (Lepper *et al.*, 2019; Mann *et al.*, 2009).

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Considering the safety of food and environment, nanotechnology (NT) has been recognized as an interdisciplinary approach that has attracted significant attention in food and agricultural applications (Singh *et al.*, 2015). Nanomaterials (NMs), which are particulate matters having a dimensional range of 1 to –100 nm, play a commendable role in NT. Also, because of their inherent properties, we can to employ these in numerous applications over their bulk counterparts. A concise depiction of applications of NMs in food, agriculture, and in environmental safety is described in Figure 1.

Nanotechnology is an environment-friendly and economically viable tool, because the potential use of NMs, such as nanosensors (NSs), NT-based nanopesticides (NPs) and nanofertilizers (NFs), nanocarriers, nanochips, nano-packaging, and NT-based genetic engineering, have great prospects for improving nontoxic agricultural food and preserving safety of the environment. Also, NMs are exploited to be used in food processing, food packaging, and as nutrient supplements in food industry (Martirosyan and Schneider, 2014). Moreover, safety of the environment is a critical factor for all these applications. Furthermore, improving health of the environment is also very important. Considering the burning issues, the current review has focused on the application of NT in terms of agricultural sustainability, and also for safety of food and the environment.

Nanotechnology in Agriculture

Agriculture is the heart of almost all states of the world; however, overutilization of resources disrupts the quality of soil, thus making it nutrient-poor for sustaining high crop productivity (Kalia and Kaur, 2019). In addition, the pros and cons of conventional agricultural strategies have focused attention on utilizing innovative approaches for cultivation. Hence, modern agriculture is currently working on higher productivity of crops with sustained use of fertilizers by minimizing agro-related expenses (Yousaf *et al.*, 2017). For instance, Abd El-Azeim *et al.* (2020) reported that field experiments done on potato cultivation in two seasons using nitrogen, phosphorus, and potassium (NPK) NFs showed 50% reduction in recommended doses compared to conventional fertilizers. In addition to the economic gain received thru reduced fertilizer usage, higher nutrient use efficiency was observed while receiving elevated harvest. Because NFs use low quantities of materials, their usage can be identified as an

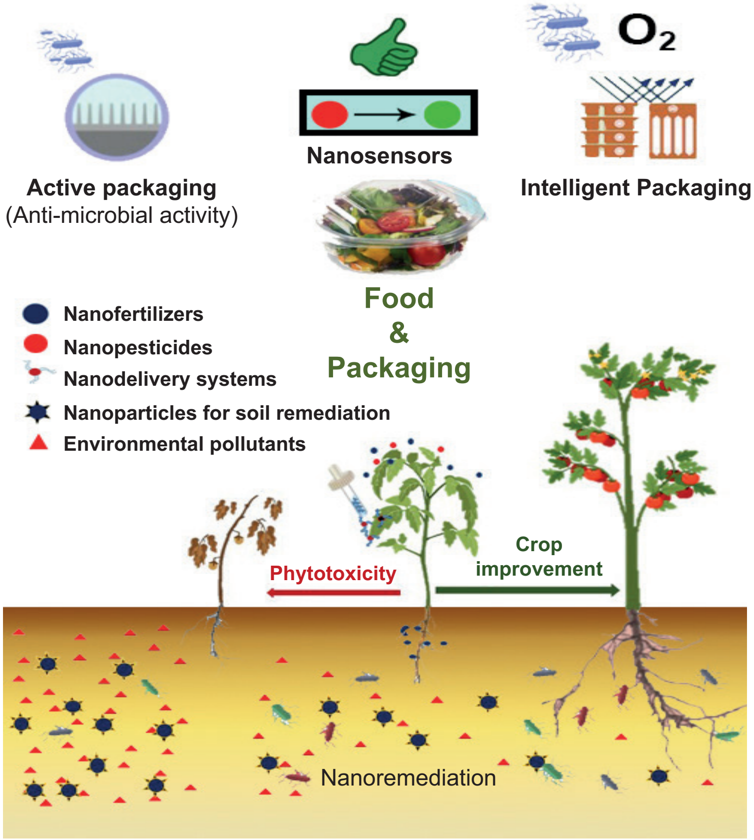

Figure 1. Role of nanomaterials in food, agriculture, and soil remediation strategies.

eco-friendly and economical alternative in comparison to conventional approaches used in crop productivity and quality. In addition, loss in profits can be controlled effectively by using NS-mediated approaches for early detection. Nanosensors can control substantial loss in profits by detecting and eradicating disease-causative agents prior to the first sight of visible symptoms (Panpatte *et al.*, 2016). Furthermore, multifunctional NFs can address issues such as low nutrient use efficiency and damages to soil profiles (Elizabath *et al.*, 2019). However, although NT is a promising approach for smart agriculture, still assessment of its economic feasibility is required (Usman *et al.*, 2020) to control mounting costs and patented expenses incurred by developing countries (Sanivada *et al.*, 2017).

Nanofertilizers enhance crop productivity

It is a well-known fact that conventional fertilizers are used to escalate crop yields. Although increase in crop production is a plus point from agricultural point of view, overconsumption has disturbed mineral balance and soil fertility by affecting terrestrial and marine ecology thru surface runoffs and hypertrophication (Chhipa, 2017; Solanki *et al.*, 2015; Zulfiqar *et al.*, 2019). Therefore, inexhaustible utilization of fertilizers has threatened crop productivity because of their adverse effects on the environment (Chhipa, 2017; El Sheikha, 2016; Solanki *et al.*, 2015), thus making it a double-edged sword.

Modern agronomical strategies, including nanostructured fertilizers, have the potential to uplift the fertilizer usage efficiency of crops via targeted administration and controlled release of plant nutrients (Solanki *et al.*, 2015). Advantageously, this can overcome several constraints of conventional fertilizers. For instance, slow and controlled release of nitrogen fertilizers from modified hydroxyapatite NPs (HANPs) was reported by Kottegoda *et al.* (2011). Compared with commercial fertilizers, nitrogen release was uniform even on the 60th day of its application, clearly showing efficacy over traditional fertilizers. Kumar *et al.* (2018a) also synthesized a nanoformulation containing carbon nanofibers (CNF) for the slow release of copper (Cu) and zinc (Zn). Experimentally, it was demonstrated that NFs facilitate the slow release of Cu and Zn NPs by enhancing the growth of chickpea plants.

Moreover, NFs are economically feasible because they reduce the requirement of transportation and cost of application. Also, use of their minute quantities to soil minimizes the risk of loading salts in contrast to over-application of traditional fertilizers. Furthermore, in modern agriculture, NMs can be easily fabricated based on the nutritional requirements of targets (León-Silva *et al.*, 2018; Zulfiqar *et al.*, 2019). Depending on the nutrient requirements of plants and properties of NMs, NFs can be divided into the following four categories: (i) macronutrient NFs, (ii) micronutrient NFs, (iii) nanoparticulate fertilizers, and (iv) NFs.

Macronutrient nanofertilizers

It is estimated that by 2050, growth in food production will increase the demand of macronutrients by up to 263 MT (Alexandratos and Bruinsma, 2012), and this would be a challenging task for world's food production. Inherent properties of NMs reduce the quantitative application of fertilizers by enhancing their efficiency over ordinary fertilizers. Therefore, the augmentation of NMs with macronutrients (e.g., N, P, K, magnesium (Mg), sulfur (S), and calcium (Ca)) can supply precise amounts of nutrients, thereby minimizing their bulk requirements (Chhipa, 2017; Ditta and Arshad, 2016). In this regard, research has synthesized and tested a range of macronutrient NFs as agricultural inputs. Ramírez-Rodríguez *et al.* (2020a) speculated the use of multi-nutrient NFs containing N and K ions-doped calcium phosphate (CaP) NPs as a slow-releasing approach for smart agriculture. Experiments conducted on wheat plants in a growth chamber showed a comparable increase in yield with the advantage of using much lower amount of N (a reduction of 40% by weight) than conventional strategies. Also, using engineered urea-doped CaP NPs on *Triticum durum* plants confirmed the possibility of applying N to plants in a more safe and efficient manner (Ramírez-Rodríguez *et al.*, 2020b). Besides, sulfpate-supplemented and chitosan (CS) NP-based NPK NFs (Dhlamini *et al.*, 2020; Ha *et al.*, 2019) showed promising results as macronutrient fertilizers on sustainable agricultural activities.

Controlled nitrogen-releasing sources using zeolite chips, HANPs, and modified layered nanohybrid structures, such as urea–hydroxyapatite-montmorillonite nanohybrid composites (Kottegoda *et al.*, 2011, 2014, 2016; Madusanka *et al.*, 2017; Millán *et al.*, 2008), in agricultural activities for longer duration is another alternative in modern-day fertilization. In addition, nano-N chelate fertilizers significantly increased the production of sugar from sugarcane by reducing nitrate leaching in soil (Alimohammadi *et al.*, 2020).

Pristine HANPs were shown as an alternative for conventional phosphorus fertilizers (Liu and Lal, 2014; Madanayake *et al.*, 2021). Recently, pot tests using multifunctional phosphorus NFs (PNFs) containing humic substances and HANPs showed improved plant growth and productivity in corn. Besides, root microbiome and resistance against abiotic stresses in *Zea mays* were also enhanced (Yoon *et al.*, 2020). Besides, phosphorus loaded with iron oxyhydroxide NPs for agricultural applications was reported as another alternative in fertilization (Bollyn *et al*., 2019).

Foliar application of potassium NFs to peanut crops grown on sandy soils increased seed, pod, and oil yields by 91.5%, 120%, and 99.8%, respectively, compared with control (Afify *et al*., 2019). Moreover, K and N containing NFs can increase the growth and fruit yield of tomato, revealing that these applications could increase crop yields (Ajirloo *et al*., 2015). Applying Mg and iron (Fe) NPs could enhance the photosynthesis efficiency of black-eyed pea, was manifested by Delfani *et al.* (2014). Moaveni *et al.* (2020) highlighted that the foliar application of Mg and iron oxide (Fe_2O_3) NPs caused some changes in physiological traits and mucilage yield of sour tea. Besides, the use of 0.01% of MgO and 0.03% of Fe_2O_3 can improve the physiological properties of sour tea.

Micronutrient nanofertilizers

Micronutrients are trace minerals required in lower quantities but essential for different metabolic processes of plants (Chhipa, 2017). Importantly, the positive impacts of micronutrient NFs on the enhanced growth and crop productivity have been reported by many authors. Biosynthesized zinc NPs (Zn NPs, 15–25 nm) were used as NFs by Tarafdar *et al.* (2014) to enhance crop productivity in pearl millets. In 6 weeks old plants, a significant increment in primary growth parameters and plant metabolic activities were observed with respect to their controls. A single spray of lower quantities of boron (B) and Zn NFs (34-mg B, or 636-mg Zn) per tree increased pomegranate fruit yield and quality (Davarpanah *et al*., 2016). Fertilization with the highest doses showed a significant improvement in fruit quality at the time of harvest. Recently, Abbasifar *et al.* (2020) utilized green-synthesized Zn and Cu NPs for basil plants. Foliar application of 4,000- ppm Zn NPs and 2,000-ppm Cu NPs significantly affected chlorophyll pigments of basil leaves. In addition, the highest phenolic and flavonoid contents were obtained with the same treatment, but the highest antioxidant activity was observed with 4,000-ppm Zn NPs only. Therefore, it was proved that the foliar application of Zn and Cu NPs could enhance qualitative and quantitative crop productivity of basil plants.

Moreover, Cota-Ruiz *et al.* (2020) tested for compounds containing Cu NPs in agrosystems to improve the agronomical and physiological performances of crops using alfalfa as the model plant. Of the potting mixtures amended with 80- and 280-mg Cu/kg of bulk, nano, and ionic Cu compounds, plants treated with bulk Cu NPs showed effective agronomical responses than its ionic forms. In addition, Cu NPs increased the relative abundance of microorganisms necessary for elemental uptake. Palchoudhury *et al.* (2018) investigated the effect of embryonic root growth in legumes using low and high concentrations of iron oxide NPs using varied pH values of seed pre-soaking solutions. It was determined that iron oxide NPs enhance root growth by 88–366% at lower concentrations (5.54×10^{-3} mg/L Fe). Also, Shebl *et al.* (2019) synthesized manganese zinc ferrite NPs ($Mn_{0.5}Zn_{0.5}Fe_2O_4$ NPs, 10–12 nm) and exploited their efficiency as NFs in *Cucurbita pepo*. It was speculated that $Mn_{0.5}Zn_{0.5}Fe_2O_4$ NPs synthesized at 180°C showed the highest vegetative growth for *C. pepo*. In addition, the highest values of vegetative growth and yield character were provided by the lowest concentrations of $Mn_{0.5}Zn_{0.5}Fe_2O_4$ NPs. Interestingly, Liu *et al.* (2016) experimented with the effects of lower concentrations (<50 ppm) of Cu, Zn, Mn, and iron oxide NPs on the germination of *Lactuca sativa* seeds in an aqueous medium. Results showed that CuO- and ZnO-NPs were slightly more toxic than their ionic counterparts. However, MnOx- and FeOx-NPs were less toxic than their ionic forms and significantly stimulated the growth of *L. sativa* seedlings by 12–54%. This proves the fact that Mn or Fe NPs have the potential to become promising candidates as NFs for agronomic activities.

Nanoparticulate fertilizer

Other NPs, including TiO_2, SiO_2, and carbon-based NMs, are also reported in literature for their potential to promote plant growth (Chhipa, 2017). Tomato plants show a concentration-dependent enhancement in growth once TiO_2 and ZnO NPs (Raliya *et al*., 2015) are applied. TiO_2 and SiO_2 enhanced the accumulation of N, seed germination, and growth in *Glycine max* (Changmei *et al*., 2002). Also in *Spinacia oleracea*a, significant increment in protein, chlorophyll, and N amounts was observed when TiO_2 NPs were sprayed solely (Gao *et al*., 2006). Moreover, improved seed germination of sorghum and switchgrass was observed with graphene and multi-walled carbon nanotubes (MWCNTs). Also, graphene NPs at 200 mg/L increased the total biomass of switchgrass by 28% (Pandey *et al*., 2018). Besides, early seed germination of Catharanthus was activated by MWCNTs and grapheme, and higher germination rates of cotton and Catharanthus seeds (Pandey *et al*., 2019) were also recorded with respect to controls (no carbon-based NMs).

Nanobiofertilizers

The application of nutrients with biofertilizers at nanoscale has been speculated as an economically friendly tactic to promote integrated nutrient management for smart agriculture (Kalia and Kaur, 2019). Effects of NMs are dose-dependent; in other words, higher concentrations show detrimental effects on flora and fauna. Hence, their applications would be problematic if they inhibit the growth of greenery. Therefore, adequate and safer approaches can increase the merits of NPs application at environmentally safer doses (Gouda *et al.*, 2018; Kalia and Kaur, 2019).

The combined application of NFs with NMs and bio-inoculants can ensure scheduled and targeted nutrient delivery to crops, besides improving the advantages received from biofertilizers (Gouda *et al.*, 2018). Studies have found that the effects of NPs on plant-microbiome-can occur via improved nutrient availability or indirectly stimulating the effects of plant growth-promoting rhizobacteria. Therefore, diverse modes of NFs applications, namely implementing NFs and biofertilizers separately or as nano-augmented bio-fertilizers, are advocated (Gouda *et al.*, 2018).

Application of nanobiofertilizers on wheat plants enhances the spike length, spike number, grain yield, and weight by reducing the duration of physiological maturity (Mardalipour *et al.*, 2014). Spraying *Brassica oleracea* plants with CS–urea NPs (1,000 mg/L) and plant mycorrhiza cut off the input of chemical nitrogen fertilizers by 33.3%; this is recorded as a comparable application for the full dose of urea (Shams, 2019). Although lack of fundamental knowledge on the interactions between NPs and plant hinders the efficient development and implementation of these formulations (Kalia and Kaur, 2019) currently, NFs proved to increase the growth and plant components of harvests by expanding the growing phase (Mardalipour *et al.*, 2014). Table 1 depicts the summary of application of NFs in agriculture.

Nanopesticides

Nanopesticides can be of various forms consisting of organic (e.g., active ingredients such as essential oils and polymers) or inorganic components, including metal oxides (Shaker *et al.*, 2017). Nano-sized delivery systems are capable of improving controllable release, photostability, and biological activity while reducing the residual activity of pesticides (Selyutina *et al.*, 2020), as seen in conventional pesticides. Therefore, nano-carriages capable of penetrating cuticles and other plant openings, allowing a precise pesticide targeting, has a greater opportunity to mitigate the challenges faced by current plant protection products (Cao *et al.*, 2016).

Polysaccharides- and oligosaccharides-based NPs have a greater penetration associated with enhanced solubility. In addition, the affinity of delivery systems to the targets and plasma membrane modification can make their applications more promising. Selyutina *et al.* (2020) prepared nano-delivery systems using glycyrrhizin and arabinogalactan nanocomposites containing pesticides: tebuconazole, imidacloprid, imazalil, and prochloraz. These delivery systems proved to enhance pesticides' solubility and improve penetration into corn and rape seeds.

Mesoporous silica NPs (MSNPs) capped with CS derivatives (CSNPs) as NP carriers for pyraclostrobin were used by Cao *et al.* (2016). Here the surface fabrication with CS derivative provided a strong electrostatic interaction for MSNPs to act as a vehicle for plant protection against *Phomopsis asparagi*. Previously, the controlled supply of water-soluble pesticides using porous hollow silica NPs was exploited by Liu *et al.* (2006).

TiO_2 NPs on Egyptian cotton leafworm, *Spodoptera littoralis*, was evaluated by Shaker *et al.* (2017). A lower concentration of lethal dose (LC_{50}) against 2nd and 4th instar larvae was observed when treated with TiO_2 NPs, showing that their lower dose of application minimized the problems caused by *S. littoralis* on their host crops. In addition, silver (Ag) NPs loaded with pyrethroid pesticides showed positive results and a successful approach to reduce pest resistance and environmental pollution (Ahmed *et al.*, 2019). Furthermore, antimicrobial activities of Ag NPs against certain plant pathogens are also reported in literature (Jo *et al.*, 2009; Roseline *et al.*, 2019), thereby proving them as promising NPs.

Currently, the focus on essential oil-based biopesticides appears to be a complementary replacement of synthetic insecticides in crop production as well as integrated pest management. Since ancient times, essential oils containing secondary metabolites of plants have been used widely as biopesticides because of their antimicrobial and pesticidal activities as well as less toxicity compared with synthetic chemical pesticides (Pascoli *et al.*, 2019).

Augmentation of NT to develop nanoformulations is expected to enhance their effectiveness while reducing toxicity toward non-target organisms, and cutting the wastage of pesticides while increasing the persistency of active ingredients (Adel *et al.*, 2019; Anjali *et al.*, 2010). Adel *et al.* (2019) introduced a new delivery system to control the black cutworm *Agrotis ipsilon* using geranium essential oil (GO) incorporated into solid lipid NPs (SLNPs) as a controlled-release formulation. The results of GO bulk forms were compared with that of oil post-loading solid NPs and tested under laboratory and field conditions for their efficiency on larval development, pupal mortality, and adult longevity. Laboratory bioassays have found that GO-SLNPs were effective on larval and pupal development as well as on the adult longevity and female fecundity compared with the bulk form of GO. Furthermore, field–laboratory experiments showed direct and residual effects in terms of speed of

Table 1. Applications of nanofertilizers in crop production systems.

Application	Type of NMs	Model plant	Effects	References
Macronutrient NFs	N and K ions-doped CaP NPs	Wheat	• Increased the yield with the advantage of using much lower amount of N (a reduction of 40% of weight) than conventional strategies	Ramírez-Rodríguez *et al*. (2020a)
Macronutrient NFs	Urea-doped CaP NPs	*Triticum durum*	• Possibility of applying N to plants more safely and efficiently with NMs	Ramírez-Rodríguez *et al*. (2020b)
Macronutrient NFs	Multifunctional P NFs containing humic substances and HANPs	*Zea mays*	• Enhanced plant growth and productivity in corn • Root microbiome and the resistance against abiotic stresses enhanced	Yoon *et al*. (2020)
Macronutrient NFs	K NFs	Peanut	• Increased the seed, pod, and oil yields by 91.5, 120, and 99.8% over the control	Afify *et al*. (2019)
Macronutrient NFs	K and N containing NFs	Tomato	• Increased the growth and fruit yield of tomato	Ajirloo *et al*. (2015)
Macronutrient NFs	Mg and iron oxide NPs	Sour tea	• Changes in physiological traits and mucilage yield • Improved the physiological properties of sour tea	Moaveni *et al*. (2020)
Micronutrient NFs	Biosynthesized Zn NPs	Pearl millets	• Enhanced crop productivity • In 6 weeks old plants, a significant increment in primary growth parameters and plant metabolic activities	Tarafdar *et al*. (2014)
Micronutrient nanofertilizers	B- and Zn-NFs	Pomegranate	• A single spray of lower quantities per tree increased fruit yield and quality	Davarpanah *et al*. (2016)
Micronutrient NFs	Green synthesized Zn and Cu NPs	Basil	• Foliar application of 4,000 ppm Zn NPs and 2,000 ppm Cu NPs significantly affected chlorophyll pigments • The highest phenolic and flavonoid contents were obtained for the same treatment, and the highest antioxidant activity was observed with 4,000-ppm Zn NPs only	Abbasifar *et al*. (2020)
Micronutrient NFs	Cu NPs	Alfalfa	• Increased the relative abundance of microorganisms required for elemental uptake	Cota-Ruiz *et al*. (2020)
Micronutrient NFs	Iron oxide NPs	Legumes	• Enhanced root growth by 88–366% at lower concentrations (5.54×10^{-3} mg/L Fe)	Palchoudhury *et al*. (2018)
Micronutrient NFs	Manganese zinc ferrite NPs	*Cucurbita pepo*	• NPs synthesized at 180°C showed the highest vegetative growth • Highest values of vegetative growth and yield characters were provided by the lowest concentrations	Shebl *et al*. (2019)
Micronutrient NFs	Cu, Zn, Mn, and iron oxide NPs	*Lactuca sativa*	• CuO NPs and ZnO NPs were slightly more toxic than their ionic counterparts • MnOx NPs and FeOx NPs were less toxic than their ionic forms and significantly stimulated the growth of L. sativa seedlings by 12–54%	Liu *et al*. (2016)
Nanoparticulate fertilizer	TiO_2 and ZnO NPs	Tomato	• Concentration-dependent enhancement in growth	Raliya *et al*. (2015)
Nanoparticulate fertilizer	TiO_2 and SiO_2 NPs	*Glycine max*	• Enhanced the accumulation of N, seed germination, and growth	Changmei *et al*. (2002)
Nanoparticulate fertilizer	TiO_2 NPs	*Spinacia oleracea*	• A significant increment in protein, chlorophyll, and nitrogen content	Gao *et al*. (2006)
Nanoparticulate fertilizer	Graphene and multi-walled CNTs (MWCNTs)	Sorghum switchgrass	• Improved seed germination of sorghum and switchgrass. • Graphene NPs at 200 mg/L increased the total biomass of switchgrass by 28%	Pandey *et al*. (2018)
Nanoparticulate fertilizer	MWCNTs and graphene	Catharanthus Cotton	• Activated the early seed germination of Catharanthus • Higher germination rates of cotton and Catharanthus seeds	Pandey *et al*. (2019)
Nanobiofertilizers	CS–urea NPs (1,000 mg/L) and plant mycorrhiza	*Brassica oleracea*	• Spraying of plants cut off the inputs of chemical nitrogen fertilizers by 33.3%.	Shams (2019)

mortality, toxicity, and stability at tested concentrations, thus proving its suitability to use under field conditions. In addition, Pascoli *et al.* (2019) described a neem oil-loaded zein NPs, showing promising results to use them as NPs in organic agriculture. Furthermore, NP-mediated botanical pesticides are also reported to be effective candidates for agricultural applications for synthetic plant protection as pesticides, anti-feedants, insect growth regulators, and repellents (Paulraj *et al.*, 2017). CNT-functionalized *Bacillus thuringiensis*-based and gene regulative NPs are also reported in literature (Devi *et al.*, 2019; Sarlak *et al.*, 2014; Zhao *et al.*, 2017). Table 2 provides the summary of NP applications.

Nanomaterials for crop improvement

Scientific progress in genetic engineering has greatly improved the manner to produce crops with enhanced growth and nutritional profiles and resistance to biotic and abiotic stresses (Mohamed and Abd-Elsalam, 2019). Although NT-based gene delivery is new for plant science, it has offered tremendous opportunities for crop improvement to increase agricultural productivity (Jat *et al.*, 2020). NMs, including CNTs, magnetic NPs, and MSNPs, are widely studied for nucleic acid delivery in plant cells (Jat *et al.*, 2020). As a novel approach, different types of NPs function as transgenic vehicles for exogenous genetic materials for plant cells (Mohamed and Abd-Elsalam, 2019).

The NPs-mediated non-viral gene delivery systems are capable of successfully controlling the copies of DNA and overcoming transgenic silencing. In addition, NPs easily functionalize as per the demand of receptors of plant cells to improve transformation efficiency (Ardekani *et al.*, 2014). Rigid walls of plant cells with cellulose microfibrils are established as a major challenge for gene delivery to plants. Although researches have explored the possibility of using protoplasts for gene delivery as a promising approach, limitations exist in optimized protocols regarding the development of plantlets from protoplast cultures. Therefore, gene delivery through cell walls is the main confrontation for genetic manipulations, but this can be overcome using NT (Jat *et al.*, 2020) for crops improvement.

The role of carbon-based NMs on crop improvement was assessed by Adeel *et al.* (2021) by suppression of viral infections in *Nicotiana benthamiana*. With 200 mg/L CNTs and graphene NPs, normal phenotypic characters were exhibited with no viral symptoms (after 5 days' post-infection). In addition, fluorescence measurements indicated that photosynthesis was equivalent to healthy controls. More importantly, upregulation of gene expression of defence-related phytohormones and synthesis were elevated by 33–52% and 94–104%, respectively. Demirer *et al.* (2019) demonstrated an efficient protocol for the delivery of plasmid DNA into plants using functionalized CNTs to improve efficient DNA delivery into arugula, wheat, and cotton plants. A high level of protein expression without transgene integration resulted as an optimized approach of DNA delivery in a species-independent mode. Furthermore, Kwak *et al.* (2019) rationally designed a CS-complexed single-walled CNTs, a selective deliver system of plasmid DNA to chloroplasts of *Eruca sativa, Nasturtium officinale, Nicotiana tabacum*, and *S. oleracea*. The authors demonstrated chloroplast-targeted transgene delivery without an external biolistic or chemical aid, reducing the efforts established in conventional methods. Therefore, these nano-carrying systems offer a pragmatic advantage in contrast to traditional methods as a novel candidate for transformation techniques. Ardekani *et al.* (2014) developed a novel gene transfer carrier using nano-CaP to effectively transfer plasmid DNA in tobacco. Results showed the successful delivery of pBI121 harboring GFP driven by 35S promoter-encoding plasmid DNA into tobacco cells.

Table 2. Applications of nanopesticides in crop production systems.

Nanopesticides	Pest	Effect	References
Mesoporous silica NPs capped with CS derivatives (MSNPs) carriers for pyraclostrobin	*Phomopsis asparagi*	• Surface fabrication with CS derivative provided a strong electrostatic interaction for the MSNPs to act as a vehicle for plant protectants against *Phomopsis asparagi*	Cao *et al.* (2016).
TiO_2 NPs	Egyptian cotton leafworm, *Spodoptera littoralis*	• Lower concentration of lethal dose (LC50) against 2nd and 4th instar larvae	Shaker *et al.* (2017)
Ag NPs loaded with pyrethroid pesticides		• A successful approach to reduce pest resistance and environmental pollution	Ahmed *et al.* (2019)
GO incorporated into solid lipid NPs (SLNPs)	Black cutworm	• Effective on larval and pupal development as well as on the adult longevity and female fecundity compared with the bulk form of GO • Field–laboratory experiments showed direct and residual effects in terms of speed of mortality, toxicity, and stability at tested concentrations	Adel *et al.* (2019)

Table 3. Applications of nanomaterials in crop improvement.

Nanomaterials (NMs)	Functions	Effects	References
Carbon-based NMs	• Suppression of viral infections on *Nicotiana benthamiana*	• At 200 mg/L CNTs and graphene NPs exhibited normal phenotypic characters with no viral symptoms after 5 days of post-infection • Upregulating the gene expression of defence-related phytohormones and synthesis	Adeel *et al*. (2021)
Functionalized CNTs	• Delivery of plasmid DNA into plants to improve the efficient DNA delivery in arugula, wheat, and cotton plants	• A high level of protein expression without transgene integration	Demirer *et al*. (2019)
CS-complexed single-walled CNTs	• Deliver system for plasmid DNA to chloroplasts of *Eruca sativa, Nasturtium officinale, Nicotiana tabacum*, and *S. oleracea*	• Chloroplast-targeted transgene delivery without an external biolistic or chemical aid	Kwak *et al*. (2019)
Nano-CaP	• Gene transfer carrier used to effectively transfer plasmid DNA in tobacco	• Successful delivery of pBI121 harboring green fluorescent protein (GFP) driven by 35S promoter-encoding plasmid DNA into tobacco cells	Ardekani *et al*. (2014)
Functionalized MSNPs	• DNA delivery technique	• Expression was clearly observed in epidermis and endodermal root tissues and the more inner cortical of *Arabidopsis thaliana* by fluorescence and antibody labeling	Chang *et al*. (2013)
Magnetic NPs	• Pollen-based transformation	• Magnetic NPs conjugated with plasmid DNA introduced into pollens under a field of force to fabricate genetically modified seeds via pollination	Zhang *et al*. (2019)

Therefore, these studies reveal the efficacy of CaP NPs as non-viral gene delivery in tobacco plant transformation as a novel system of plant genetic modification.

Chang *et al*. (2013) proposed a facile DNA delivery technique using functionalized MSNPs to develop a gene expression system. Expression was clearly observed in epidermis and endodermal root tissues and the more inner cortical of *Arabidopsis thaliana* by fluorescence and antibody labeling. Hence, these data provide information on engineering functional NPs as an alternative of traditional techniques. Moreover, Zhang *et al*. (2019) presented a pollen-based transformation (pollen magnetoreception) protocol using magnetic NPs to build transgenic seeds with no tissue culture. Magnetic NPs were conjugated with plasmid DNA introduced into pollens under a field of force to fabricate genetically modified seeds via pollination. Therefore, this could be emphasized as a systemic platform of genetic transformation for economically important crops. A tabulated summary is provided in Table 3.

Nanomaterials for soil remediation and environmental security

Overutilization of resources has threatened the environmental balance, affecting the lives of flora and fauna. Owing to this, environmental health and security has become an utterly important factor for our survival. Therefore, remediating of the environment with possible contaminants and pollutants has been forced on every government of the world. Hence, environmental remediation can be simply identified as a systematic approach to eliminate pollutants or contaminants from different environmental compartments to protect every individual to maintain environmental health (Ingle *et al*., 2014).

In contrast to different environmental compartments, soil has a range of utility with a critical role in the balanced flow of ecosystem. From agricultural perspective, maintaining a healthy soil profile is the ultimate goal of every state. Therefore, the remediation of soil has fostered a lot for environmental safety. Presence of contaminants, excluding their minimum levels, in soils, causing deleterious effects on organisms, is defined as soil pollution (Sarkar *et al*., 2019). Primarily, industrial and anthropogenic activities lead to the release of large quantities of heavy metals and metalloids into surroundings, causing deleterious effects on the environs (Parmar *et al*., 2013). Even at lower concentrations, soil contaminants can risk human health (Baragaño *et al*., 2020b; Wuana and Okieimen, 2011). For instance, arsenic (As) released from natural or artificial sources causes highly toxic effects on the biota, and chronic defects and carcinogenic effects in humans (Gil-Díaz *et al*., 2016). Therefore, remediating these pollutants can minimize the risks caused to human and environmental health.

Currently, available approaches (physical, chemical, and biological) have more or fewer limitations, which may be laborious, time-consuming, and significantly expensive (Ingle *et al*., 2014). Owing to this, nanotechnological approaches to eliminate toxic components from the environment have become quite attractive. In contrast to conventional approaches, unique properties of NPs have fostered to use them more effectively and efficiently for soil or waste-water, or groundwater management. First, the size of NPs enables to inject them easily into tiny spaces and maintain their activities for extended durations. Second, high surface area aids in high enzymatic activity. Third, NPs can be easily transported with water flow while controlling them thru gravitational sedimentation. Finally, NPs can be adsorbed on solid matrices, allowing them for remediation strategies (El-Ramady *et al*., 2017; Sarkar *et al*., 2019). Hence, this section focuses on some of the NMs used in soil remediation for sustained environmental security.

Iron-based NPs

Most of the studies have focused on utilizing iron-based NMs for soil remediation strategies (Baragaño *et al*., 2020a; Fajardo *et al*., 2020; Gil-Díaz *et al*., 2016, 2019). For instance, Gil-Díaz *et al*. (2019) used nano zero-valent iron (nZVI) to remediate soils contaminated with As and mercury (Hg) in two regions (A and B) differing in contaminant loads (region B is having lower contaminant load). Results indicated that with 2.5% dosage of treatment, there was a significant reduction in the availability of As and Hg. However, region B showed the highest immobilization of As and Hg (decreasing by 70% and 80%, respectively). In contrast, there was 65% and 50% reduction in As and Hg, respectively, in region A. Therefore, this finding confirms the use of nZVI as an effective approach to nano-remediate soils contaminated with heavy metals.

Calcium peroxide NPs

Eliminating aromatic pollutants from soils is highly focused by the studies related to calcium peroxide NPs. Primarily, calcium peroxide NPs are capable of speeding the reaction rates by enhancing the aspect ratio of reactive surfaces. In addition, reduced agglomeration of individual moieties of calcium peroxide NPs has attracted its application for nano-remediation (Khodaveisi *et al*., 2011). Moreover, these NPs have been successfully used in the removal of liquid fuels from soil (Mueller and Nowack, 2010). Generation of oxygen during degradation of NPs from contaminants facilitate an aerobic environ critical for bioremediation (Mueller and Nowack, 2010; Sarkar *et al*., 2019) process to provide a synergistic effect in remediation strategies.

Other nanopesticides

Carbon-based NPs, polymeric NPs, nanocomposites, and bio-NPs having viruses, plasmids, and proteins (Rizwan *et al*., 2014) are utilized for nano-remediation applications. Graphene oxide NPs (GOx NPs) is effectively applied for immobilizing Cu, lead (Pb), and cadmium (Cd), with a slight effect on soil pH and soil electrical conductivity. Therefore, immobilization strategies using GOx could be regarded as an emerging approach for soil nano-remediation (Baragaño *et al*., 2020b).

Remediation of radioactive materials from soils has gained much attention because of their risks on flora and fauna. For instance, Mallampati *et al*. (2012) showed that nano-metallic Ca/PO_4 effectively immobilized caesium by ball milling method. In addition, nano-metallic Ca/PO_4 significantly decreased the time of ball milling method. Therefore, NT-based approaches have become a promising candidate to remediate radioactive-contaminated soils. Lower solubility, high stability under reducing and oxidizing conditions, and high sorption capacity of HANPs make them an ideal material for the immobilization of heavy metals. He *et al*. (2013) assessed the efficiency and mechanism of HANPs to trap Pb and Cd in contaminated soils. Surface complexation of HANPs and dissolution of HANP amendments and precipitation of Pb/Cd-containing phosphates were indicated as possible mechanisms of Pd and Cd immobilization; because of this, HANPs had reduced the phyto-availability of Pb and Cd by 65.3% and 64.6%, respectively, in contaminated soils. In addition, biochar-containing composites are used successfully in environmental remediation strategies (Ashiq *et al*., 2019a, 2019b). These are some of the applications of these potent agents in the field of agriculture. Hence, securing the environment can sequester several merits, including clean and safe environment.

Nanomaterials in the Food Industry

Food-related industries have experienced a greater influence and interest of NT by the opening of new possibilities in food sector. Currently, application of NT is focused on manufacturing food packaging systems for active packaging, materials barriers, and sensing and signaling of relevant information (Sekhon, 2010). Therefore, NT has opened novel pathways for rapid restructuring of food sector. Hence, this section discusses different NMs utilized in the food industry with respect to their functional aspects.

Sliver NPs in the food industry

Among metallic NPs with biocidal properties, silver NPs (Ag NPs) have the highest effectivity against a wide range of food pathogens (Carbone *et al.*, 2016). For instance, green-synthesized Ag NPs using the wild mushroom *Ganoderma sessiliforme* showed a greater antimicrobial activity against the following food pathogens genera: *Escherichia, Bacillus, Streptococcus, Listeria*, and *Micrococcus spp.* (Mohanta *et al.*, 2018). Therefore, inherent microbicidal characteristics of Ag NPs and their nanocomposite derivatives have become interesting active packaging materials of food arena (Rodino *et al.*, 2019; Santos *et al.*, 2020).

Becaro *et al.* (2015) synthesized low-density polyethene (LDPE) films containing Ag NPs for food packaging. Authors demonstrated microbiological experiments using *Escherichia coli* and *Staphylococcus aureus*, which showed promising results in enhancing food shelf life. Kumar *et al.* (2018b) fabricated a biodegradable nanocomposite containing Ag NPs with CS and gelatin (GL) biopolymer hybrid for active food packaging. The CS–GL films, with respective proportion of 0.05% and 0.1%, showed a desirable mechanical strength with protective packaging to extend the longevity of foods. Anthocyanin-rich purple corn extract (PEC) and Ag NPs-incorporated CS film was developed by Qin *et al.* (2019) for smart packaging. Synergistic effects of PCE and Ag NPs of CS films had remarkably strengthened the light and water vapor barrier properties with stronger mechanical, antioxidant, and antimicrobial features. In addition, pH-dependent color variations can monitor the quality of packaged foods.

Optical and electronic properties of Ag NPs have been provenly used as a productive catalytic material in food industry. Faster starch degradation via Ag NPs-immobilized ∝-amylase was described by Ernest *et al.* (2012) when compared with free starch. Furthermore, it was noted that constraints of enzyme activity from steric orientation forms and the collision frequency were mitigated by NPs-immobilized enzymes to enhance the rate of substrate degradation.

Gold NPs

The enhanced shelf life of minced camel's meat was observed by Gharehyakheh *et al.* (2020), when green-synthesized gold NPs (Au NPs) from *Satureja hortensis* leaves were applied. The Au NPs showed antioxidant activity against 2,2-diphenyl-1-picrylhydrazyl with no cytotoxic effects on human normal cell lines. Besides, antibacterial effects against *E. coli* and *L. monocytogenes* were also highlighted in this study. Moreover, amelioration of protein oxidation, lipid peroxidation substances, and sensory attributes evidenced efficacy of Au NPs as food preservatives.

Ability to detect live microbes in food samples is imperative to prevent the production and distribution of contaminated food. However, detection of microbial contamination using conventional methods is time-consuming and expensive. In contrast, biosensor-mediated approaches to detect pathogens have become attractive due to their short duration of identification (Davis *et al.*, 2013; El Sheikha *et al.*, 2018; Ricci *et al.*, 2007). Biocompatibility, conductivity, and the aspect ratio of Au NPs showed greater attention for their use in biosensor-mediated applications (Guo and Wang, 2007). More importantly, unique optical properties of Au NPs make it easier to detect smaller variations in Au NPs under agglomerated conditions (Verma *et al.*, 2015). Davis *et al.* (2013) developed a carbon electrode biosensor fabricated with Au NPs to detect *L. monocytogenes.* It was reported that the minimum detection limit for the assay was 2 log CFU/mL in blueberry, and showed higher explicitness over other enteric bacteria. This biosensor requires approximately 1 h for the accurate detection of contamination, and is proved to be a quick and effective biosensor to identify food pathogens. Furthermore, Fu *et al.* (2017) proposed a quick and simple technique to discover lysozyme using fluorescence switch biosensors with quantum dots and Au NPs. Fluorescent energy transfer between quantum dots–lysozyme and anti-lysozyme–Au NPs provided a strong fluorescence signal for detection. Under optimized conditions, the minimum threshold of detection (33.43 ng/mL) of lysozyme could be achieved by this method.

Copper NPs

In literature, many studies have highlighted the antibacterial potential of Cu-based nanocomposites over Gram-positive and Gram-negative bacteria. In addition, possible modes of action of Cu nanocomposites are speculated (Santos *et al.*, 2020). Tamayo *et al.* (2016) explained that Cu composites primarily attack bacterial cells thru several steps. First, by releasing Cu ions; second, thru Cu NPs release from composites; and third, thru the suppression of biofilms. Therefore, Cu NP products are used for impregnated films in food packaging.

Saravanakumar *et al.* (2020) prepared an antibacterial polymeric film impregnated with copper oxide NPs (CuO NPs). Higher antimicrobial activity was shown by CuO NPs against *S. aureus*, *E. coli*, *Salmonella*sp., *C. albicans,* and *Trichoderma* spp., proving it to be an active food packaging system. Besides, Lomate *et al.* (2018) exploited a LDPE–Cu nanofilm for active packaging to enhance the expiration duration of Peda. Uniform distribution of Cu NPs in LDPE provided an improved mechanical property. In addition, nanocomposite had shown superior antimicrobial effects averse to test *S. aureus* and *E. coli*.

Quick and easy detection of hydrogen peroxide (H_2O_2) content is important in biological, pharmaceutical, and environmental systems as well as in food sector (Ensafi *et al*., 2014; Martin *et al*., 2014; Vasconcelos *et al*., 2019). Liang *et al*. (2018) developed a sensitive H_2O_2 electrochemical sensor using Cu NPs in polyaniline film for water analysis. The prepared electrochemical sensor obtained a wider linear range for H_2O_2 detection with a limit of 0.33 μM. Hence, this manifests the potential of Cu NPs in the application of electrochemical sensors. Therefore, these are few of their promising applications in food industry; however, it is endless to discuss merits of Cu NPs at industrial scale.

Montmorillonite nanoclay

The montmorillonite nanocomposite containing curcumin was found as an emulsifier for hydrophobic polyphenols to augment their anti-bacterial and cancer properties in food industry (Madusanka *et al*., 2015). In addition, utilization of nylon nanofiber montmorillonite composites over polypropylene membranes to extend the longevity of foods inhibiting lipid peroxidation and growth of microbes through reduced air and moisture transfer shows their promising applications in the food sector (Agarwal *et al*., 2014).

Consequences of nanotechnology in crop production systems

The imbalance and unconsciously used of NMs has emerged many consequences in the ecosystem. Deliberate and accidental release of NMs and their uptake into production systems affect plants, leading to phytotoxicity. Phytotoxicity of NPs can occur thru chemical toxicity and NPs causing stress in plants. Accumulation of NPs can inhibit plant surrounding activities by altering the surface activity of plant components on other nutrients. Therefore, the toxicity of NMs on plants has two aspects, viz. cytotoxicity and genotoxicity (Chandrika *et al*., 2018; Giorgetti, 2019).

Cytotoxicity is the disruption of vital cellular activities related to growth and development of plants, including respiration, photosynthesis, and other metabolic activities. Genotoxicity, in the sense, includes inhibition of activities like meiosis, mitosis, composition of genetic materials, etc. (Chandrika *et al*., 2018). However, phytotoxicity primarily depends on the physical and chemical properties of NMs (Slomberg and Schoenfisch, 2012). Frazier *et al*. (2014) evaluated the impact of TiO_2 NPs on tobacco and speculated that higher concentrations could significantly inhibit the primary growth parameters of tobacco seedlings. Also, micro-RNAs (miRNAs) expression, important for plant stress tolerance, was significantly influenced by TiO_2 NPs, showing the dose-dependent effects of NPs. Exposure to mesoporous carbon-based NMs (MCNMs) have a negative effect on rice growth by changing the levels of plant growth-promoting substances. Also, size-dependent toxicity and exposure to 150 mg/L MCNMs (150 nm) diminished root and shoot lengths. In addition, 80 nm size MCNMs significantly decreased root and shoot elongations if treated with the same concentration (Hao *et al*., 2019). Therefore, comprehensive knowledge of the means of phytotoxic effects of NMs is imperative to understand the doses of NPs for production systems to obtain their maximum benefits.

Conclusions

To meet the food security of an increasing world population, crop improvement is of great concern thru application of smart agriculture. While in traditional farming systems, a large scale of synthetic fertilizers and pesticides is a great challenge for human health and environmental security. Therefore, it is of great concern to mitigate the adverse effects of synthetic agricultural inputs by including environment-friendly and cost-effective agricultural technologies in existing traditional farming systems, particularly in developing countries. NT has been envisioned as a potent mediator in agriculture and food sectors for sustainable utilization of resources. NMs are comprehensively used in the agricultural sector as NFs based on macro- and micronutrients. It has been recognized that NFs enhance agricultural productivity by increasing its utilization efficiency and by minimizing environmental pollution. Therefore, the augmentation of NF strategies with biological approaches is measured as a novel approach for sustaining agricultural productivity under changing climate. Not only NFs, the use of NMs as plant protectants have been also evidenced as a successful approach to minimize the consequences of synthetic pesticides. Use of NMs as NPs can minimize the residual effects of pesticides, leading to safe environment and human health. Recently, NT has been applied successfully in genetic engineering for the development of stress tolerance and high yielding crop cultivars. Besides the above-mentioned beneficial aspects in agriculture and the environment, unique properties of NMs, such as antimicrobial activity, and capability to apply as sensors in food products, have been highly authenticated in the food industry. It is noteworthy to say that NT approaches are capable to mitigate the consequences of imbalanced use of fertilizers and pesticides for the safety of human health and the environment. The current review overviewed the evidence of earlier findings for effective understanding of NT in response to agricultural sustainability, food, and environmental safety.

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Compliance with ethical standards

This review paper does not include animal or human experiments

Conflict of interest

Authors declare no conflict of interest.

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