Prospects of Nanotechnology in Improving the Productivity and Quality of Horticultural Crops

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Abstract: Nanotechnology shows high promise 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. This review aimed to provide an update on the recent advancement of nanomaterials and their potential uses for enhancing productivity, quality of products, protection from pests and reduction of the postharvest losses of the horticultural crops. This study reveals that nanotechnology could be used to generate cutting-edge techniques towards promoting productivity and quality of horticultural crops to ensure food and nutritional security of ever-increasing population of the world.

Keywords: nanocapsulation; biosensor; nutrient use efficiency; nanofilm; climate-smart agriculture

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 [2–6]. In fact, nanoparticles demonstrate excitingly different features than the bulk materials because of their high surface to volume ratio [5–8]. Furthermore, the
quantum phenomena that occur in the nanoscale of any molecule or element or material remarkably increase its catalytic activity [5,7,9–11]. 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.

A considerable amount of literature is available on the effects of nanomaterials in improving yield, quality and postharvest losses of various crop plants [12,13]. Although the potential of nanotechnology in agriculture is the subject matter of many reviews, no comprehensive review has so far been highlighted the enhancement of yield, quality and reduction of postharvest losses of horticultural crops by the application of nanomaterials. Therefore, we aimed to summarize recent literature and discuss future directions on the application of nanotechnology in enhancing productivity, quality, protection, and reducing the postharvest losses of horticultural crops.

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 nanofertilizer 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]).
2.1.1. Macronutrient Nanofertilizers

The essential nutrient elements that are required in relatively larger quantity for good plant growth and productivity are known as macronutrients. To enhance their use efficiency, one or more of these nutrient elements are usually associated with nanoparticles to add an appropriate ratio of nutrients elements to the target crops and decrease their extent quantity with additional benefits [33,37].

The macronutrient nanofertilizers consist of one or more nutrient elements in an encapsulated form with certain nanoparticles. The N, P and K utilization in crop production is estimated to raise up to 265 million tons by the year 2020 [38]. The N source nano-fertilizers such as zeolites, mesoporous silica nanomaterials and hydroxyapatite are known as slow or controlled release nanofertilizers. Nanofertilizers show promising results in increased efficiency and productivity of the crop plants [39,40]. A biosafe nanofertilizer is one where phosphorus (P) is a component. It is a nanoscaled (60–120 nm) suspension of water-phosphorite particles. To elucidate the precise mechanisms of action of applied nanofertilizers while interacting with plants, soil and plant microbiome and the environment, more research is needed. The fate of nanofertilizer application in the environment warrants detailed research for ensuring safety of their application. The cost-effectiveness and market availability of the nanofertilizers facilitate larger application of these novel agrochemicals.

2.1.2. Micronutrient Nanofertilizers

Micronutrients are linked with the biosynthesis of proteins, carbohydrates, and the regulation of hormones (e.g., auxins), thereby protecting plants from the attack of pathogens and pests [41]. The usefulness of zinc-based nanofertilizers in many horticultural crop plants such as garden pea, cucumber, spinach, tomato, eggplants, chilli, coriander and onion is reported (Table 1) [42–47].

Table 1. Impact of different micronutrient nano-fertilizers on various horticultural crops.

| Micronutrients Delivered as Nanoparticles | Dose Used (mg/L) | Crops                  | Effect on Plant Growth and Development                          | Reference |
|-----------------------------------------|-----------------|------------------------|----------------------------------------------------------------|-----------|
| Zinc (Zn)                               | 1000            | Cucumber               | Root tip deformation and growth inhibition.                     | [42]      |
|                                         | 1000            | Spinach                |                                                                    |           |
|                                         | 1               | Tomato, eggplant       |                                                                    |           |
|                                         | 100, 200, 500   | Chilli pepper          | Reduces plant growth                                              | [43]      |
|                                         | 0–400           | Coriander              | Reduces fungal disease.                                           | [44]      |
|                                         | 5, 10, 20       | Onion                  | Improves germination.                                             | [45]      |
|                                         | 500             | Garden pea             | Inhibits root growth.                                             | [46]      |
|                                         |                 |                        | Decreases chlorophyll and H$_2$O$_2$ contents.                   | [47]      |
|                                         | 50–2000         | Cucumber               | Enhances biomass production and activities of antioxidant enzymes in dose-dependent manners. | [49]      |
| Iron (Fe)                               | 10 and 20       | Lettuce                | Reduces chlorophyll contents and growth but increases activities of the antioxidant enzyme. | [50]      |
|                                         | 30 to 60        | Garden pea             | Improves seed mass and chlorophyll content.                       | [51]      |
Table 1. Cont.

| Micronutrients Delivered as Nanoparticles | Dose Used (mg/L) | Crops                  | Effect on Plant Growth and Development                                                                 | Reference |
|------------------------------------------|------------------|------------------------|---------------------------------------------------------------------------------------------------------|-----------|
| Copper (Cu)                              | 0, 100, and 500  | Squash                 | Increases ionic Cu in media treated with bulk Cu compared to nCu.                                        | [52]      |
|                                          | 130, 660         | Lettuce                | Increases shoot and root length ratio.                                                                   | [53]      |
|                                          | 0, 10, 20        | Lettuce                | Negatively influences on nutrient content, water content, seedlings growth and dry biomass.               | [50]      |
| Copper (Cu)                              | 0–1000           | Cucumber               | Reduces growth and increases antioxidant enzymes.                                                         | [54]      |
|                                          | 10–1000          | Radish, grasses        | Causes of DNA damage and growth inhibition.                                                               | [55]      |
|                                          | 50–500           | Tomato                 | Improves fruit firmness and antioxidant content.                                                          | [56]      |
|                                          | 100, 250, 500    | Bean                   | Causes of growth inhibition and nutrition imbalance.                                                       | [57]      |
|                                          | 100–500          | Garden pea             | Reduces the growth of plants, enhances the production of ROS and the peroxidation of lipid.                | [58]      |

Similarly, the application of Zn nanoparticles in a non-horticultural field crop, pearl millet (*Pennisetum americanum* L.), increased grain yield by about 38%. The enhancement of grain yield was associated with an enhancement of shoot height (15%), root length (4%), root area (24%), chlorophyll accumulation (24%), total soluble protein (39%) in leaf and plant biomass (12%) in comparison to control [49]. Using Zn nanoparticles, a significant yield increase was noticed in rice, wheat, maize, sugarcane, potato, sunflower and *Brassica* [40]. Application of iron (Fe) source nanofertilizers improve yields in various horticultural crops such as cucumber, lettuce and garden pea [49–51].

Another important micronutrient, copper (Cu), is essential for growth and development of plants. Application of appropriate concentration of Cu nanoparticles remarkably enhances the physiological development of many horticultural crop plants such as lettuce and tomato [53,56]. However, elevated doses of Cu have negative impacts on several crop plants [50,54–58]. Manganese (Mn) also plays a critical role during physiological and metabolic developments of plants. It also facilitates plants tolerance to diverse environmental stresses by controlling different enzyme activity as a co-factor. Nano-Mn fertilizer improves the growth and yield of crop plants if the soil is deficient in this micronutrient [59]. Generally, recommended doses of any micronutrients are imperative for the growth and yield of horticultural plants. Therefore, soil analysis is necessary before recommending the application of any nanofertilizers as a source of micronutrient.

2.2. Nano-Plant Growth Stimulator

The application of NMIs in horticulture is remarkably increased in the last few decades [59,60]. The form and constituents of the NMIs 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 NMIs 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 |
|---------------|-------------|------------------------|----------------------------------------------------------------------------------------------------------|-----------|
| CeO₂          | 125 to 4000 | Cucumber               | Negative impacts at the molecular and biochemical levels in plants.                                       | [61]      |
| TiO₂          | 1000 to 2000| Spinach                | Promotes growth and photosynthesis.                                                                       | [62,63]   |
| Carbon nanotubes (MWCNT) | 10–40 | Tomato                 | Enhances germination and growth rate but inhibits elongation of root in tomato.                           | [64,65]   |
| Carbon nanotubes (MWCNT) | 10–40     | Onion and cucumber    | Enhances elongation of root.                                                                               | [65]      |
| 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. | [66]      |
| Fe₃O₄         | 0.67        | Lettuce, spinach, radish, cucumber, tomato, peppers | Inhibits seed germination.                                                                               | [66]      |
| ZnO           | 100–1000    | Garden pea             | No effect on seed germination but affects nodulation and root length                                       | [67]      |
| Ag            | 800         | Faba bean              | Declines germination                                                                                        | [68,69]   |
| 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 nanoto 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) [70].
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 [71]. 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. Their use also reduces the cost by half compared to conventional pesticides [72].

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 nanoevacapsulation. 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 [73].

2.4.1. Nanoinsecticides

Nanoencapsulation assists the slow discharge of a chemical substance to the specific host for controlling pest insects through different mechanisms that consist of biodegradation, dissolution, osmotic pressure and diffusion at a particular pH [74]. NPs containing garlic oil effectively control Tribolium castaneum [75]. The nano-encapsulated insecticides are
usually targeted to a certain insect, thereby diminishing the extent of the quantity needed as compared to conventional pesticides. Significant mortality of two insects, *Rhyzopertha dominica* and *Sarocladium oryzae*, has been recorded in wheat after 3 days of treatment with nanostructured alumina [76]. The insecticide ethiprole has been encapsulated by poly (lactic) acid and polycaprolactone nanospheres. The investigation of the nanoformulation revealed that nanospheres do not yield a controlled release (CR) of active ingredients of agrochemical but rather, owing to the tiny size of nanospheres, they improve the entry of the active ingredient into the plant cell compared to the non-nano-formulated suspension [77]. An in vivo experiment conducted with the larvae of Egyptian cotton leaf-worm (*Spodoptera littoralis*) revealed that the toxicity of nanoparticles of novaluron simulated the traditional commercial formulation [78]. The potential of nanoformulations, including a commercial one, to control some major pests of soybean such as stem fly (*Melanagromyza sojae*) and whitefly (*Bemisia tabaci*) was investigated. A majority of imidacloprid CR formulations effectively control targeted insect pests better than non-CR industrial formulations. Moreover, application of some CR formulations gave a higher crop yield compared to the non-CR insecticide formulations and untreated control [79]. Similarly, imidacloprid and carbofuran CR formulations showed improved management of leafhopper, *Amrasca biguttula* Ishida, and aphid, *Aphis gossypii* on potato compared to conventional non-CR insecticide formulations.

The population of fruit flies is eco-friendly when managed by pheromones. Nano-pheromones offer a simple and easy sampling method for the trapping of insect pests in guava and mango orchards. A nanogel containing methyl eugenol and pheromone with a low-molecular-weight organic gelator e.g., all-trans tri (p-phenylene vinylene) bis-aldoxime offers higher stability under ambient environmental conditions, minimizes evaporation and secures the optimum release of the active ingredient of the pheromone [80]. This nanopheromone also provided a smooth sampling approach for the rapid trapping of pests in guava and mango orchards. Importantly, the association of the pheromone nano-gel-based results in efficient control of a notorious fruit insect pest, *Bactrocera dorsalis*, which causes significant damage in guava and mango [80].

2.4.2. Nanofungicides

Fungal diseases are controlled by chemically diverse fungicides such as dicarbox-imides, cupric salt, dithiocarbamates, dinitrophenol, triazoles, thiabendazole, organotin compounds and thiocarbamates. Most of these fungicides are poorly suited for their target specificity (TS). The application of nanotechnology can easily ensure the TS of these chemical fungicides. This incorporation depends on the formulation of nanofungicides. A recent study by Kumar et al. [81] developed a nanoform of an industrially used fungicide that contains 25% trifloxystrobin and 50% tebuconazole to effectively control a broad-host-range fungus, *Macrophomina phaseolina*. The formulated nanoform had an extensive reaction with augmented inhibitory effects such as alteration in hyphal morphology, destruction of hyphal cells and formation of abnormal sclerotia in *M. phaseolina*. Similarly, Antonoglou et al. [82] formulated an economic Cu-Zn bimetallic nanoparticle to control *Saccharomyces cerevisiae*. This metallic nano-fungicide shows a minimum influence on the photosystem II of the leaves of tomato but demonstrated greater effectiveness in antifungal activity against *S. cerevisiae*.

2.4.3. Nanonematicides

To control nematode pests by chemical nematicides is a challenging task in crop production. The conventional nematicides used in agriculture are aldicarb, fenamiphos, fosthiazate and oxamyl compounds [83]. Due to the rapid release of toxic active ingredients, the toxicity of these nematicides is harmful to both human health and the environment [84]. Novel nanotechnological approaches seem effective in addressing these challenges. A good example of such an approach is the control of *Malodogyne incognita* and *M. graminis* by silver nanoparticles [85]. Similarly, green silver nanoparticles have been found more effective
in nematicide in controlling *M. javanica* in eggplant compared to traditional chemical nematicides [86].

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.

2.5.1. Nanofilms/Coatings

Nanofilms are used as transporters of metal NPs as antimicrobial agents in the form of protective barriers. These novel materials minimize the respiration rate, govern the decomposition and colour alteration, balance the storage nature, and lengthen the shelf-life of horticultural crops. Edible nanofilms are proposed as a viable way of balancing the characteristics of horticultural products during storage and shelf-time. Recently a nano-composite edible film comprising glycerol, aloe vera gel and ZnO-NPs solutions was developed by Dubey et al. [87]. Among these nanocomposite edible films, ZnO-NPs solutions could enhance the shelf-life and quality of mango fruits up to 9 days at normal temperature through reducing mass loss, maintaining lower soluble solids, increasing titratable acidity and ascorbic acid concentration in fruit, maintaining pH, increasing thickness, and transmittance. A list of nanofilm/coating components and their effects on different horticultural crops is presented in Table 3.

### Table 3. Effect of nano components on different horticultural crops.

| Nanofilm/Coating Component | Beneficial Effect on Fruit | Fruit | Reference |
|----------------------------|----------------------------|-------|-----------|
| Chitosan/procyanidin       | Decreases mould and yeast growth, preserve firmness and increases the activity of antioxidants. | Blueberry | [88]       |
| Chitosan                   | Delays senescence process, loss of water and firmness of fruits. | Mango | [89]       |
| Chitosan/spermidine        | Induces the defensive mechanism against anthracnose pathogen, and improves firmness and delays deterioration of fruit. | Mango | [90]       |
| Chitosan                   | Reduces weight loss, respiratory rate, antioxidant process, and enhances firmness. | Guava | [91]       |
| Chitosan, chitosan/chitosan-g-salicylic acid and salicylic acid | Enhances the activities of the enzymes such as chitinase, lyase, and glucanase. Decreases respiration rate, weight loss and decay incidence. The coating is effective as an antimicrobial agent. Positively influences titratable acidity, weight loss, water vapour resistance, pH, and respiration rate. | Grape | [92]       |
| Chitosan-carboxymethyl cellulose/ *Mentha spicata* essential oil | The coating is effective as an antimicrobial agent. | Strawberries | [93] |
| Chitosan/ *Mentha × villosa* Huds. essential oils or *Mentha piperita* L. | Inhibits spore germination and mycelial growth. Sensory and physicochemical properties are unaffected during storage. | Cherry tomato | [94] |
| Chitosan vs. propolis vs. thyme essential oil | Retains total carotenoids and flavonols (by chitosan), total soluble sugar (by thyme and chitosan), and total terpenes and organic acids (by propolis). Chitosan alone performed the best. | Tomato | [95] |
| Nano-ZnO                   | Nano-packaging enhances the storage time of fresh-cut apples by 6 days. | Apple | [96]       |
| Nano-ZnO                   | Nano-ZnO reduces microbial spoilage during storage and significantly increased the shelf life. | Carrot | [97]       |
2.5.2. Nanopackaging

Generally wrapping and processing constituents have a great role in enhancing the shelf-life and quality of food products [98]. Due to the absence of appropriate packing knowledge and technologies, a huge amount of food is spoiled every year globally. Among the frontier food processing and packaging technologies, nano-based technologies have already been established as most effective ones. Nano wrapping and processing methods include nanomaterials that can improve and preserve the superior quality and lifespan of food. Active food nano-packaging materials include metal nanoparticles such as Ag, Cu, TiO$_2$ and MgO [99], edible antimicrobial nano-composite films and gas scavengers [100]. For example, the incorporation Ag-NPs nanoparticles enhanced the shelf-life of fruits and vegetables through absorbing ethylene gas [101]. Oxygen is responsible for the quick degradation of fruits and vegetables, thus the incorporation of gaseous scavenger-NPs with packaging and processing materials can prevent oxidative reactions, ultimately enhancing the quality and storage life of fruits and vegetables [102]. Nanocrystalline-TiO$_2$ was found to act as an oxygen scavenger during the packaging and processing of food [103]. Kasai [104] found that the incorporation of nano-Si as a surface coating in food packaging increases the quality and storage ability of horticultural crops. Ag-NPs coated packaging materials can lessen the microbial activity, leading to an increase shelf-life of food materials [105]. Besides, Ag-NPs, ZnO-NPs, TiO$_2$-NPs, MgO-Nps, CuO, chitosan nanoparticles, carbon nanotubes, quantum dots, etc., are commercially very important for improving the quality and shelf-life of storage fruits, vegetables and exporting foods, since these NPs have anti-microbial activity [102,106–108].

2.5.3. Nanomaterials for Enhancing the Shelf-Life of Fruits

Increasing in shelf-life of horticultural crops, especially fruits and vegetables is the objective of studies of nano-based tools to enhance the stability and improve quality of these products [109,110]. Recently, organic and synthetic coating NPs such as chitosan, Si, TiO$_2$ and their derivative composites are being utilized as coating-materials for short shelf-life fruits. For example, these nanomaterials improve the shelf-life of Chinese bayberry [111], loquat [112] and strawberry [110] by modulating their mechanical and antimicrobial properties. A few promising NPs and their potential effects for improving the shelf-life of agriculture commodities are described in the following sub-sections.

Silver (Ag) Nanoparticles

It has been well documented that different types of Ag nanoparticles (NPs) have varying impacts on the shelf-life of fruits. Many countries rich in agriculture like China, India, Brazil and the United States have been extensively using Ag NPs to increase the shelf-life of fresh produce. India, which is the second-largest producer of fresh produce in the world, uses many NPs based on silver nanostructures to extend the long-term storage capability of fruits and vegetable and their freshness. For example, A-Ag NPs improve the shelf-life of lime (Citrus aurantifolium) and apple (Malus domestica) [113]. Another study conducted by Chowdappa [114] noted that chitosan-based Ag-NPs composites greatly minimize post-harvest losses in fresh mangoes and also boost quality because of their anti-fungal properties. Kumar et al. [115] observed that Ag-NPs, along with biocompatible coating materials such as chitosan and glycol, improved the storage duration of red grapes up to 14 days. The inclusion of Ag-nanostructures in coating organic polymers augmented the mechanical properties of coating films [115]. Like India, China is also widely applying Ag-NPs to boost the storage and freshness of fruits and vegetables [105]. Owing to the significant antimicrobial characteristics of Ag-NPs, the shelf-life of cherry tomatoes can be enhanced by up to 15 days. In Brazil, biologically synthesized Ag-NPs incorporating Myxobacteria virescens extract is also utilized to improve the storage duration of fresh apples [116]. These biologically active Ag-NPs are integrated and also synthesized directly on the paper which is adopted for the packaging of fruits. Synthesis of Ag-NPs on paper
shows tremendous antibacterial effects and increases the preservation time of fresh apples by 2 weeks [116].

Hexanal

Hexanal (C₆H₁₂O₆) is an extremely volatile and a flavour-producing compound during ripening. It hinders the enzymatic activity on the fruit surface reducing the production of ethylene at the time of fruit ripening, and ultimately reduces post-harvest diseases [117]. Therefore, hexanal is used commercially in the form of pre-harvest sprays or dip treatments to extend fruit freshness by up to 2–3 weeks without any loss of fruit quality. It has been proved that use of 0.02% hexanal as a post-harvest dip for 10 min (2 L of solution kg/fruit) and dry shed storage decreased the ethylene evolution rate, physiological weight loss and soluble solids and increased chlorophyll content, delaying the ripening process in mango by at least 2 days under ambient conditions (25 ± 0.8 °C and 60 ± 10% relative humidity) [118].

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 [119], due to higher microbial contamination [120]. 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 [121,122]. 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 [122–125]. 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 [126].

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 [127]. 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.

| 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. | [128]    |
|                      |                         | The sting of the odour and undesirable constituents in food items.  
• Distribution of enzymes, flavours, and so-forth for improving the quality of food. | [129]    |
Table 4. Cont.

| 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. | [130]     |
|                | "Nano-cochleate"        | Assist to enlighten the superiority of desirable processed foodstuffs. | [131]     |
| Daily Boost    | "Nano-emulsions"        | Used for the nano-encapsulation of invigorated desirable vitamins and bioactive components in foods. | [132]     |
|                | "Brominated vegetable oil, ester gum, dammar gum and sucrose-acetate isobutyrate" | Assist to spread and obtainability of the nutrients in the processed food. | [134]     |

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 [135]. 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 [136]. 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 [157]; (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.

3. Concluding Remarks and Prospect of Nanotechnology

Nanotechnology is advancing as a state-of-the-art tool in modern agriculture to facilitate sustainable crop production. It also has a great promise in horticulture, where different kinds of nanomaterials are used to increase productivity and quality of produce and reduce post-harvest spoilage of fruit and vegetables. Nanotechnology takes advantage of the power of nanomaterials and their distribution methods for improvement of the productivity of horticultural crops. They reduce the over-use of chemical fertilizer and pesticides.
Nanomaterials are simple, cost-effective, and eco-friendly, allowing them to be produced in a minimum time and with less effort and without causing any harm to the environment. Nanotechnology promotes the quality and enhancement of the shelf-life of non-processed and processed horticultural fruits, vegetables and cut flowers. Nanosensors are used to monitor the soil moisture, detect pesticide residue, determine nutrient requirements and diagnose crop pests. On the other hand, improper use of nanomaterials will be harmful to the crop plants and the environment. For this reason, research-based proper use of nanomaterials is needed for the reduction of post-harvest spoilage of horticultural crops and improvement of the quality food production. Finally, it is demonstrated that substantial practice of nanotechnology would significantly promote growth, increase yields and reduce production costs and post-harvest losses through maintaining the superior quality and storage duration of fresh and processed fruits and vegetables. The availability of useful nanoparticles and safety assessments of their field application are needed for ensuring food and nutritional security of the ever-increasing world population in a changing climate scenario. Larger application of nanotechnology will lead to a climate-smart horticulture, reduce post-harvest losses and improve the overall quality of the produce.

Author Contributions: Conceptualization, T.I.; writing—original draft preparation, R.A.R. and T.I.; writing—review and editing, R.A.R., T.I., A.H., M.S., M.B., M.N.S., E.K., N.U.M., D.R.G., A.H., M.P. and V.H.; funding acquisition, M.S., M.B., A.H., M.P. and V.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was co-funded by the EU—Project “NutRisk Centre” (No. CZ.02.1.01/0.0/0.0/16_019/0000845) and a project (No. BS-145) of the Ministry of Science and Technology of the People’s Republic of Bangladesh (to T.I. and D.R.G.).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: All authors have given consent to publish this article.

Data Availability Statement: All data are included and available in the article.

Acknowledgments: We gratefully acknowledge financial support from the EU—Project “NutRisk Centre” (No. CZ.02.1.01/0.0/0.0/16_019/0000845), and Ministry of Science and Technology of the People’s Republic of Bangladesh for project grant to T.I. and D.R.G. (project No. BS-145).

Conflicts of Interest: All the authors have read the manuscript and have no conflict of interest to declare.

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