Nanotechnology in Horticultural Crops

Subjects: Biotechnology & Applied Microbiology | Horticulture
Contributor: Tofazzal Islam

Nanotechnology shows high potential in the improvement of agricultural productivity thus aiding future food security. In horticulture, maintaining quality as well as limiting the spoilage of harvested fruit and vegetables is a very challenging task. Various kinds of nanomaterials have shown high potential for increasing productivity, enhancing shelf-life, reducing post-harvest damage and improving the quality of horticultural crops. Antimicrobial nanomaterials as nanofilm on harvested products and/or on packaging materials are suitable for the storage and transportation of vegetables and fruits. Nanomaterials also increase the vitality of the cut flower. Nanofertilizers are target-specific, slow releasing and highly efficient in increasing vegetative growth, pollination and fertility in flowers, resulting in increased yield and improved product quality for fruit trees and vegetables. Formulated nanopesticides are target-specific, eco-friendly and highly efficient. Nanosensors facilitate up-to-date monitoring of growth, plant disease, and pest attack in crop plants under field conditions. These novel sensors are used to precisely identify the soil moisture, humidity, population of crop pests, pesticide residues and figure out nutrient requirements.

Keywords: nanoencapsulation ; biosensor ; nutrient use efficiency ; nanofilm

1. Introduction

The word ‘nanotechnology’ is coined from the Greek word “nano”, meaning dwarf. The emergence of nanotechnology is deeply connected to a historic statement by the Nobel Prize winner Richard Phillips Feynman [1]: “*There is plenty of room at the bottom*”. The science, engineering, and technology at the nanoscale (about 1 to 100 nanometers) is called nanotechnology [2][3][4][5][6]. In fact, nanoparticles demonstrate excitingly different features than the bulk materials because of their high surface to volume ratio [5][6][7][8]. Furthermore, the quantum phenomena that occur in the nanoscale of any molecule or element or material remarkably increase its catalytic activity [5][7][9][10][11]. Therefore, nanoparticles are hugely used in communication technology, electronics, textiles, the automotive industry, biomedical tools, environmental technology, biotechnology and renewable energy. In agriculture, novel nanomaterials have shown high potential for the development of new crop varieties through genetic engineering, hybrid varieties of crops, and novel high efficient agrochemicals for the nutrition and protection of crop plants [12][13]. Furthermore, the application of nanomaterials improves food processing, packaging, food safety, plant nutrition, efficiency of pesticides and fertilizers, and the reduction of environmental pollution and the production of nutraceuticals [14][15]. The scope of application of specifically designed nanoparticles in agriculture especially in horticultural crop production is illustrated in **Figure 1**.

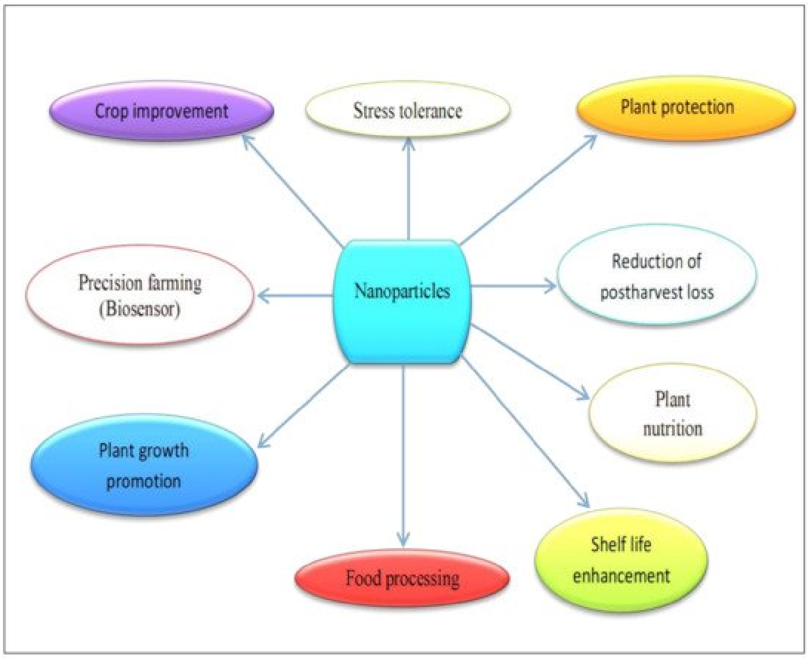

Figure 1. Scope of nanoparticles in agriculture as well as in productivity and quality of horticultural crops.

Nanotechnology is an emerging technology, which has a history of over 2000 years [16]. It has been flourishing as an advanced tool in multiple areas of science including chemistry, physics, medicine, materials science, aeronautical, pharmaceutical, agriculture, and food and even in horticulture [17]. Horticulture can be defined as a branch of agricultural science and art of cultivation and management of fruits, vegetables, flowers, and ornamental plants. Ensuring the food and nutritional security of the ever-increasing population of the world is indeed a formidable challenging task in the changing global climate. Therefore, increasing productivity and decreasing post-harvest losses by using frontier technological approaches such as nanotechnology and biotechnology are considered as the best strategies for addressing this challenging task. In horticulture, the application of nanomaterials seems important for increasing the productivity, quality of the products and reducing the post-harvest losses of fruits and vegetables. It is determined that up to 30% of horticultural crop products are lost in developing countries due to microbiological spoilage and physiological processes. By the application of nanofilm and nano-packaging with antimicrobial nanomaterials, we can significantly decrease this amount of post-harvest losses to 5–10%, which ultimately saves huge amounts of nutritious foods. Reducing these losses can not only improve farmers' income, but could also ensure better quality and nutrition of the food products. The currently used synthetic fertilizers and pesticides are hazardous to the environment and human health and highly expensive. A large proportion of these applied chemical inputs are lost through leaching, volatilization, evaporation and rainwater. On the other hand, the innovative formulations of nanopesticides and nanofertilizers are highly efficient, target-specific and safe.

2. Nanomaterials on Growth and Development of Horticultural Crops

Nanoparticles are solid colloidal particles that consist of macromolecular materials. Active ingredients such as bioactive materials or drug molecules are entrapped, dissolved, encapsulated or absorbed in the nanoparticles. Nanofertilizers are cost-effective and environment-friendly inputs that promote highly efficient plant nutrition and ultimately increase the yield of crop plants. Nanofertilizers supply nutrients to crop plants in the following three ways: (i) the nutrient can be covered by the nanoparticles in the form of nanoporous materials or nanotubes; (ii) wrapped by a thin defensive film of polymer; and (iii) provided as emulsion or particles of nanoscale measurements. Nanofertilizers are slowly, target-specifically and efficiently released to the plants. For example, ZnO nanoparticles improve the yield of peanuts (*Arachis hypogaea*) [18]. Similarly, the application of SiO_2 nanoparticles enhances plant biomass and the contents of biomolecules such as chlorophyll, proteins, and phenols in the grains of maize [19]. Nanotubes of carbon at a low concentration enhance the root growth of hexaploidy wheat [20], seed germination and seedling growth of mustard (*Brassica juncea*) [21], black gram (*Phaseolus mungo*) [22], rice (*Oryza sativa*) [23] and cell growth (16% increase) of tobacco (*Nicotiana tabacum*) [24]. The use of TiO_2 and SiO_2 nanomaterials enhances nitrate reductase activity and apparently hastens seed germination and seedling growth of soybean [25]. Similar to field crops, the application of nanomaterials also promotes the growth and development of horticultural crops.

In horticulture, nanofertilizers are used to increase vegetative growth, pollination and fertility of flowers, resulting in increased yield and improved product quality for fruit trees [26][27]. Exogenous supplementation of nano-Ca on blueberries under saline stress conditions result in increased vegetative growth and increased chlorophyll content in the leaf [28]. Similarly, nano-boron spray on the leaves of mango trees shows a positive effect in increasing the overall yield and chemical properties of fruits likely to be linked with the enhancement of contents of chlorophyll and essential nutrient elements e.g., nitrogen (N), phosphorus (P), potassium (K), manganese (Mn), magnesium (Mg), boron (B), zinc (Zn) and iron (Fe) in the leaves [29]. The spraying of mango trees with nano-zinc also leads to increase in fruit weight, fruit number and yield, contents of leaf chlorophyll and carotene, and concentrations of several nutrient elements including N, P, K, and Zn [26]. Similarly, the application of nano-boron and nano-zinc fertilizers improves the quality of fruits, increases the number of fruits, the ratio of total soluble sugars (TSS) and maturity index, total sugars and total phenols in pomegranates [30].

2.1. Nanofertilizers

A fertilizer can be defined as any synthetic or natural substance (other than liming materials) that is mixed into the soil or sprayed on plant tissues to provide one or more essential nutrient element(s) to promote the nutrition of crop plants [31][32]. There are diverse sources of fertilizers available, either natural or synthetically produced. The application of fertilizers is indispensable for the higher productivity of crops in modern agriculture. One of the big bottlenecks of fertilization in crops is that substantial parts of the used fertilizers are lost in various ways and ultimately pollute the environment and increase the production cost. A notable recent progress in reducing the loss of applied fertilizers to the environment is the application of nanofertilizers. Nanofertilizers are being formulated by incorporating with plant nutrients into nanomaterials, applying a fine layer of nanomaterials on nutrient molecules, and producing nanosized emulsions. Nanofertilizers and nanobiofertilizers encompass both natural and synthetic materials, respectively, thus judiciously improve the bioavailability and soil fertility compared to the traditional fertilizers [33]. Nevertheless, the most important characteristics of nanofertilizers are (i) the individual size of the particles ≤100 nm; (ii) a bulk size of approximately 100 nm; and (iii) the nanoproduct must be environmentally safe and durable. Another property of a nano-fertilizer is the retention of its nanosize and aggregates during interactions with the soil particles or the roots of crop plants. The reactivity of nanofertilizers is fully dependent on the shape and size of nanoparticles [34]. The escalation of nutrient use efficiency, regulating the active ingredients and minimum residual impact on biodiversity in soil are the most crucial components of nanofertilizers [35]. According to their distribution, nutrient balance and the amount required by the plant, the nanofertilizers are mainly subcategorized as macronutrient and micronutrient nanofertilizers (**Figure 2**).

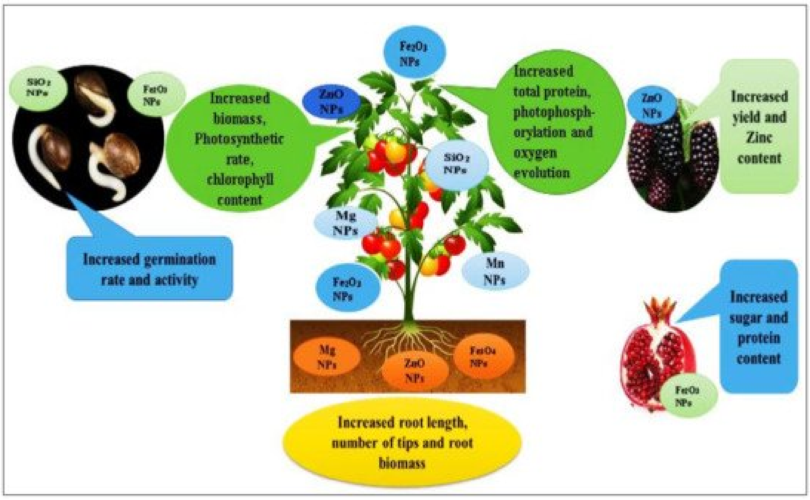

Figure 2. Schematic overview of improvements of germination of seeds, growth of plants, and production of higher biomass or yield by the application of various kinds of nano-fertilizers (adapted and redrawn from Zhao et al. [36]).

2.2. Nano-Plant Growth Stimulator

The application of NMs in horticulture is remarkably increased in the last few decades [37][38]. The form and constituents of the NMs are used in pest and disease management to enhance the growth and productivity of plants [4]. Nevertheless, both beneficial and detrimental effects of application of nanomaterials on plants have also been reported (**Table 2**). The impacts of NMs on the germination of seeds, growth, development and yield of horticultural plants are summarized and presented in **Table 2**. Although the mechanisms are not fully understood, reports showed that higher doses of nanoparticles are toxic for plants.

Table 2. Influence of nanoparticles (NPs) on germination, growth, development and yield of horticultural crops.

Nanoparticles	Dose (mg/L)	Crop	Effect on Plant Growth and Development	Reference
CeO_2	125 to 4000	Cucumber	Negative impacts at the molecular and biochemical levels in plants.	[39]
TiO_2	1000 to 2000	Spinach	Promotes growth and photosynthesis.	[40][41]
Carbon nanotubes (MWCNT)	10–40	Tomato	Enhances germination and growth rate but inhibits elongation of root in tomato.	[42][43]
Carbon nanotubes (MWCNT)	10–40	Onion and cucumber	Enhances elongation of root.	[43]
Carbon nanotubes (MWCNT)	0, 500, 1000 or 5000	Zucchini, tomato, corn, soybean	Reduces biomass in corn and soybean (500 mg/kg), but the development of tomato and zucchini unaffected.	[44]
Fe_3O_4	0.67	Lettuce, spinach, radish, cucumber, tomato, peppers	Inhibits seed germination.	[44]
ZnO	100–1000	Garden pea	No effect on seed germination but affects nodulation and root length	[45]

Nanoparticles	Dose (mg/L)	Crop	Effect on Plant Growth and Development	Reference
Ag	800	Faba bean	Declines germination	[46][47]
Ag	0, 125, 250, 500	Radish	No effect on germination	

2.3. Nutrient Uptake and Subsequent Translocation in Plant

Nanoparticles are easily absorbed to plant surfaces and uptaken by plants via nano- to micrometre-scale natural openings of plants. Nanoparticles (NPs) uptake into the plant body can use different pathways (**Figure 3**). Uptake rates depend on the surface properties and size of the NPs. Very small-sized NPs can be penetrated via the cuticle. Large size NPs can enter via non-cuticle areas e.g., hydathodes, stomata, and the stigma of flowers. Nanoparticles must traverse the cell wall to enter into the protoplast of the plant cell. Several lines of evidence suggest that NPs less than 5 nm in diameter are efficient in traversed the wall of the undamaged plant cell (**Figure 3**) [48].

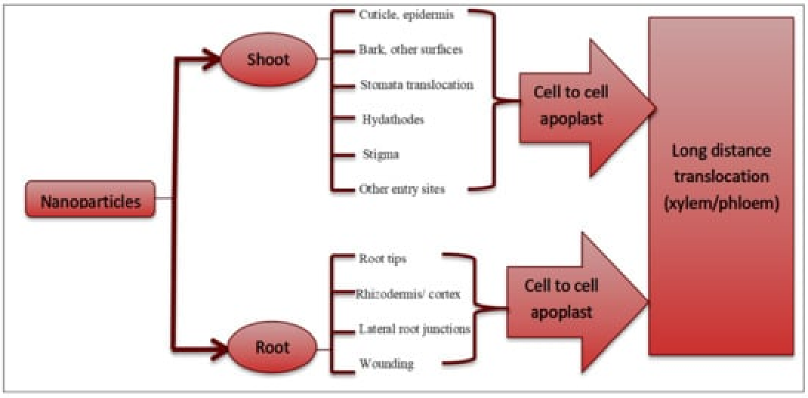

Figure 3. Putative pathways of nanoparticle uptake and translocation in plants. Redrawn and adapted from Tarafdar [48].

2.4. Nanopesticide

Pests are the most important limiting factors for crop yield and need to be efficiently controlled. Pest control by traditional means involves the use of large quantities of chemical pesticides, which results in environmental problems and increases the cost of production [49]. Pesticide dilution with nanotreated water could greatly improve their efficiency and reduce the quantity of chemicals used. Nanopesticides are more efficient than conventional pesticides in controlling pests. There use also reduces the cost by half compared to conventional pesticides [50].

Most nanopesticides are eco-friendly, and the majority of nano-pesticide formulations are highly target-specific and controlled release. These properties of nano-pesticides enhance the utilization of pesticides and remarkably decrease residue levels and environmental pollution. For example, highly polymeric nanomicrocapsule formulations have slow release and protection performance because they have been formulated employing light-sensitive, humidity-sensitive, temperature-sensitive, enzyme-sensitive and soil pH-sensitive materials. Nanopesticide formulations improve the adhesion of droplets on plant surfaces, which improves the dispersion and bioactivity of the active ingredient of pesticide formulations. Therefore, nanopesticides have a higher efficacy compared to conventional pesticide formulations. The higher efficacy of nanopesticides is associated with their small size, wettability, improvable pesticide droplet ductility and target adsorption. Insecticidal value can also be developed by using nanoencapsulation. In this method, the nanosized active pesticide ingredient is sealed off by a thin protective coating. This approach greatly improves the effectiveness and reduces the amount of pesticide required and related environmental pollution. The clay nanotubes known as “Halloysite” are an example of pesticide carrier, which greatly reduces the amounts of required pesticides for controlling target pests [51].

2.5. Enhancement of Shelf-Life of Horticultural Crops by Nanomaterials

Owing to their perishable attributes, the satisfactory shelf-life periods of most fruits and vegetables are at risk when stored under normal conditions. There are several traditional preservation techniques, however, all these techniques are expensive and barely efficient in the enhancement of shelf-life or limited by an undesirable residue. Because of several regulatory characteristics of nanomaterials, nanotechnology-based exploitation of shelf-life expansion techniques has the power to lessen the drawbacks of classical methods.

2.6. Enhancing the Vitality of Cut Flowers

Cut flowers have ornamental value and are commercially very important, but the flowers' shelf-life is very short [52], due to higher microbial contamination [53]. The early wilting of the flowers is due to microbial and stem barrier infection that causes stem blockage which limits the uptake and transport of water, leading to water imbalances [54][55]. Hence, it is important to overcome stem blockage by controlling microbial infections. Several reports have suggested that nano-silver has the potential to broaden the vase life of cut flowers [55][56][57][58]. The most important nanoparticle, graphene oxide (GO) is a graphene imitating carbon-based NPs containing enormous quantities of oxygenated groups with an extensive surface area that contributes a first-rate capability to transfer nourishment for sluggish-discharge fertilizers [59].

2.7. Nanomaterials in Food Processing

Food processing techniques are employed for the enhancement of the flavour as well as the quality of the food product for a longer period. Radioactivity, high hydrostatic force and ohmic warming are insufficient conservation techniques used of food processing [60]. Nowadays, the use of different NPs and their technology in the food processing industry are rapidly increasing and some of the current trends are summarized in **Table 4**.

Table 4. Roles and mechanisms of nanomaterials for the enhancement of food processing.

Nano-Technique	Example and Composition	Effects of the Technique on Food Processing	Reference
Nanoencapsulation	Nano-capsules	• Enhanced stability, protection against oxidation, and safeguarding of uneven constituents. • Flavour creation and moistness activated measured release. • pH directs to control for slow release. • Boosted bioavailability and effectiveness.	[61]
	Nano-liposomes	• The sting of the odour and undesirable constituents in food items. • Distribution of enzymes, flavours, and so-forth for improving the quality of food.	[62]

Nano-Technique	Example and Composition	Effects of the Technique on Food Processing	Reference
Nano-emulsions	**Colloidosomes**	• Supply indispensable vitamins and minerals in the food. • Aggregate the essential nutrients in desirable food.	[63]
	Nano-cochleate	• Assist to enlighten the superiority of desirable processed foodstuffs.	[64]
	Daily Boost	• Used for the nano-encapsulation of invigorated desirable vitamins and bioactive components in foods.	[65]
	Nano-emulsions	• For improving food safety and quality, nano-emulsions use in a salad, flavoured oils, sweets, beverages, and other desirable foods.	[66]
	Brominated vegetable oil, ester gum, dammar gum and sucrose-acetate isobutyrate	• Assist to spread and obtainability of the nutrients in the processed food.	[67]

2.8. Nanosensors in Precision Horticulture

A nanosensor can be defined as any device that is capable of conveying data and evidence about the behavior and characteristics of NPs at the nanoscale level to the macroscopic level [68]. Nanosensors are necessary for facilitating real-time tracking of field crop, crop growth, and pest and disease incidence. Nanosized materials which can be used for sensor manufacturing are metal nanotubes, nanowires, nanofibers, nanocomposites, nanorods, and nanostructured polymers, different allotropes of carbon including carbon nanotubes, graphene, and fullerenes [69]. Real-time monitoring can minimize the excess use of pesticides and fertilizers in crop production, which is helpful in the reduction of environmental pollution and production costs. Application of nanosensors changes conventional agriculture into smart agriculture, which is more energy-efficient and eco-friendly for sustainable agricultural practices. Smart agricultural practices in horticultural crop production involve: (i) nanoformulation-based fertilizers or pesticide delivery systems, which increase the dispersion and wettability of nutrients [70]; (ii) nanodetectors for pesticide or fertilizer residues; and (iii) remote-sensing-based monitoring systems for disease incidence and crop growth. Nanosensors are used in horticulture to identify the moisture content of the soil, pesticide residues, nutrient requirements and crop pest detection.

References

1. Feynman, R.P. There’s plenty of room at the bottom. Eng. Sci. 1960, 23, 22–36.
2. Curtis, J.; Greenberg, M.; Kester, J.; Phillips, S.; Krieger, G. Nanotechnology and nanotoxicology: A primer for clinicians. Toxico Rev. 2006, 25, 245–260.
3. Bhattacharyya, D.; Singh, S.; Satnalika, N.; Khandelwal, A.; Jeon, S.-W. Nanotechnology, big things from a tiny world: A review. Adv. Electron. Electr. Engin. 2009, 2, 29–38.
4. Servin, A.D.; White, J.C. Nanotechnology in agriculture: Next steps for understanding engineered nanoparticle exposure and risk. NanoImpact 2016, 1, 9–12.
5. Satalkar, P.; Elger, B.S.; Shaw, D.M. Defining nano, nanotechnology and nanomedicine: Why should it matter? Sci. Eng. Ethics. 2016, 22, 1255–1276.
6. Sia, P.D. Nanotechnology among innovation, health and risks. Procedia Soc. Behav. Sci. 2017, 237, 1076–1080.
7. Singh, A.; Prasad, S.M. Nanotechnology and its role in agro-ecosystem: A strategic perspective. Int. J. Environ. Sci. Technol. 2017, 14, 2277–2300.

8. Khan, J.H.; Lin, J.; Young, C.; Matsagar, B.M.; Wu, K.C.; Dhepe, P.L.; Islam, M.T.; Rahman, M.; Shrestha, L.K.; Alshehr i, S.M.; et al. High surface area nanoporous carbon derived from Bangladeshi jute. Mater. Chem. Phys. 2018, 216, 491 –495.

9. Purohit, R.; Mittal, A.; Dalela, S.; Warudkar, V.; Purohit, K.; Purohit, S. Social, environmental and ethical impacts of nan otechnology. Mater. Today Proc. 2017, 4, 5461–5467.

10. Jiang, B.; Li, C.; Dag, O.; Abe, H.; Takei, T.; Imai, T.; Hossain, M.S.A.; Islam, M.T.; Wood, K.; Henzie, J.; et al. Mesopor ous metallic rhodium nanoparticles. Nat. Commun. 2017, 8, 15581.

11. Iqbal, M.; Li, C.; Jiang, B.; Hossain, M.S.A.; Islam, M.T.; Henzie, J.; Yamauchi, Y. Tethering mesoporous Pd nanoparticl es to reduced graphene oxide sheets forms highly efficient electrooxidation catalysts. J. Mater. Chem. A. 2017, 5, 2124 9–21256.

12. Islam, M.T. Applications of nanomaterials for future food security: Challenges and prospects. Malay J. Halal. Res. 2019, 2, 6–9.

13. Hossain, A.; Kerry, R.G.; Farooq, M.; Abdullah, N.; Islam, M.T. Application of Nanotechnology for Sustainable Crop Pro duction Systems. In Nanotechnology for Food, Agriculture, and Environment; Nanotechnology in the Life Sciences; Tha ngadurai, D., Sangeetha, J., Prasad, R., Eds.; Springer: Cham, Switzerland, 2020; pp. 135–159.

14. Maqbool, Q.; Barucca, G.; Sabbatini, S.; Parlapiano, M.; Ruello, M.L.; Tittarelli, F. Transformation of Industrial and Orga nic Waste into Titanium Doped Activated Carbon-Cellulose Nanocomposite for Rapid Removal of Organic Pollutants. J. Hazard. Mater. 2021, 423, 126958.

15. Handford, C.E.; Dean, M.; Spence, M.; Henchion, M.; Elliott, C.T.; Campbell, K. Awareness and attitudes towards the e merging use of nanotechnology in the agrifood sector. Food Control 2015, 57, 24–34.

16. Elnashaie, S.S.; Danafar, F.; Rafsanjani, H.H. Nanotechnology for Chemical Engineers. Nanotechnol. For. Chem. Eng. 2015, 1, 278.

17. Duhan, J.S.; Kumar, R.; Kumar, N.; Kaur, P.; Nehra, K.; Duhan, S. Nanotechnology: The new perspective in precision a griculture. Biotechnol. Rep. 2017, 15, 11–23.

18. Prasad, T.N.V.K.V.; Sudhakar, P.; Sreenivasulu, Y.; Latha, P.; Munaswamy, V.; Reddy, K.R.; Sreeprasad, T.S.; Sajanlal, P.R.; Pradeep, T. Effect of nanoscale zinc oxide particles on the germination, growth and yield of peanut. J. Plant. Nutri. 2012, 35, 905–927.

19. Suriyaprabha, R.; Karunakaran, G.; Yuvakkumar, R.; Prabu, P.; Rajendran, V.; Kannan, N. Growth and physiological re sponses of maize (Zea mays L.) to porous silica nanoparticles in soil. J. Nanopart. Res. 2012, 14, 1294–1296.

20. Wang, X.; Han, H.; Liu, X.; Gu, X.; Chen, K.; Lu, D. Multi-walled carbon nanotubes can enhance root elongation of whe at (Triticum aestivum) plants. J. Nanopart Res. 2012, 14, 1–10.

21. Ghodake, G.; Seo, Y.D.; Park, D.; Lee, D.S. Phytotoxicity of carbon nanotubes assessed by Brassica juncea and Phas eolus mungo. J. Nanoelect. Optoelect. 2010, 5, 157–160.

22. Mondal, A.; Basu, R.; Das, S.; Nandy, P. Beneficial role of carbon nanotubes on mustard plant growth: An agricultural pr ospect. J. Nanopart. Res. 2011, 13, 4519–4528.

23. Nair, R.; Varghese, S.H.; Nair, B.G.; Maekawa, T.; Yoshida, Y.; Kumar, D.S. Nanoparticulate material delivery to plants. Plant. Sci. 2010, 179, 154–163.

24. Khodakovskaya, M.V.; de Silva, K.; Biris, A.S.; Dervishi, E.; Villagarcia, H. Carbon nanotubes induce growth enhancem ent of tobacco cells. ACS Nano 2012, 6, 2128–2135.

25. Changmei, L.; Chaoying, Z.; Junqiang, W.; Guorong, W.; Mingxuan, T. Research of the effect of nanometer materials o n germination and growth enhancement of Glycine max and its mechanism. Soybean Sci. 2001, 21, 168–171.

26. Zagzog, O.A.; Gad, M.M.; Hafez, N.K. Effect of nano-chitosan on vegetative growth, fruiting and resistance of malforma tion of mango. Trends Hortic Res. 2017, 7, 11–18.

27. Zahedi, S.M.; Karimi, M.; da Silva, J.A.T. The use of nanotechnology to increase quality and yield of fruit crops. J. Sci. Food Agric. 2020, 100, 25–31.

28. Sabir, A.; Yazar, K.; Sabir, F.; Kara, Z.; Yazici, M.A.; Goksu, N. Vine growth, yield, berry quality attributes and leaf nutrie nt content of grapevines as influenced by seaweed extract (Ascophyllum nodosum) and nanosize fertilizer pulverization s. Sci. Hort. 2014, 175, 1–8.

29. Abdelaziz, F.H.; Akl, A.M.M.A.; Mohamed, A.Y.; Zakier, M.A. Response of keitte mango trees to spray boron prepared b y nanotechnology technique. N. Y. Sci. J. 2019, 12, 48–55.

30. Davarpanah, S.; Tehranifar, A.; Davarynejad, G.; Abadía, J.; Khorasani, R. Effects of foliar applications of zinc and boro n nano-fertilizers on pomegranate (Punica granatum cv. Ardestani) fruit yield and quality. Sci. Hort. 2016, 210, 57–64.

31. Bhardwaj, D.; Ansari, M.W.; Sahoo, R.K.; Tuteja, N. Biofertilizers function as key player in sustainable agriculture by im proving soil fertility, plant tolerance and crop productivity. Microb. Cell Fact. 2014, 13, 1–10.

32. Dong, W.; Zhang, X.; Wang, H.; Dai, X.; Sun, X.; Qiu, W.; Yang, F. Effect of different fertilizer application on the soil fertil ity of paddy soils in red soil region of southern China. PLoS ONE 2012, 7, e44504.

33. Sidorowicz, A.; Maqbool, Q.; Nazar, M. Future of Nanofertilizer. In Nanotechnology for Agriculture: Crop Production & P rotection; Panpatte, D., Jhala, Y., Eds.; Springer: Singapore, 2019; pp. 143–152.

34. Dimkpa, C.O.; Bindraban, P.S. Nano-fertilizers: New products for the industry? J. Agric. Food Chem. 2017, 66, 6462–6 473.

35. Sempeho, S.I.; Kim, H.T.; Mubofu, E.; Hilonga, A. Meticulous overview on the controlled release fertilizers. Adv. Chem. 2014, 2014, 63071.

36. Zhao, L.; Lu, L.; Wang, A.; Zhang, H.; Huang, M.; Wu, H.; Xing, B.; Wang, Z.; Ji, R. Nano-Biotechnology in Agriculture: Use of Nanomaterials to Promote Plant Growth and Stress Tolerance. J. Agric. Food Chem. 2020, 68, 1935–1947.

37. Tarafdar, J.C.; Raliya, R.; Mahawar, H.; Rathore, I. Development of zinc nano-fertilizer to enhance crop production in pe arl millet (Pennisetum americanum). Agric. Res. 2014, 3, 257–262.

38. Vance, M.E.; Kuiken, T.; Vejerano, E.P.; McGinnis, S.P.; Hochella, M.F.; Hull, D.R. Nanotechnology in the real world: Re developing the nanomaterial consumer products inventory. Beilst. J. Nanotechnol. 2015, 6, 1769–1780.

39. López-Moreno, M.L.; Avilés, L.L.; Pérez, N.G.; Irizarry, B.Á.; Perales, O.; Cedeno-Mattei, Y.; Román, F. Effect of cobalt f errite (CoFe2O4) nanoparticles on the growth and development of Lycopersicon lycopersicum (tomato plants). Sci. Tota l Environ. 2016, 550, 45–52.

40. Hong, F.; Yang, F.; Liu, C.; Gao, Q.; Wan, Z.; Gu, F.; Wu, C.; Ma, Z.; Jhou, Z.; Yang, P. Influences of nanoTiO2 on the c hloroplast aging of spinach under light. Biol. Trace Elem. Res. 2005, 104, 249–260.

41. Yang, F.; Hong, F.; You, W.; Liu, C.; Gao, F.; Wu, C.; Yang, P. Influences of nano anatase TiO2 on nitrogen metabolism of growing spinach. Biol. Trace Elem. Res. 2006, 110, 179–190.

42. Khodakovskaya, M.V.; Kim, B.S.; Kim, J.N.; Alimohammadi, M.; Dervishi, E.; Mustafa, T.; Cernigla, C.E. Carbon nanotu bes as plant growth regulators: Effects on tomato growth, reproductive system, and soil microbial Community. Small 20 13, 9, 115–123.

43. Cańas, J.E.; Long, M.; Nations, S.; Vadan, R.; Dai, L.; Luo, M.; Olszyk, D. Effects of functionalized and nonfunctionalize d single-walled carbon nanotubes on root elongation of select crop species. Environ. Toxicol. Chem. 2008, 27, 1922–19 31.

44. Torre-Roche, R.D.L.; Hawthorne, J.; Deng, Y.; Xing, B.; Cai, W.; Newman, L.A.; White, J.C. Multiwalled carbon nanotub es and C60 fullerenes differentially impact the accumulation of weathered pesticides in four agricultural plants. Environ. Sci. Technol. 2013, 47, 12539–12547.

45. Raliya, R.; Nair, R.; Chavalmane, S.; Wang, W.-N.; Biswas, P. Mechanistic evaluation of translocation and physiological impact of titanium dioxide and zinc oxide nanoparticles on the tomato (Solanum lycopersicum L.) plant. Metallomics 20 15, 7, 1584–1594.

46. Abd-Alla, M.H.; Nafady, N.A.; Khalaf, D.M. Assessment of silver nanoparticles contamination on faba bean-Rhizobium l eguminosarum bv. viciae-Glomus aggregatum symbiosis: Implications for induction of autophagy process in root nodul e. Agric. Ecosyst. Environ. 2016, 218, 163–177.

47. Zuverza-Mena, N.; Armendariz, R.; Peralta-Videa, J.R.; Gardea-Torresdey, J.L. Effects of silver nanoparticles on radish sprouts: Root growth reduction and modifications in the nutritional value. Front. Plant. Sci. 2016, 7, 90.

48. Tarafdar, J.C. Nanoparticle Production, Characterization and its Application to Horticultural Crops; ICAR: Jodhpur, Raja sthan, 2015; pp. 222–229.

49. Sharon, M.; Choudhary, A.K.; Kumar, R. Nanotechnology in agricultural diseases and food safety. J. Phytol. 2010, 2, 83 –92.

50. Huang, S.W.; Wang, L.; Liu, L.M.; Fu, Q.; Zhu, D.F. Nonchemical pest control in China rice: A review. Agron. Sustain. D ev. 2014, 34, 275–291.

51. Devendra, K.; Nisha, M.; Singh, S.R. Emerging technologies to enrich agricultural and horticultural crop quality and pro duction. Ann. Hort. 2019, 12, 55–61.

52. Solgi, M.; Kafi, M.; Taghavi, T.S.; Naderi, R. Essential oils and silver nanoparticles (SNP) as novel agents to extend vas e-life of gerbera (Gerbera jamesonii cv. “Dune”) flowers. Post Biol. Technol. 2009, 53, 155–158.

53. Lü, P.; He, S.; Li, H.; Cao, J.; Xu, H. Effects of nano-silver treatment on vase life of cut rose cv. Movie Star flowers. J. S ci. Food Agric. Environ. 2010, 8, 1118–1122.

54. Witte, Y.D.; Harkema, H.; Doorn, W.G. Effect of antimicrobial compounds on cut Gerbera flowers: Poor relation between stem bending and numbers of bacteria in the vase water. Post Biol. Technol. 2014, 91, 78–83.

55. Lü, P.; Cao, J.; He, S.; Liu, J.; Li, H.; Cheng, G.; Ding, Y.; Joyce, D.C. Nano-silver pulse treatments improve water relations of cut rose cv. Movie Star flowers. Postharvest Biol. Technol. 2010, 57, 196–202.

56. Amingad, V.; Sreenivas, K.N.; Fakrudin, B.; Seetharamu, G.K.; Shankarappa, T.H.; Sangama; Venugopalan, R. Comparison of silver nanoparticles and other metal nanoparticles on postharvest attributes and bacterial load in cut roses var. Taj Mahal. Int. J. Pure Appl. Biosci. 2017, 5, 579–584.

57. Li, H.; Huang, X.; Li, J.; Liu, J.; Joyce, D.; He, S. Efficacy of nano-silver in alleviating bacteria-related blockage in cut rose cv. Movie Star stems. Postharvest Biol. Technol. 2012, 74, 36–41.

58. Alekasir, K.; Hassani, R.N.; Azar, A.M. Effects of silver nanoparticles (SNPs) pulsing treatment and sucrose holding on flower and leaf senescence of cut rose. J. Ornamen Plants. 2017, 7, 103–113.

59. Zhang, M.; Gao, B.; Chen, J.; Li, Y.; Creamer, A.E.; Chen, H. Slow-release fertilizer encapsulated by graphene oxide films. Chem. Eng. J. 2014, 255, 107–113.

60. Neethirajan, S.; Jayas, D.S. Nanotechnology for the Food and Bioprocessing Industries. Food Biol. Technol. 2011, 4, 39–47.

61. Sekhon, B.S. Food nanotechnology—An overview. Nanotechnol. Sci. Appl. 2010, 3, 1–15.

62. Thomas, K.; Sayre, P. Research strategies for safety evaluation of nanomaterials, part I: Evaluating the human health implications of exposure to nanoscale materials. Toxicol. Sci. 2005, 87, 316–321.

63. Klaine, J.S.; Alvarez, P.J.J.; Batley, G.E.; Fernandes, T.F.; Handy, R.D.; Lyon, D.Y.; Mahendra, S.; Mclaughlin, M.J.; Lead, J.R. Nanomaterials in the environment: Behavior, fate, bioavailability, and effects. Environ. Toxicol Chem. 2008, 27, 1825–1851.

64. Abbas, K.; Saleh, A.M.; Mohamed, A.; MohdAzhan, N. The recent advances in the nanotechnology and its applications in food processing: A review. J. Food Agric. Environ. 2009, 7, 14–17.

65. Liu, X.; Wang, J.-H.; Yuan, J.-P. Pharmacological and antitumor activities of ganoderma spores processed by top-down approaches. J. NanoSci. Nanotechnol. 2005, 5, 2001–2013.

66. Oberdorster, G.; Stone, V.; Donaldson, K. Toxicology of nanoparticles: A historical perspective. Nanotoxicology 2007, 1, 2–25.

67. Kang, S.; Pinault, M.; Pfefferle, L.D.; Elimelech, M. Singlewalled carbon nanotubes exhibit strong antimicrobial activity. Langmuir 2007, 23, 8670–8673.

68. Scoville, S. Implications of Nanotechnology Safety of Sensors on Homeland Security Industries. Nanotechnol. Saf. 2013, 175–194.

69. Márquez, F.; Morant, C. Nanomaterials for sensor applications. Soft Nanosci. Lett. Sci. Res. 2015, 5, 1–2.

70. Hoque, M.I.U.; Chowdhury, A.N.; Islam, M.T.; Firoz, S.H.; Luba, U.; Alowasheeir, A.; Rahman, M.M.; Rehman, A.U.; Ahmad, S.H.A.; Holze, R.; et al. Fabrication of highly and poorly oxidized silver oxide/silver/tin(IV) oxide nanocomposites and their comparative anti-pathogenic properties towards hazardous food pathogens. J. Hazard. Mater. 2021, 408, 124896.