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REVIEW

Nanofertilizers for sustainable fruit production: a review

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Abstract

The demand for quality food is expected to increase with the rising population across the globe. Fruits are a major source of nutraceuticals, yet nutrient depletion in soils is altering fruit cultivation. Conventional fertilizers have raised food production after the green revolution, yet intensive agriculture has induced soil degradation and food contamination by pesticides. Conventional fertilizers are poorly efficient, and only about 20% or less of the applied fertilizer is used by the crop plant, the rest being mineralized or leached to groundwater and rivers, causing issues of cost, eutrophication and human health. Alternatively, nanofertilizers appear promising because nanoparticles display unique properties due to their physicochemical characteristics at the nanoscale. Here, we review applications of nanoparticles in fruit crops. Benefits include fruit productivity, quality and shelf life through their positive effects on anatomical, morphological, physiological, physicochemical and molecular traits. We also discuss the role of nanofertilizers in gene expression, regulation and translocation for mitigating abiotic stresses.

Keywords Abiotic stress · Nanotechnology · Shelf life · Uptake and transport · Yield and quality

Introduction

The global population will be around 9.1 billion by 2050 that is 34 percent greater than the existing population (FAO 2009). Ultimately, the demand for food is expected to rise with the same pace (Kumar et al. 2018). Furthermore, the degradation of arable land is a major bottleneck in crop production due to lack of resources coupled with the urbanization. To overcome this situation, the use of fertilizers and pesticides, genetically modified crops, insect pests and disease-resistant varieties has been in great demand with the farmer communities for the last five decades (Yadav et al. 2013). In fact, fertilizers have played a pivotal role in improving the productivity of agricultural crops in general and fruits in particular. But, these chemical fertilizers when used in excess have resulted in the deterioration of food quality as well as soil health (Zamir 2001; Conley et al. 2009; Bai et al. 2020). Fruits are a good source of healthy diet, and their consumption helps to prevent major diseases. Unfortunately, less consumption of fruits and vegetables, especially in the developing world, is one of the ten risk factors of mortality. The Global Burden of Disease reports revealed that about 3.4 million deaths are ascribed to less consumption of fruits (GBD 2013).

Fruit crops are heavy feeders of nutrients and therefore a good nutrient management strategy is required for proper growth and production (Rivero et al. 2009; Ramírez et al. 2011; Kumari et al 2020). The nutritional status varies from plant to plant, species to species, climatic condition, growth medium and the availability of nutrients (Cabriales et al. 2002; Benton 2012). The essential nutrient elements for plants are categories into macro- and micronutrients. Several scientists have reported that only 30 percent of applied

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fertilizers are utilized by plants and rest are susceptible to leaching, mineralization and bioconversions (Bollag et al. 1992). To combat this situation, few strategies have been devised to increase nutrient use efficiencies, such as precision fertilization, integrated nutrient management, split or localized placement, fertigation and use of nanofertilizers (Chhipa 2017). Nanofertilizers are the important assets of nanotechnology which might be instrumental in horticultural sector for increasing the productivity (Chhipa and Joshi 2016) (Fig. 1). Nanofertilizers are the nanomaterials of 1–100 nm size that supply at least one or more types of nutrients to the plants (Guo 2004; Liu and Lal 2015; Singh 2017). These have a high surface area, absorption capacity and controlled release kinetics to active sites with a smooth delivery system (Guo 2004; Rameshaiah et al. 2015; Chhipa and Joshi 2016). Based on plant nutrient requirements, nanoparticles can be classified as macro-nanofertilizers, micro-nanofertilizers, nano-biofertilizers, nanoparticulate fertilizers and nanocoatings or packaging materials (Table 1).

The various types of nanotechnological materials such as carbon nanotubes, copper, manganese, molybdenum, zinc, iron, silicon, their oxides and nanoformulations of commercially used agricultural inputs like urea, phosphorus and sulfur are available (Trobisch and Schilling 1970; Lin and Xing 2007a, b, 2008; Mahajan et al. 2011; Nekrasova et al. 2011; Ghafariyan et al. 2013; Pradhan et al. 2013; Taha et al. 2016; Alshaal and Ramady 2017). The abovementioned materials can be applied through various modes of applications, viz., soil application, injection to the plant, in vitro and the foliar application. The foliar application of nutrients has been proved as a quick way to rectify nutrient deficiencies and ameliorate crop productivity (Roemheld and El-Fouly 1999). The applications of nanofertilizers have been found to reduce abiotic stresses and improvement in nutrient utilization by the crop (Abou El-nour et al. 2010). Furthermore, the nanoparticles can be a promising tool as an alternative source of nutrients and packaging that enhances the growth, production, quality and shelf life of the fruits (Chowdhury et al. 2017; Kaphale et al. 2018). This article elucidates the current status of the knowledge on the use of nanoparticles for sustainable fruit production. In addition, the prospects and the possible value realization of nanotechnology-related techniques in fruit production have also been discussed.

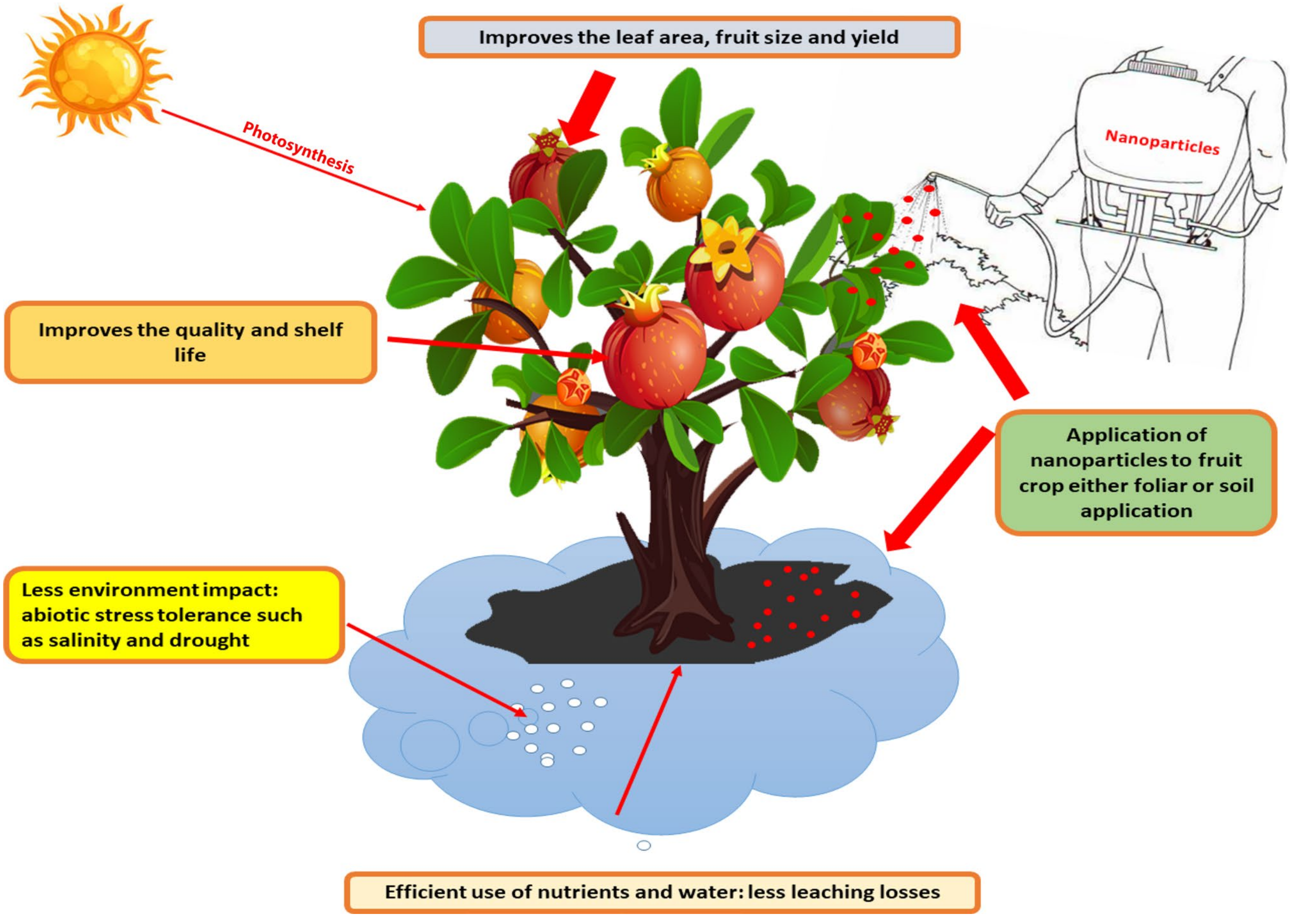

Fig. 1 Benefits of nanofertilizers for fruit production

Table 1 Classification of nanoparticles and examples

Categories of nanoparticles	Definition	Examples	References
Macro-nanofertilizers	Macronutrients combined with nanomaterials to deliver a precise amount of nutrients to the plants and reduce the bulk requirements as well as decreasing purchase and transportation cost	Nano-ultra-fertilizer organic matter: 5.5% + nitrogen (N): 10% + phosphorus (P): 9%, potassium (K): 14% + magnesium (Mg): 3%	Prasad et al. (2017); Azam (2002)
		Nanocapsule-N: 0.5% + P: 0.7% + K: 3.9% + calcium (Ca): 2.0% + Mg: 0.2% + silicon (S): 0.8% + iron (Fe): 2.0% + manganese (Mn): 0.004% + copper (Cu): 0.007% + zinc (Zn): 0.004%	
		PPC Nano (120) ml M protein: 19.6% + Na_2O: 0.3% + K: 2.1% + N: 1.7% + diluents: 76%	
		N + P nanofertilizers	Khan (2019)
Micro-nanofertilizers	Micronutrient elements are required by the plant in trace amount or minor quantities but are essential to maintain crucial metabolic processes in the plants	Nano-micronutrient (EcoStar) (500) g Zn, 6%; boron (B), 2%; Cu, 1%; Fe, 6% +; molybdenum(Mo): 0.05%; Mn: 5% + amino acids: 5%	Prasad et al. (2017); Azam (2002)
		Fe(III)-ethylendiaminedi(o-hydroxyphenylacetate)	Davarpanah et al. (2020)
Nano-biofertilizers	Materials are made up of interaction b/w nanoparticles and microorganisms, improve the shelf life of bio-fertilizers and its delivery. For example, interaction between gold nanoparticles and plant growth-promoting rhizobacteria that act as nano-biofertilizers	Nanosize calcite + sea weed extract	Sabir et al. (2014)
		Nano-seaweed extract	Jubeir and Ahmed (2019)
		Biozar nanofertilizer combination of organic materials, micronutrients and macromolecules	Prasad et al. (2017); Azam (2002)
		TAG NANO-N, P and K + zinc + calcium + micronutrients + vitamins + probiotics + seaweed extract + humic acid	
		Nano-ZnFeMnB	El-Sayed (2018);
Nanoparticulate fertilizers	The consolidation formulation of nanotubes and nanoparticles leads to form new complex materials that are active in nature and act as nanofertilizers	Carbon nanotubes	Abdel-Hak et al. (2018)
		Silicon dioxide nanoparticles (SiO_2 NPs)	Zarafshar et al. (2015); Rastogi et al. (2017)
		Silver nanoparticles (Ag NPs)	Aslani (2014); El-Batal et al. (2016)
Nanocoating material	Nanocoating is the thin layer material that helps to increase the shelf life of fresh commodity	Chitosan/nano-silica	Zagzog et al. (2017); Song et al (2016); Shi et al. (2013)
		Nanotitanium dioxide-low-density polyethylene (TiO2-LDPE)	Li et al. (2016)

Classification of nanoparticles

Macro-nanofertilizers

Fertilizer is one of the major inputs accounting for nearly one-third of the cultivation cost. The intensive production of nitrogenous fertilizers and fast depleting reserves of phosphatic and potassic fertilizer sources will be of great concern for various countries where energy security is still to be achieved (Schader 2009). The rising population concerns will increase the demand for food, thereby increasing the requirement of macronutrient fertilizers (Wang et al. 2016). Due to its nanosize dimensions, macro-nanofertilizers are the alternate option to reduce the bulk quantity of nutrients. There is a need to generate new fertilizers with high nutrient use efficiencies as well as environmentally safe. Macronutrients like nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), sulfur (S) and calcium (Ca) are mixed with nanomaterials with the purpose to supply an optimum amount of nutrients to the plants and reduce the cost of cultivation (Ditta and Arshad 2016; Chhipa 2017).

Nitrogen is the key nutrient element that is deficit in almost all the agricultural soils. Urea is a commercial nitrogenous fertilizer which is susceptible to rapid volatilization and leaching (Kahrl et al. 2010). The Sri Lankan Institute of Nanotechnology prepared a sophisticated nitrogen nanofertilizer with the help of coated urea hydroxylapatite nanoparticles which is slow release nitrogenous fertilizer (SRNF) and has better chemical compatibility with the phosphorus sources (Kottegoda et al. 2017). Phosphorus is also an essential nutrient element to all biological organisms. The major issue for phosphatic fertilizers is low nutrient uptake efficiency. Furthermore, there are global environmental issues of eutrophication which is due to increased phosphorus levels in the water (Pote et al. 1996; Richardson 2001; Shenoy and Kalagudi 2005). Nanotechnology is a great option which can produce the phosphorus fertilizers along high phosphorus uptake efficiency. Biosafe nanofertilizer is the first phosphatic nanofertilizers with a particle size of 60–120 nm which is a prime source of phosphorus. Tarafdar et al. (2012) synthesized fungal-mediated phosphorus nanoparticles along with tricalcium phosphate of 28 nm size. Liu and Lal (2015) developed a nanoparticle called carboxymethyl cellulose-stabilized hydroxyapatite with a size of 16 nm.

These macronutrients can be applied through soil application, injection, or foliar spray (Sharonova et al. 2015). Several researchers have reported the positive effects of the macro-nanofertilizers on the vegetative growth, pollination, fruit yield and quality of fruit crops (Davarpanah et al. 2017; Zagzog et al. 2017; Zahedi et al. 2019). The foliar application of nano-nitrogen at a concentration of 250–500 ppm increased the fruit yield by 17–44 percent and number of fruits per plant by 15–38 percent in *Punica granatum* cv. Ardestani. Physicochemical properties like fruit size, aril juice, total soluble solids and titratable acidity were also improved (Davarpanah et al. 2017). Likewise, nanosize calcite product contains 40 percent calcium carbonate ($CaCO_3$), 4 percent silicon dioxide, 1 percent magnesium oxide (MgO) and 1% ferric oxide (Fe_2O_3) which improve the cluster number, cluster weight, berry weight, volume and length, total soluble solids and reduce the acidity in *Vitis vinifera* (Sabir et al. 2014).

Micronutrient nanofertilizers

Micronutrients are trace elements that are needed in lesser quantity (< 100 ppm) but essential for the physiological, anatomical, and morphological processes of the plants (Broadley 2007; Sharonova et al. 2015; Noreen et al. 2018). Zinc (Zn) is an essential trace element that is required for proper growth and development (Vallee and Falchuk 1993). The maximum cultivated land is Zn deficient because its availability is only limited to the root zone which reduces the nutrient uptake by the plants (Lindsay 1972). Due to ultra small size of ultra-small size and high surface area, Zn nanoparticles can be transported easily into the plant system (Lindsay 1972; Pandey et al. 2010; Dimkpa et al. 2013; Raliya et al. 2016; Shankar and Rhim 2019). Iron (Fe) is an essential nutrient for crop growth and development because it is having a role in biosynthesis of electron transfer chain (ETC) (Lindsay and Schwab 1982). Nanoparticles like oxides of Fe have been extensively used for catalytic processes (Laurent et al 2008; Madhura et al. 2019) and significantly improve several crop traits such as chlorophyll content, photosynthesis, light absorption, nitrogen and phosphorus metabolisms besides fruit and biomass yields.

Boron (B) is involved in the biosynthesis of cell wall and various other physiological processes (Davarpanah et al. 2016). Recent advances in micro-nanofertilizer research are presented in Table 2. Hence, the application of nanochelates of boron and zinc to fruit crops is done for getting the higher yield with better quality. A study has shown that lower amounts of B and Zn nanofertilizers @ 34 and 636 ppm, respectively, enhanced the yield by 30 percent in *P. granatum* cv. Ardestani (Davarpanah et al. 2016). The application of nanoparticles of zinc oxide @ 10 ppm in *Coffea arabica* L. boosted the net photosynthetic rate up to 55 percent and improved the fruit set and quality (Rossi et al. 2019). Similarly, the nanoiron chelate application @ 2000 ppm ameliorated the leaf area, chlorophyll content, catalase enzyme activity, total soluble solids, ascorbic acid and total phenol contents in *Cydonia oblonga* Mill (Rahemi et al. 2019).

Table 2 Impact of nanoparticles on fruit crops: different fertilizers have been developed in nanoform and their effects on physiological, anatomical, morphological and physico-biochemical characteristics of different fruit crops are summarized

Nanoparticles	Mode of application	Conc	Crop name, 'cutivar' & botanical Name	Effects	References
Nano-Optimus plus and K Chelate + AA	Drenching	1.5 ml L^{-1}	Lime (*Citrus aurantifolia* L.)	↑↑ Seedlings height, number of branches, stem diameter, number of leaves, leaf area, leaf content of total chlorophyll and dissolved carbohydrates	Amin et al. (2020)
Fe(III)-ethylendiaminedi(o-hydroxyphenylacetate)	Foliar	2.1 mM	Pomegranate (*P. granatum*)	↑↑ Leaf iron (Fe) concentrations Enhanced fruit yield and leaf Fe	Davarpanah et al. (2020)
Nanocalcium	Foliar	2.0%	Apple cv. 'Red Delicious' (*Malus domestica* Borkh.)	↑↑ Fruit weight, density, length, diameter and length/diameter ratio ↑↑ Titratable acidity, total phenolic content, total anti-oxidant activity, fiber and starch content	Ranjbar et al. (2020)
Nanopowder potassium sulfate	Foliar	150–200 g $vine^{-1}$	Grapevines cv. 'Crimson Seedless' (*V. vinifera*)	↑↑ Vegetative growth leaf area, internodal length, internodal thickness and chlorophyll content ↑↑ Cluster weight, length, width, berry weight, berry diameter, nutrient uptake and yield	Shalan (2020)
Nano-potassium (Nano K)	Foliar	50% mineral + 1000 ppm Nano K	Grapevines cv. 'Flame seedless' (*V. vinifera*)	↑↑ Vegetative growth like shoot diameter and leaf area ↑↑ Yield and berries quality ↑↑ N and K content in petiole	Doaa et al. (2019)
Nanoboron	Foliar	10 ml L^{-1}	Mango cv. Keitte Mango (*M. indica* L.)	Ameliorate photosynthetic pigments and N, P, K, Mg, B, Zn, Fe and Mn content ↑↑ Fruit setting, fruit retention, number of fruits and yield per tree Improve the chemical components	Farouk et al. (2019)
Nano-seaweed	Foliar, injection in trunk & soil application	2,1 & 4 ml L^{-1}, respectively	Date palms (*P. dactylifera* L.)	↑↑ Weight of fruit pulp and bunch weight	Jubeir and Ahmed (2019)
Nano-nitrogen + phosphorus	Foliar	300 ppm N + 50 ppm P	Apple cv. 'Red delicious' (*Malus × domestica Borkh.*)	↑↑ Yield and net benefit/cost ratio	Khan (2019)

Table 2 (continued)

Nanoparticles	Mode of application	Conc	Crop name, ‘cutivar’& botanical Name	Effects	References
Nano-iron chelate	Foliar & Soil application	9% (2000 ppm)	Quince (*Cydonia oblonga* Mill.)	↑↑ Leaf area and chlorophyll content ↑↑ Catalase enzyme activity ↑↑ Total soluble solids (TSS), ascorbic acid and total phenol contents ↑↑ Fruit firmness ↑↑ Fe and Ca content in the leaves and fruits	Rahemi et al. (2019)
Zinc oxide nanoparticles (ZnO NPs)	Foliar	10 ppm	Coffee (*Coffea arabica* L.)	↑↑ Fresh and dry weight of roots and leaves ↑↑ Net photosynthetic rate up to 55 percent Ameliorate the fruit set and quality ↑↑ Zn content in leaves	Rossi et al. (2019)
Nano-nitrogen chelate	Foliar	6000–8000 ppm	Olive (*Olea europaea* L.)	↑↑ The fruit set Maximum oil percentage with 8 g N L^{-1}	Vishekaii et al. (2019)
Magnesium oxide + zinc oxide nanoparticles (MgO + ZnO NPs)	Foliar	1000 ppm	Pummelo (*Citrus maxima*)	Uptake and translocation of metal oxide and lipid peroxidation	Xiao et al. (2019)
Selenium nanoparticles (N-Se)	Foliar	2 µM	Pomegranate cv. ‘*Malase Saveh*’ (*P. granatum*)	↑↑ Leaf area (1.22–1.34%) and chlorophyll content (1.34%) ↑↑ Number of fruits/trees, peel thickness (1.27–1.33%), fruit diameter (1.08–1.10%) and yield (1.17–1.16%) Increased N, P, K, Ca, Fe and Se in leaves	Zahedi et al. (2019)
Carbon nanotubes (CNTs)	Soil application	80%N from RDF + 0.6% CNTs	Grapevine cv. ‘Flame Seedless’ (*V. vinifera*)	↑↑ Leaf area, fresh and dry weight, total carbohydrate percent and concentration of N, P, K, Mg and Fe in leaves, ↑↑ Weight and juice content per 100 berries	Abdel-Hak et al. (2018)

Table 2 (continued)

Nanoparticles	Mode of application	Conc	Crop name, 'cutivar'& botanical Name	Effects	References
Nano-selenium	Soil application	50 ppm	Acid lime (*C. aurantifolia* L.)	↑↑ Germination percentage by 30–36 percent ↓↓ Damping off in seedlings and albino percentage, and reduced total phenols content ↑↑ Seedlings stem length and diameter, ↑↑ Total indoles and in acid lime seedling leaves	Ahmed et al. (2018)
Nano-iron chelate	*In-vitro* application	100 ppm	Apple cv. Gala (*M. domestica* Borkh.)	↑↑ Growth like number of nodes, shoots, & leaves, nodes & shoots length, leaf area, fresh and dry weights of shoots ↑↑ Chlorophyll index	Avestan et al. (2018)
Nanocalcium (N-Ca)	Foliar	500 ppm	Pomegranate cv. 'Ardestani' (*P. granatum*)	↓↓ Fruit cracking ↑↑ Marketable fruit yield	Davarpanah et al. (2018)
Nano-ZnFeMnB	Foliar	0.004%	Date palms cv. 'Sakkoti' (*P. dactylifera* L.)	↑↑ Leaflet area, leaf area chlorophylls contents, total carotenoids leaf N, P and K ↑↑ 3X yield and fruit quality, edible to portions of fruits	El-Sayed (2018)
Nano-NPK Mg	Foliar	0.1%	Mango cv. ' Keitte' (*M. indica* L.)	↑↑ Fruit production up to 38.0 kg and quality flesh percent up to 75.0; vitamin C up to 47.9 mg per 100 g ↑↑ Pulp mango shoots and leaves and fiber up to 0.71	Saied (2018)
Iron nanoparticles + potassium silicate	Foliar	2 mM + 0.8 ppm	Grape cv. 'Khoshnaw' (*V. vinifera*)	↑↑ Total protein content ↓↓ Proline, enzymatic antioxidant activity and hydrogen peroxide ↑↑Membrane stability index ↓↓ Malondialdehyde content Protect against salinity stress	Mozafari et al. (2018a)

Table 2 (continued)

Nanoparticles	Mode of application	Conc	Crop name, 'cutivar'& botanical Name	Effects	References
Iron nanoparticle	Foliar	0.8 ppm	Strawberry cv. 'Queen Elisa' (*Fragaria* × *ananassa* Duch.)	Improved all growth-related parameters ↑↑ Pigment content, Leaf relative water content, and iron and potassium contents of the mature plants ↓↓ Sodium content under salinity conditions	Mozafari et al. (2018b)
Nano-nitrogen (N–N)	Foliar	250–500 ppm	Pomegranate cv. 'Ardestani' (*P. granatum*)	↑↑ Fruit yield up to 44 percent ↑↑15 to 38 percent number of fruits per plant ↑↑ Aril juice and TSS & titratable acidity	Davarpanah et al. (2017)
Nano-titanium dioxide–low-density polyethylene (TiO2-LDPE)	Coatings	–	Strawberry (*Fragaria* × *ananassa* Duch.)	↓↓ Decay rate and weight loss, firmness and titratable acid. The activities of antioxidant enzymes involved in reactive oxygen species activity Inhibition anthocyanin accumulation, ↑↑ Ascorbic acid and total phenolic contents	Li et al. (2016)
Iron oxide nanoparticles (Fe_2O_3 NPs)	Hydroponic nutrient solution	50 ppm	Pummelo (*C. maxima*)	↑↑ Chlorophyll content by 23.2 percent and root activity by 23.8 percent Activating many physiological and molecular processes	Hu et al. (2017)
Nano-zinc oxide + Carboxymethyl cellulose	Coatings	–	Pomegranate (*P. granatum*)	↓↓ Total yeast + mould + mesophilic bacteria ↓↓ Physiological loss in weight = juice percent Suppressed total phenol changes = Total anthocyanin, vitamin C and antioxidant capacity	Saba and Amini (2017)
Nanochitosan	Foliar	5 ml L^{-1}	Mango cv. 'Zebda' (*M. indica* L.)	↑↑ Fruits yield, number of fruits or weight/tree and ↓↓ Malformation percentage as well as improving studied attributes especially	Zagzog et al. (2017)

Table 2 (continued)

Nanoparticles	Mode of application	Conc	Crop name, 'cutivar'& botanical Name	Effects	References
Zn-NPs	Foliar	1000 ppm	Mango (*M. indica* L.)	↑↑ Flowering quality by the lowered malformation problem ↑↑ Fruit weight by 33.74 percent yield by 57.36 percent	Zagzog and Gad (2017)
Nano-potassium chelate	Foliar	1000 ppm	Grapevine cv. 'Bidaneh Sefid' (*V. vinifera)*	↑↑ Chlorophyll and anthocyanin in leaves ↑↑ Anthocyanin in fruit and superoxide dismutase Ameliorate the enzymatic activity of the ascorbate	Zangeneh and Rasouli (2017)
Nano-zinc and boron chelate	Foliar	Zn: 636 ppm + B: 34 ppm	Pomegranate cv. 'Ardestani' (*P. granatum*)	↑↑ Fruit yield 17 to 44 percent Ameliorate the fruit quality, like TSS, decreases in titratable acidity 20.6–46.1 percent ↑↑ Maturity index and total phenolic compounds	Davarpanah et al. (2016)
Nano-chelate super plus (zinc, iron and manganese) ZFM	Foliar	2000 ppm	Almond cvs. 'Shokufeh, Monagha and Sahand' *(Prunus dulcis)*	↑↑ Percentages of fruit set and yield per shoot in Shokufeh cultivar ↓↓ Fruit abscission up to 25 percent	Kamiab and Zamanibahramabadi, (2016)
Nano-zinc oxides (ZnO)	Coatings	–	Kiwifruit (*Actinidia* spp.)	↓↓A lower ethylene content and water loss = The texture of the fruit	Meng et al. (2014)
Nano-NPK	Foliar	500, 250 and 250 g $\text{Palm}^{-1}\ \text{yr}^{-1}$	Date Palm 'Zaghloul' *(P. dactylifera* L.)	↑↑Average fruit weight (g.), pulp percent, TSS & total sugars percent ↓↓ Total acidity fibers, soluble tannins	Roshdy and Refaai (2016)
Nano-ZnO	Coatings	0.5%	Strawberry (Fragaria × ananassa Duch.)	↓↓ The microbial load Retards the weight loss, = Fruit firmness, anthocyanin, vitamin C, phenol content and antioxidant activity	Sogvar et al.(2016)
Chitosan/nano-silica	Coatings	–	Loquat cv. 'Baiyu' (*Eriobotrya japonica* Lindl.)	↑↑ The shelf life,	Song et al (2016)
Boron nanoparticles (B-NPs) + wheat seed sprout extract	Foliar	(0.05%) + (1.0%)	Date palm cv. 'Zaghloul' *(P. dactylifera* L.)	↑↑ The bunch weight, TSS and pulp percent ↓↓ The seed percentage, acid content and tannin	Refaai (2014)

Table 2 (continued)

Nanoparticles	Mode of application	Conc	Crop name, ‘cutivar’& botanical Name	Effects	References
Nano-calcite + seaweed extract	Foliar	500 ppm	Grapevines (*V. vinifera*)	↑↑ The cluster number, cluster weight, pruning weight, berry weight, berry volume, berry length, berry diameter, soluble solids content, acidity ↑↑ Leaf nutrient contents	Sabir et al. (2014)
Nano-hydrophobic sand	SA	–	Date palm (*P. dactylifera* L.)	↑↑ Shoot and root fresh and dry weight of seedlings ↑↑ Root length (up to 40%) of seedlings Heavy metal concentrations in date	Salem et al. (2013)
Chitosan/nano-silica	Coatings	(2.0% w/v) + glacial acetic acid (0.5%, v/v)	*Logan* cv. ‘Shijia’ (*Dimocarpus longan* Lour.)	↑↑ The shelf life, ↓↓ The browning index, weight loss problem, malondialdehyde content and polyphenol oxidase activity ↓↓ The losses of TSS, titratable acidity and ascorbic acid contents	Shi et al. (2013)
Nano-ZnO	Coatings	–	Apple cv. ‘Fuji’ (*M. domestica* Borkh.)	↑↑ Storage period by 6 days ↓↓ Fruit decay rate and accumulation of malondialdehyde ↓↓ Polyphenoloxidase and pyrogallol peroxidase	Li et al. (2011)

↑↑ Increased; ↓↓:Decreased; = Maintained

Nano-biofertilizers

Biofertilizers are the formulations or preparations of living entities with different strains that moderate soil productivity, nitrogen fixation and solubilization of phosphorus which are required for the synthesis of plant growth-regulating substances. Ultimately, biofertilizers promote the plant growth and developmental processes (Brahmaprakash and Sahu 2012; Malusá and Vassilev 2014; Singh et al. 2016; Sharma et al. 2018). Likewise, nano-biofertilizer is a conglomerate of plant growth-promoting rhizobacteria (PGPR) along with nanomaterial coatings of silver (Au) (Shukla et al. 2013; Malusá and Vassilev 2014; Simarmata et al. 2016; Thirugnanasambandan 2018). The aforesaid applications are found to improve the shelf life as they increase the strength of biofertilizers with respect to desiccation, heat and inactivation of ultraviolet radiation (UV rays) (Simarmata et al. 2016; Jampílek et al. 2017). Significant challenges exist with the use of nano-biofertilizers. To overcome this situation, development of production techniques and mass production will enhance the use of nano-biofertilizers in fruit production. The interaction between nanoparticles and biofertilizers has shown a positive effect on the growth and development of some fruit crops. The foliar spray, injection into trunk and soil fertilization of nano-seaweed extract in *Phoenix dactylifera* L. triggered the fruit weight, pulp and bunch weight at variable concentrations ranging from 1 to 4 ppm (Jubeir and Ahmed 2019). Similarly, the application of nanofertilizers along with seaweed extract (*Ascophyllum nodosum*) at a rate of 500 ppm significantly increased the vine growth and berry quality attributes of grapes. This was also suggested against abiotic stresses in *V. vinifera* L. (Sabir et al. 2014).

Nanoparticulate fertilizers

The consolidation of nanotubes and nanoparticles leads to form new complex materials that might have several kinds of applications (Hasobe et al. 2005; Kongkanand et al. 2008; Mohapatra et al. 2008). Several researchers noticed that carbon nanotubes attached to the functional nanostructures act as nanoparticulate fertilizers (Sun et al. 2004). Recently, multiple uses of oxide nanoparticles, carbon nanotubes (CNTs) and titanium dioxide nanoparticles (TiO_2 NPs) hybrids have extended their importance due to combined CNTs with TiO_2 NPs which can boost the photo-catalytic activities (Jitianu et al. 2004; Tan et al. 2012). Besides this, the application of TiO_2, silicon dioxide (SiO_2) and CNTs also improved the actions of plant growth regulators (Khodakovskaya et al. 2012). The CNTs application @ 0.6 percent in *V.vinifera* cv. Flame Seedless ameliorated the vegetative characters, yield, physicochemical characteristics, total carbohydrate content and the leaf nutrient contents (Abdel-Hak et al. 2018). However, limited information is available on the TiO_2, CNTs and SiO_2 in fruit crops. Applications of TiO_2 and SiO_2 combination ameliorated the seed germination (Changmei et al. 2002), but the incorporation of TiO_2 alone enhanced the total nitrogen, protein and chlorophyll contents. The CNTs improved the plant growth and yield and promoted the water uptake capacity in horticultural crops (Gao et al. 2006; Lin and Xing 2007a, b; Srinivasan and Saraswathi 2010; Khodakovskaya et al. 2012).

Nanocoatings and packaging materials

Nanotechnology is a novel tool which helps to attain postharvest disease management of fruits**.** Recently, nanomaterials are widely used in various food industries for the packing purposes (Brandelli et al. 2017; Kuswandi 2017; Sarkar et al. 2017; Kaphale et al. 2018; Rai et al. 2019). The nanomaterials in fruit production can improve the quality, shelf life and freshness (Van Hung et al. 2011; Shi et al. 2013; Flores-López et al. 2016; Song et al. 2016; Dasgupta et al. 2017; Yata et al. 2017) . Nanocoating of 5 nm size thin material reduced the loss of moisture content in fruits and reduced the gaseous exchange which ultimately improved the shelf life of product as compared to the conventional packaging (Azeredo et al. 2009). The nano-packaging materials like chitosan (nano-silica) and nano-TiO_2–LDPE (titanium dioxide–low-density polyethylene) have the capacity to maintain the physiological and physicochemical characteristics as compared to the normal packing material (Li et al. 2016) because it inhibits the pathogen, mycelia growth, mitochondrial reactive oxygen species, matrix metalloproteinase and adenosine triphosphate (ATP) content of the pathogen (Van Aken 2015; Malerba and Cerana 2018).

Thus, nanotechnology is an important tool in postharvest technology for management of postharvest diseases and improvement in packaging appearance with the ease of tagging and labeling (nanobiosensors). Several nanomaterials have been enumerated along with their potential effects on the postharvest management of fruit crops in Table 2.

Influence of nanoparticles on fruit growth, yield, quality and shelf life

The information on the use of nanoparticles for enhancement of growth, yield, quality and postharvest shelf life of fruit crops has been reviewed and presented in Table 2.

Impact on the flowering, fruit growth and yield

Nanofertilizers promote the blooming, growth and yield of the fruit plants, but there is scanty information on their influence on the flowering of fruit crops. The promotion of flowering with the application of calcite nanofertilizer

@ 30 ppm via foliar spray produced upper-quality flowers than the controlled ones. The combined application of seaweed extract and nano-calcite improved the pollen viability percentage, pollen germination and the flower quality in *V. vinifera* (Sabir 2015). Spraying nanochitosan @ 50 ml L^{-1} on the mango leaves ameliorated the number of panicles and fruits besides protecting from mango malformation (Zagzog et al. 2017). The nanofertilizer application also promotes the growth of fruit crops. Selenium nanoparticles (N–Se) application @ 2 µM via foliar application in *P. granatum* L. cv. Malase Saveh enhanced the leaf area by 1.22–1.34 percent and chlorophyll content up to 1.34 percent (Zahedi et al. 2019). Application of trace elements like nano-ZnFeMnB @ 0.004 percent in date palm cv. sakkoti ameliorated the leaf area, total chlorophyll content and total carotenoids and promoted the leaf nutrient contents (El-Sayed 2018). Foliar application of nanofertilizers as macro- or micronutrients has shown positive yield effects on several fruit crops. Davarpanah et al. (2016) reported that foliar spray of zinc @ 120 ppm and boron @ 6.5 ppm in pomegranate increased the fruit yield by 17–44 percent and number of fruits per plant by 15–38 percent. The combined application of wheat seed sprout extract (1.0%) and boron nanoparticles (B-NPs) (0.05%) also increased the yield and bunch weight in date palm resulting in better fertilization of these (Refaai, 2014). The spray application of NPKMg-NPs @ 0.1 percent enhanced the growth, pigments, nutrients, yield and fruit quality over the control in *Mangifera indica* (Saied 2018).

Impact on the quality and shelf life of fruit crops

Nanofertilizer applications also improve the quality and postharvest life of fruit crop. Some studies have shown that nanofertilizers are better than the traditional fertilizers as they promote growth yield and fruit quality of different fruit crops (Table 2).

Davarpanah et al. (2016) applied foliar sprays of zinc @ 120 ppm and boron @ 6.5 ppm as nanoparticles in pomegranate and found optimum fruit quality parameters like total soluble solids, titratable acidity, maturity index and total phenolic compounds. Likewise, spray application of nanochitosan @ 0.1% w/v enhanced growth and metabolic activity through promotion of protease inhibitors, glucanases and peroxidase enzymes. The foliar application of boron nanoparticles applied (0.05%) along with wheat seed sprout extract (1.0%) in date palm cv. Zaghloul ameliorated the bunch weight, total soluble solids and the pulp percentage with decreased seed percentage, acid content and tannins. The micro-nanofertilizers 0.005–0.04 percent ZnFeMnB NPs application via foliar spray in sakkoti cultivar of date palm @ enhanced the fruit yield and quality as compared to control (El-Sayed 2018).

The fruits are climacteric and non-climacteric in nature on the basis of ethylene evolution rate (Sanzani et al. 2016) and regular biological processes like transpiration and respiration play an important role after harvesting (Romanazzi et al. 2016). Accordingly, the fruit quality is deteriorated due to polyphenol oxidase (PPO) activity (Duan et al. 2016; Huang et al. 2014), tastelessness (Bastianello et al. 2016), over ripening (Deng et al. 2019), shrivelling (Lee et al. 1995) and loss of nutritional value (Caprioli et al. 2016). In fruit production, the postharvest shelf life is a global concern because approximately 10–40 percent of horticultural produce is spoiled due to poor transportation, storage facility and disease infestation after harvesting (El-Ramady et al. 2015) which makes the produce unacceptable for the market (Liu et al. 2017). Hence, there is an urgent need of research on the shelf life of fruit crops. Nanotechnology might be one of the research areas that can enhance the postharvest life and decrease the losses in fruit crops (Davarpanah et al. 2016; 2017; Song et al. 2016). Nanomaterials have three principles that retard the senescence process, via regulation of respiration, reduction in activity of microorganisms and reduced water evaporation of the fruit which can be achieved by maintaining relative humidity of the environment (Song et al. 2009; Yan et al. 2010; Li et al. 2017).

The advancements made in coating materials like nanoparticles of chitosan, silica, titanium dioxide, boron and zinc nanoparticles are the materials that can increase the postharvest life of the fruit. Browning index, physiological loss in weight, malondialdehyde content and polyphenol oxidase activity in the fresh fruits of *Dimocarpus longan* Lour. cv. Shijia have been reported with the application of hybrid films like nano-silica or chitosan (2.0% w/v) coating solution mixed in an aqueous solution of glacial acetic acid (0.5%, v/v). Besides this, there is a significant reduction in losses of total soluble solids, titratable acidity and ascorbic acid contents of fruit (Shi et al 2013), while the nano-TiO_2–LDPE packaging enhanced anti-oxidative enzymes activities, ascorbic acid and total phenolic contents in strawberry fruits. This packaging retards the decay percentage and accumulates anthocyanin, ascorbic acid and phenolic contents (Li et al. 2017).

Regulation and translocation of nanoparticles

The regulation and translocation of nanofertilizers in the plant is an advanced field of research. It varies from plant to plant, species to species, climatic factors, age of plant species, biological activity of the plant and the method of application of nanoparticles. These materials have smart delivery systems (Villaseñor and Ríos 2018). However, the procedures for estimation of nanoparticles within the cell are not yet well described. Rico et al. (2011) proposed systematic regulation, uptake and translocation of nanoparticles along with their modes of application in plant system (Fig. 2–3). The nanoparticles penetrate into the cell wall and cell membrane of root epidermis accompanied by a complex series of events to enter plant vascular bundle (xylem) and move onto the stele simplistically. They are further translocated to the leaves (Fig. 2). Further, these move through the pores into cell membrane (Fleischer et al. 1999; Moore 2006; Navarro et al. 2008; Ma et al. 2010; Rico et al. 2011).

The nanoparticles move passively through the apoplast of endodermis (Judy et al. 2011). Xylem serves as the key carrier in the regulation and translocation of nanoparticles (Aslani et al. 2014a, b) via cell wall that acquiesces the water molecules and solute particles (Carpita and Gibeaut, 1993). Many researchers have reported that the uptake of nanoparticles into plant is through binding of transporter proteins (aquaporin) and ion channels (Moore 2006; Nair et al. 2010). This type of material can also move into the plant through transporters or root exudates by establishing complex structures (Kurepa et al. 2010) and via leaf stomata or trichomes (Eichert et al. 2008; Fernandez and Eichert 2009; Tripathi et al. 2017).

The uptake and translocation of titanium oxides–alizarin red complex root exudates develop hydrogel complex of pectin that is the carrier for entry of nanoparticles dye complex in *Arabidopsis thaliana* (Kurepa et al. 2010). Sun et al. (2014) studied the mechanism of nanoparticles uptake and translocation in mesoporous silica nanoparticles. They observed that entry of the nanoparticles through symplastic and apoplastic pathways of roots is through the xylem to upper parts of the plants. However, the mechanism of nanoparticle uptake by plants is not described yet. After entry of nanoparticles into the cell, it can move via apoplastic or

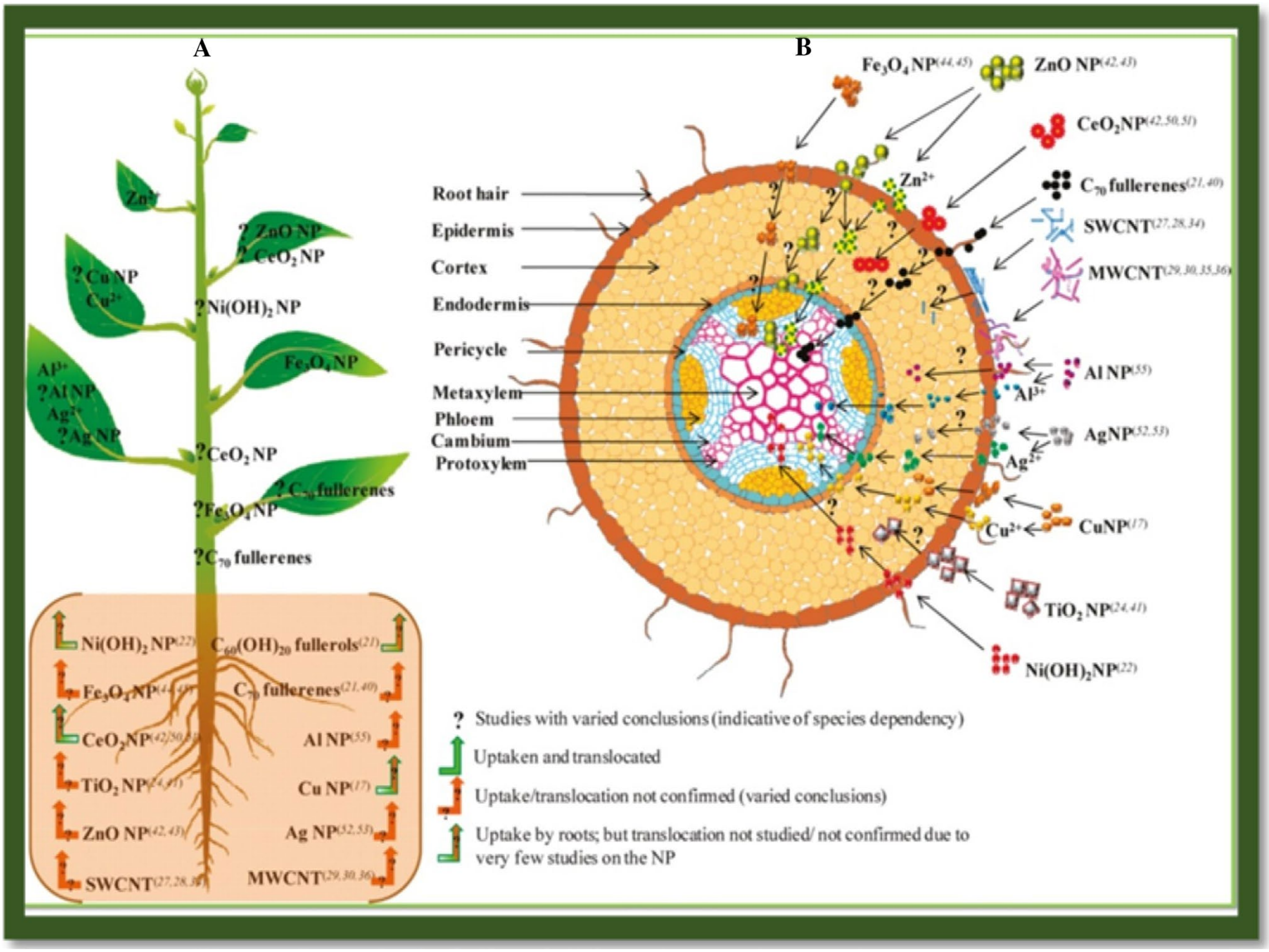

Fig. 2 Nanoparticles uptake, translocation and biotransformation pathways in a plant system: **a** process of uptake and translocation of nanoparticles. **b** Transverse section of root absorption zone presenting the distinct nanoparticle interactions. The superscripts illustrate the references mentioned in the original paper. Reprinted from [Rico et al. (2011)] with permission of © (2011) American Chemical Society

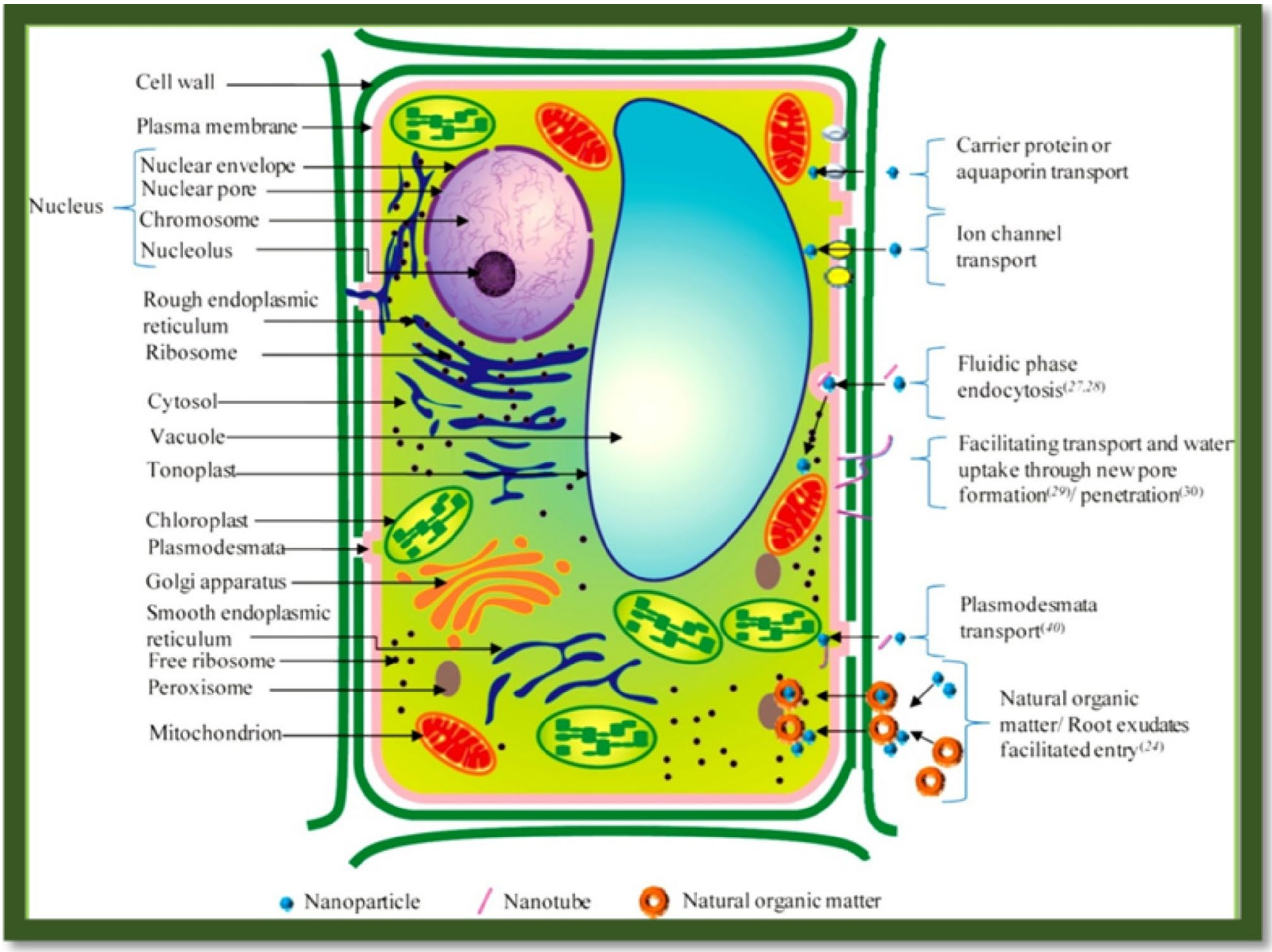

Fig. 3 Possible modes of cellular uptake of nanoparticles in plants. The superscripts illustrate the references mentioned in the original paper. Reprinted from [Rico et al. (2011)] with permission of © (2011) American Chemical Society

symplastic pathways (Rico et al. 2011; Tripathi et al. 2017). There is very limited research information on the fruit crops, but some work has been done in horticultural crops. The nanofertilizers applied on the aerial part of the plant via foliar application in Grapevines cv. 'Bidaneh Sefid' mediated plant growth and chlorophyll content. This transportation could be through leaf stomata or trichomes (Nayereh Zangeneh and MousaRasouli 2017).

Mitigating abiotic stresses

The abiotic stresses such as drought, flooding, temperature, salinity, alkalinity and nutrient toxicity/deficiencies are scrutinized as chief factors that decline the growth and productivity of plants (Boyer 1982). The crops might develop their defense mechanism against environmental stresses at certain levels by moderating molecular, biological and physico-chemical pathways. To overcome stresses, plant might adopt molecular pathways through modification of gene expressions. Nanoparticles are involved in regulation of antioxidant enzymes like superoxide dismutase, catalase, peroxidase and proline oxidase (Laware and Raskar 2014) and metabolites associated with signaling responses having ability to adapt to the climatic factors. This response arises due to translocation of adequate amount of essential nutrients delivered to the plants with the help of bio-stimulants like nanofertilizers (Cabrera et al. 2018; Juárez et al. 2019). This causes the biostimulation effect due to integration of nanoparticles and nanomaterials along with proteins, membranes, nucleic acids and various metabolites that prompt the redox signals or transition of metal ions, capable of inducing the oxidative stress (Morales et al. 2017; Juárez et al. 2019). The optimal doses of nanofertilizers are helpful to maintain the oxidative stress up to threshold level, and induction of defense mechanism through activating the resistance genes, defense proteins, metabolites and antioxidants (Juárez et al. 2019; Van Aken 2015). This bio-stimulation impact accompanied by stress tolerance delivers a summary of different studies that were reviewed by Juárez et al. (2018). The application of zinc oxides brings tolerance against water stress due to which plant defended from desiccation (Sedghi et al. 2013), while application of oxides of zinc and iron nanoparticles helps to mitigate the salinity stress (Qu et al. 2012; Solimon et al. 2015).

The application of calcite nanofertilizers @ 500 ppm reduced the duration from full bloom to maturity in *V. vinifera* cv. narince under calcareous conditions (Sabir et al. 2014). The foliar application of selenium nanoparticles (Se-NPs) @ 10–20 ppm mitigates salt stress by the activation of salt tolerance mechanism coupled with increased yield in strawberry plantation. It also improved the photosynthetic pigments like chlorophyll a and chlorophyll b by 12.19 and 40.47 percent, respectively, and enhanced the free proline levels (Zahedi et al. 2019). The main problem created by the drought stress is fruit cracking in pomegranate which can be reduced with the spray application of Se-NPs @ 1 and 2 μM. The application of iron nanoparticles (Fe-NPs) and salicylic acid in *Fragaria* × *ananassa* Duch. cv. Queen Elisa cuttings significantly affected performance of strawberry plantlets under in vitro condition (Mozafari et al. 2018b).

Cost-effectiveness of nanofertilizer

Nanofertilizers are a unique tool for attaining sustainable fruit production because it facilitates the nutrient availability to the plants due to which high yield is achieved (Pitambara and Shukla 2019). Nanofertilizers have a great role to provide an income to the farmer because it is cost-effective and provides more benefits to the farmers. Thus, their application can improve the socioeconomic status of the farmers. The efficacy of nanofertilizers depends on doses applied to the plant and varies from plants to plants. The foliar application of zinc oxides nanoparticles at the rate of 150 ppm along with iron oxide nanoparticles concentration of 150 ppm facilitates the maximum returns and also provides the highest benefit/cost ratio of 5.96 (Kumar et al. 2017).

Bottlenecks and future prospects

The fruit crops are chief source of nutrients, vitamins and fibers. To attain food security with the limited resources like land, labor and monetary, the perspective of a novel approach using, nanotechnology for fruit crop management is of paramount importance. Nanofertilizers intermingled with macro, micro, and engineered products, and biological agents like plant growth-promoting rhizobacteria (PGPR) can provide long-term benefits to the fruit crops. Keeping both the positive and negative aspects of nanofertilizers in mind, there is prerequisite to create a broad effort toward improvisation over the risk associated with nanofertilizers through advanced research procedure.

Bottlenecks

Mass production

Many studies have elucidated the positive impact of nanoparticles on the fruit production. Therefore, lot of scientific work has been published on the potential implications of nanofertilizers. However, nanofertilizers or nanotechnology-based products have not gained momentum yet as compared to conventional fertilizers (Cheng et al. 2016). The primitive issue under the implication of nanofertilizers is the production cost as well as the benefit returns. There are lot of uncertainties in farmer's opinions about the use of these products.

Unavailability of safety standards and risk assessment protocols

Nanofertilizers are the sources of nutrients to the crops, but there are lot of chances to release the contaminants as well, so there is a need to elucidate the impact of these nano-based technologies on the crops, human as well as microorganisms as depicted in Fig. 4. The increased use of nanofertilizers might show the negative results on the environment. This safety concern of nanofertilizers is another bottleneck that can be a hurdle for the commercialization at large scale (Peralta-Videa et al. 2014; Kaphale et al. 2018), whereas the toxicity of nanofertilizers chiefly depends on the size of the particle, doses and mode of application as well as the nature of the fertilizers (Mahawar et al. 2018). The larger size of nanoparticles blocks the pores and hinders water absorption and nutrient uptake. Toxicity can cause a reduction in plant growth, and thus increased oxidative stress can damage genetic material (Morales et al. 2017) coupled with reduction in activity of microflora (Aruoja et al. 2015). It also changes the properties of cell membrane (Huang et al. 2017), leading to the absorption of nanoparticles by the cell, and ultimately the generation of reactive oxygen species (Loria et al. 2011; Van Aken 2015). The scientific community and government might legalize the use of nanofertilizers along with the permissible and safety measures.

Technical challenges and lack of awareness

A systematic experimentation is must in field as well as under laboratory conditions to find out the environmentally safe doses of nanofertilizers (Hu et al. 2016). Due to less commercialization, the use of nanofertilizers by the farmers is not up to the mark as compared to conventional fertilizers.

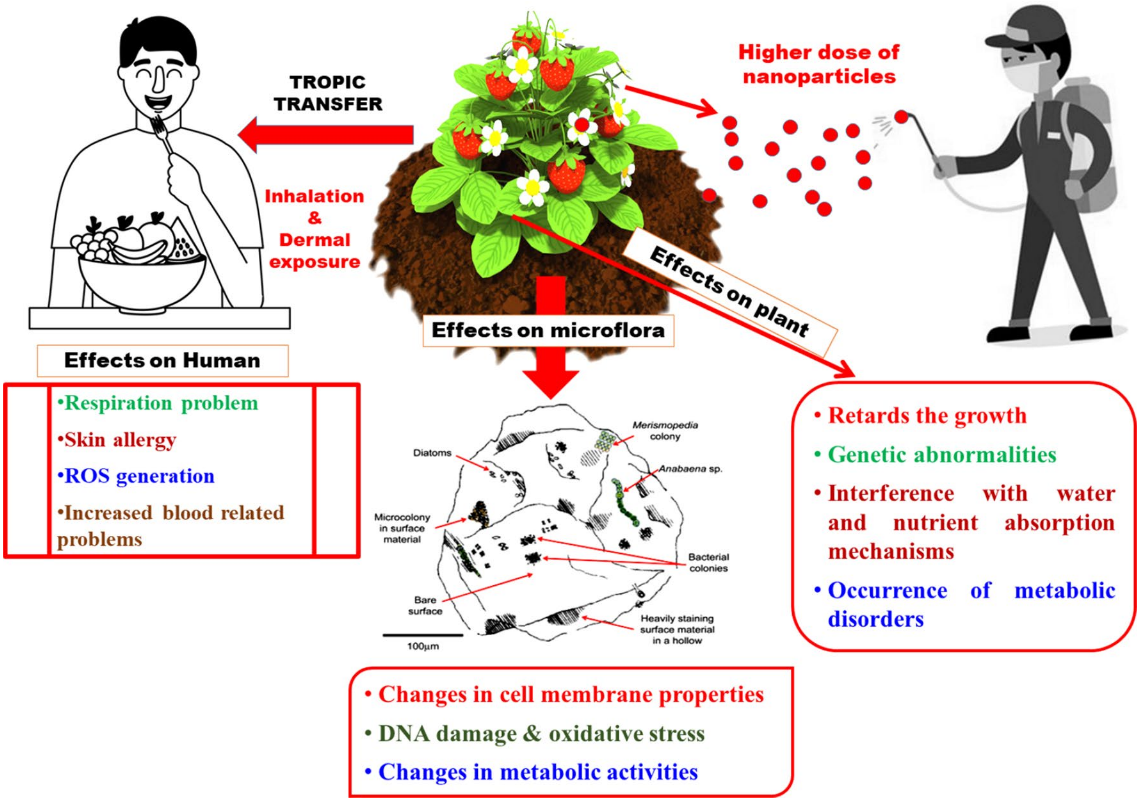

Fig. 4 Toxicity issues of nanoparticles in plants, soil microflora and human being

There is a need to disperse the technical demonstration for the use of nanofertilizers.

Future prospects

Assessment of toxicity and transformation of nanoparticles in the soil

Various reports are available on the size as well as concentration of nano-based products, but there are limited studies on the toxicity of nanoparticles. The application of nanoparticles, especially metal oxide, may lead to the discharge of toxic metal ions to the environment, which might reduce the soil health. These ions follow the process of integration or aggregation, resulting in binding with the organic molecules (Batley et al. 2013; Karimi and Fard 2017; Sengul and Asmatulu 2020). The nanoparticles may accumulate in higher quantity whether it is applied in low or higher doses which lead to the toxic effects to the plant as well as soil (Hu et al. 2016). The accumulation is dependent on the soil type and its physicochemical characteristics namely soil aeration, maximum water holding capacity, soil texture, soil organic matter, organic carbon and microbial diversity. These factors also determine the stability and transformation of nanofertilizers, whereas the degradation of nanoparticles is also a mode of transformation. The soil biota can decline or incline toxicity after the degradation which is called as soil bio-magnification. The transformation of nanofertilizers may exhibit significant changes in the properties of nanofertilizers, which require careful appraisal. Studies regarding nanotoxicology are also required.

Need to review the interactions of nanoparticles with human body and food chain

The application of nanofertilizers in fruit crop production not only provides a positive impact, but may cause antagonistic effects on the crops like conventional fertilizers. Foliar application of nanofertilizers leads to form aerosol in the environment and can cause respiration problems in humans by moving into the different organs of the human body (Lucarelli et al. 2004; Som et al. 2011). The low concentration of titanium dioxide may lead to the tumor incidences in human body (Lee et al. 1986; Heinrich et al. 1989) and also accumulate in various organs like kidney, brain and spleen (Sengul and Asmatulu 2020). There is a need to research on the toxicity-related problems caused by the nanoparticles and suggest the suitable techniques for reducing the toxicity.

Appraisal of environmental safe doses

The assessment of safe nanofertilizer doses is a crucial task to get sustainable production. The optimum doses can negate the least negative effects on the crop as well as environment. Boxall et al. (2007) used various tools to analyze the variable concentrations of nanofertilizers in soil by direct means. They concluded that appraisal of environment safe doses is dependent on the mode of application, rooting depth of the crop and soil physicochemical properties.

Adaptation of lethal effects by soil microflora

The regular use of nanofertilizers may lead to adaptability of soil microflora to a limited extent (Dhas et al. 2014). This can also be considered as prospects for sustainable production of crops through adaptation.

Implication under different ecological areas

There is limited research on the nanofertilizers applications in fruit crops under different ecological areas. There is a need to conduct the experimental trials in different ecological zones which will provide information related to the performance of nanofertilizers in different environments.

Economic analysis of the nanofertilizer against other conventional fertilizer

There is very limited literature on the cost-effectiveness of nanofertilizers as compared to conventional fertilizers. This leads to improvement in commercialization of these products at large scale because this will provide information to the farmers about monetary returns from the crops after using nanofertilizers. This will also lead to gaining momentum for the adoption of nanofertilizers.

Conclusion

It can be concluded from the formal deliberations that the nanoparticles, especially nanofertilizers, are the next-generation technologies that can work as tool for upgrading the conventional farming systems. Various nanomaterials have shown their potential roles in fruit crops with respect to plant vigor, yield improvements and environmental stability. But, there is a long way for advocating such technologies for sustainable fruit production as many challenges like legal procedures are required to be addressed for implementation on large scale. The potential uses of nanofertilizers will definitely create a rebellion under fertilizer industry and will meet out the problem of food insecurity in developing world.

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Compliance with ethical standards

Conflict of interest All authors declare that they have no conflict of interest.

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