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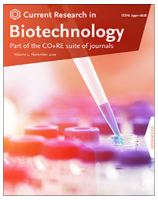

Nanobiotechnology-mediated sustainable agriculture and post-harvest management

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ABSTRACT

Humans directly depend on food and agriculture. However, an estimated one-third of agricultural produce is wasted every year post-harvest loss. The major reasons for post-harvest loss include microbial contamination, moisture content, degradation, and adverse effects of the physical and chemical methods used for storage. Conventional post-harvest methods do not adequately prevent the loss of agricultural produce therefore, new strategies are increasingly needed to address the shortcomings of traditional agricultural post-harvest practices. In this regard, nanotechnology (the manipulation of materials at < 100 nm) has emerged as a promising field to replace traditional practices. The use of engineered nanoagroparticles greatly enhances agricultural productivity and mitigates the environmental issues posed by conventional chemical fertilizers. This review aims to describe applications of nanotechnology in various fields of agriculture including seed storage, seed germination, plant growth, priming, fertigation and crop productivity. In addition, nanomaterials used as intelligent delivery systems for crop productivity, stress tolerance and plant adaptation are discussed. Moreover, nanomaterials used as sensors for precision agriculture and crop protection are described in detail. Importantly, we discuss the use of nanomaterials as fertilizers to replace chemical fertilizers in sustainable agriculture. Finally, we emphasize the use of nanomaterials for the post-harvest management of fruits and vegetables.

Contents

Abbreviations: CNPs, Chitosan NPs; NPs, Nanoparticles; Zno NPs, Zinc Oxide Nanoparticles; AgNPs, Silver Nanoparticles.

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Introduction

Agriculture has seen a surge in innovative advancements in food production and security in the past several decades (Dwivedi et al., 2016). Nanotechnology is a major recent innovation with numerous agricultural applications. In agriculture, fertilizers are essential for enhanced crop production. However, a drawback of excessive use of fertilizers is the irreversible alteration of the chemical nature of soil, thereby negatively affecting crop productivity. Similarly, the use of other agrochemicals, such as pesticides, for crop protection, can also increase the risks of food and water contamination, thus endangering human and environmental health (Kah et al., 2013). In contrast, nanotechnology can potentially facilitate qualitative and quantitative agricultural output by enabling intelligent management of inputs, such as fertilizers, pesticides and irrigation. The use of nanoagroparticles can also potentially aid in mitigating the environmental issues associated with currently used chemical fertilizers and pesticides in conventional modern agriculture (Sekhon, 2014; Liu and Lal, 2015). Although nanotechnology was first conceived nearly five decades ago by Norio Taniguichi, in 1974, the utility of nanoparticles (NPs) in agriculture is a relatively very recent concept development is ongoing. (Gogos et al., 2012; Khan and Rizvi, 2014).

The terminologies used for nanoagroparticles, such as *nanopesticides* and *nanofertilizers* can be described in greater detail in a wide range of products according to their size, characteristics, processes of development, and agricultural utility (Kah et al., 2013) (Gogos et al., 2012). Engineered nanoagroparticles are a unique technological innovation projected to enhance the performance of agricultural systems. Nanotechnological interventions may aid in addressing agricultural challenges such as biotic stresses (herbivory and pestilence) and abiotic stresses (pollution and nutrient deficiency), thereby facilitating productivity. Such productivity can be achieved through precision agriculture by using wireless networking and sophisticated miniature sensors to remotely monitor and manage field crops in both pre- and post-harvest stages (Dwivedi et al., 2016) (Shafi et al., 2019). In addition, the use of nanosensors in agriculture can enable accurate observation of environmental challenges, thus enhancing plant defense responses against stresses (Afsharinejad et al., 2015; Kwak et al., 2017). NPs are extremely small materials with nanoscale sizes ranging from 1 to 100 nm, which are composed of organic, inorganic, polymeric, or hybrid materials (Babu et al., 2010; Babu et al., 2012; Babu and Doble, 2018). NPs synthesized with chemicals as reducing agents are cytotoxic, and therefore cannot be used for biomedical and other applications. However, the synthesis of NPs through green nanotechnology by using plants and microorganisms (bacteria, algae, and fungi) offer more attractive alternatives, because they are more environment-friendly and easier to produce (Babu et al., 2010; Babu et al., 2012; Sharma et al., 2012; Babu et al., 2013; Panpatte et al., 2016; Park et al., 2016; Dahoumane et al., 2017; Babu and Doble, 2018; Babu et al., 2018; Babu et al., 2020). For instance, numerous plant species are currently used to synthesize gold, silver, nickel, cobalt, zinc, or copper NPs (Panpatte et al., 2016; Babu et al., 2012; Ghormade et al., 2011; Iravani, 2011; Kitching et al., 2015) (Babu et al., 2010; Babu et al., 2012; Sharma et al., 2012; Babu et al., 2013) (Babu et al., 2011; Babu et al., 2011; Babu et al., 2013). Similarly, several microbial species are being used for the synthesis of NPs comprising silicon (diatoms), gold (*Pseudomonas stutzeri*) or, cadmium sulfide (*Klebsiella aerogenes*). In metal-based NPs synthesis, several fungal species such as *Aspergillus* spp., *Verticillium* spp., *Phanerochaete* spp., and *Fusarium* spp. are often used (Panpatte et al., 2016) (Kitching et al., 2015). Engineering NPs with improved three-dimensional structures remains an evolving process with a focus on achieving efficient and sustainable agriculture with fewer environmental impacts (Cheng et al., 2016). Intelligent nanosystems can help plants take up the nutrients encapsulated in NPs and simultaneously decrease eutrophication by preventing the leaching of nitrogen into soil and water (Liu and Lal, 2015). Some of the most relevant applications of nanotechnology in agriculture are shown in Fig. 1. Several countries are facing serious losses of agricultural produce due to insufficient post-harvest disease control, Traditionally, post-harvest diseases are managed with fungicides however, microorganisms have developed resistance to traditional methods. Thus, effective alternative approaches for controlling these diseases are required and can be achieved through nanotechnological approaches. In this review, we emphasize the necessity of post-harvest management and describe the various agricultural applications of nanomaterials in plant growth and productivity, stress tolerance and plant adaptation, precision agriculture, crop production and nanofertilizers (González-Estrada et al., 2019)."

Nanobiotechnology and nanotechnology for intelligent delivery systems

The most innovative contributions of nanotechnology include smart management and delivery systems, thereby, greatly enhancing sustainable agriculture. The conventional agricultural application of agrochemicals can be disadvantageous, because most of the chemicals are lost to leaching, microbial or photo-degradation, or hydrolysis, thus preventing the target plants from receiving adequate doses (Nair et al., 2010; Yang et al., 2016). Therefore, for agriculture to be sustainable, efficient bioavailability of fertilizers and pesticides in an environment-friendly manner is crucial (Panpatte et al., 2016). NPs can enable efficient delivery of agrochemicals because of their unique properties in terms of size, surface area, penetration, and consistency (Ghormade et al., 2011). An example is the cost-effective encapsulation of potassium nitrate in thin films of graphene oxides, which significantly prolongs fertilizer release in the soil (Zhang et al., 2014). NP-encapsulation protects agrochemicals from degradation and prevents the overuse of chemicals by enhancing their efficacy (Jayanta Kumar Patra et al., 2018; Xiaoping Xin, 2022). Nanotechnology can also aid in the smart delivery of foreign DNA or chemicals in genetic engineering through the use of NPs, nanofibers, or nanocapsules. For example, silicon dioxide (SiO2) NPs are used for safely delivering DNA molecules into plants such as corn and tobacco (Galbraith, 2007). NPs-coated DNAs or RNAs, such as chitosan-coated siRNAs, can be bombarded into cells and tissues through biolistics to generate transgenic crops resistant to insect pests (Vijayakumar et al., 2010; Zhang et al., 2010). The use of positively charged arginine NPs (ArgNPs) for the delivery of sgRNA helps mitigate the problems of low DNA editing efficiency and off target effects associated with CRISPR/Cas9 technology, thus potentially advancing crop improvement (Mout et al., 2017).

Nanomaterials in plant growth and productivity

Important applications of nanotechnology in agriculture include improving the germination of seeds, and achieving proper plant growth and development. The germination of seeds of several crop plant species, such as maize, wheat, soybean, barley, groundnut and tomato, is significantly improved by the application of NPs, such as multi-walled carbon nanotubes, SiO_2, Fe/SiO_2, TiO_2, and zeolite (Changmei et al., 2002; Najafi Disfani et al., 2017; Joshi et al., 2018; Manjaiah et al., 2019). Although the exact mechanism through which NPs improve seed germination is unknown, it is believed to be based on NPs' ready penetration of the seed coat and facilitation of water imbibition into seeds (Changmei et al., 2002; Banerjee and Kole, 2016). Similarly, several NPs, including multi-walled carbon nanotubes, TiO_2, ZnO, FeO, ZnFe, CuO and hydroxy fullerenes have been shown to improve the quality of growth and development of many crop plants (Gilbertson et al., 2020; Shang, 2019; Shojaei et al., 2019). The important positive effects of NPs on plants include enhanced growth of hypocotyls and significantly increased yield, size number of fruits, essential oil content, quality etc. (Gao et al., 2011; Kole et al., 2013; YOUSEFZADEH and Sabaghnia, 2016). Efficient

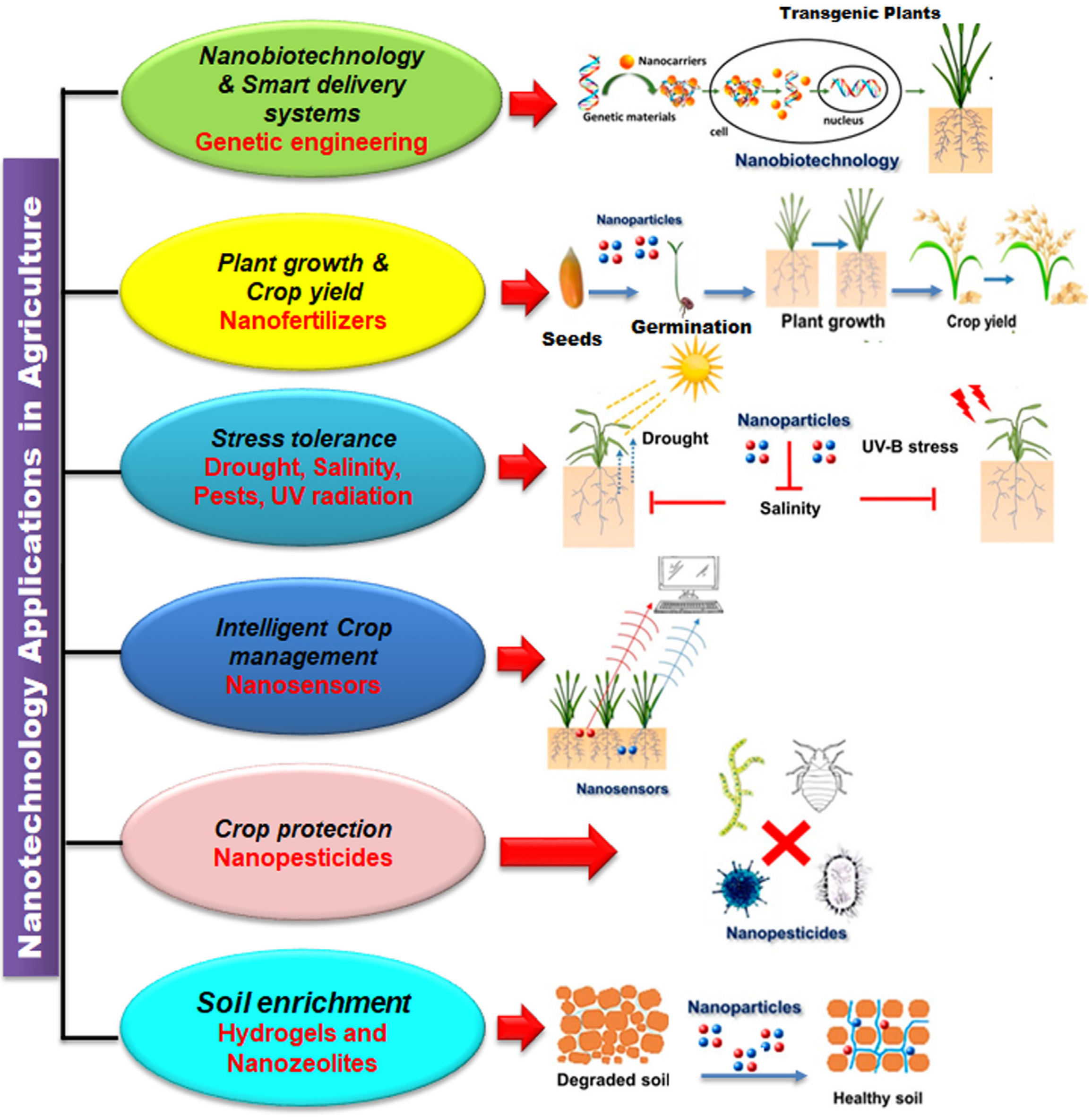

Fig. 1. Nanotechnological applications in modern agriculture: Smart delivery systems in nano-based genetic engineering promote crop improvement; nanopesticide formulations can be used for crop protection; nanosensors can be used for intelligent management of agriculture; nanoparticles are applied to induce plant stress tolerance and adaptation; nanofertilizers are used for controlled release of nutrients to increase plant growth and crop yield; nanomaterials can be used for enriching the soil for better crop growth.

use of nanotechnology can potentially overcome several natural factors that limit seed germination, such as genotypic traits, soil fertility and moisture availability and can aid in proper plant growth and development, thereby facilitating sustainable agriculture.

Nanomaterials for stress tolerance and plant adaptation

In the past several centuries, the Earth has undergone many changes in climatic conditions, including temperature, soil pH, rainfall, soil, air and water pollution. These challenging environmental conditions can have adverse effects on plants, particularly crop plants. Fig. 2 illustrates various stress inducers and plant responses (Pérez-Clemente et al., 2013).

The application of nanotechnology, e.g., nanofertilizers, in modern agriculture can enhance crop productivity under adverse climatic conditions. The appropriate application of SiO2 and $FeSO_4$ NPs has been found to induce the tolerance to salinity stress in crop plants such as tomato, squash and sunflower, and to increase seed germination, plant growth and yield (Haghighi et al., 2012; Siddiqui and Al-Whaibi, 2014; Torabian et al., 2017). Silicon NPs have been reported to induce harmful UV-B radiation stress in wheat and to help crop plants such as rice withstand toxic heavy metals such as Cd, Pb, Cu and Zn (Wang et al., 2015; Tripathi et al., 2017). Importantly, nanomaterials have been shown to be highly effective against pests and diseases, thus providing a potential solution to the health and environmental issues associated with heavy pesticide use in agriculture. Examples of nanomaterials effective against bacterial, fungal and viral plant pathogens include NPs of silver (AgNPs) and metal oxides, such as CuO, ZnO and MgO (Giannousi et al., 2013; Imada et al., 2016; Shenashen et al., 2017; Malandrakis et al., 2019). Similarly, nanocomposites such as Ag-chitosan with the fungicides Antracol show higher pesticide efficacy and longer shelf-life than of the individual component. Transcriptomic analyses of NP-treated plants have shown that most of the induced genes are associated with stress responses, thus indicating that NPs

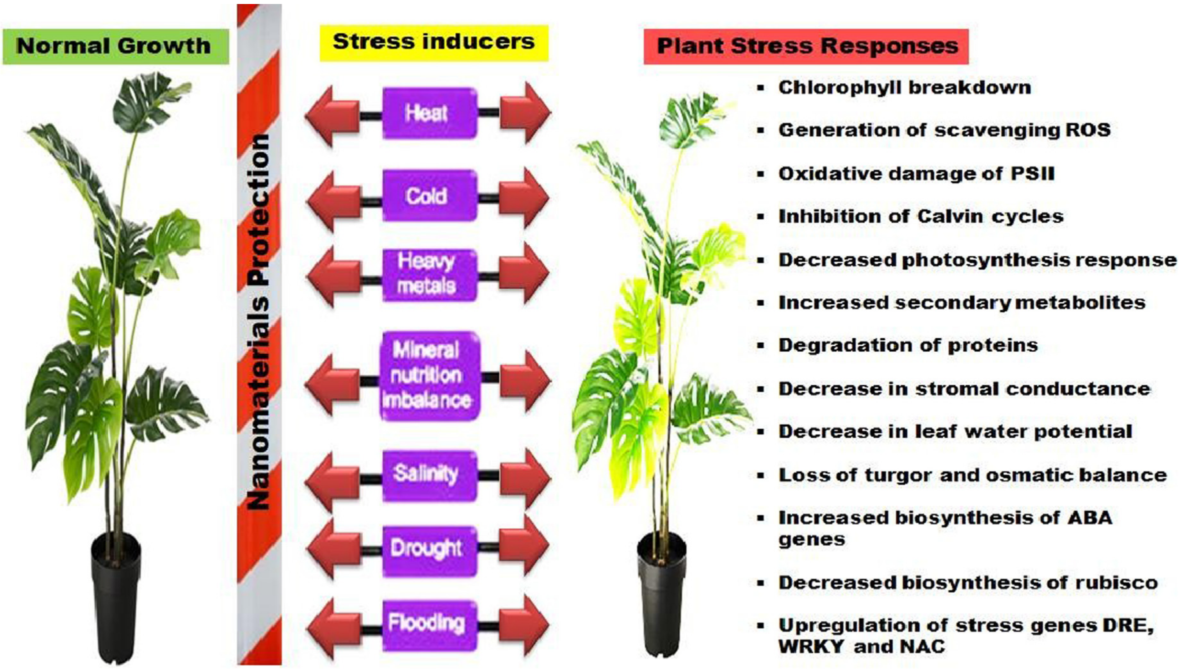

Fig. 2. Pictorial representation of various stress-inducing factors and responses (biological and physical) in plants (Pérez-Clemente et al., 2013).

facilitate plant protection against environmental stresses (Onaga and Wydra, 2016). Therefore, the proper application of nanomaterials can greatly enhance agricultural productivity in a clean and environment-friendly manner.

NP application is considered an effective and promising technique to alleviate drought stress in plants. Soyabean plants under drought-induced conditions have been treated with various metal NPs (iron, copper, cobalt and zinc oxide) and shown significant improvements in desired physiological traits such as the drought tolerance index, relative water content and biomass reduction rate, particularly in iron NP-treated plants (Nidhi et., al 2022). Moreover, the gene expression and metabolomics of plants under salt stress conditions can be regulated and plant tolerance to salt can be increased with the use of nanomaterials (Abideen et al., 2022; Li et al., 2022)

Nanosensors for precision agriculture

Achieving precision agriculture and farming can be enabled by using nanomaterials as nanosensors for enhanced production efficiency while requiring low cost and effort and minimizing environmental issues. Nanosensors can aid in monitoring agricultural crops, soil nutrient and water conditions, disease prevalence and the environmental hazards of agrochemicals (Cheng et al., 2016). The natural sensory properties of biological organisms can be enhanced with nanomaterials and exploited to increase sensitivity to potential signals (Dubey and Mailapalli, 2016). Networks of nanosensors can wirelessly provide real-time data on field conditions throughout the seasons, thus allowing for remote agricultural monitoring (El Beyrouthya and El Azzi, 2014). Nanosensors can also be used for monitoring soil water levels, automated irrigation, detection of potential pests or diseases, such as insects and microbial pathogens (Afsharinejad et al., 2015) (Singh et al., 2010; Kinjal Mondal, 2021) and detection of plant hormonal responses to stress (Wang et al., 2010) and the presence of pesticides or toxic metal ions (Panpatte et al., 2016) (Fang et al., 2017). Although the agricultural use of nanosensors remains in a nascent stage, the technology is rapidly emerging as an excellent tool for sustainable farming. Potential applications of various nano-based sensors in agriculture are listed in Fig. 3.

Nanotechnology in crop production

Nanotechnology has been valuable in crop protection and consequent productivity increases through the efficient use of NP-treated pesticides, including insecticides, fungicides and herbicides. Pesticides can be encapsulated in NPs, which may themselves also have pesticidal properties (Haq and Ijaz, 2019). Nanoencapsulation involves the coating of active pesticides (internal phase) with NPs of different sizes (external phase). This nanoformulation significantly enhances the controlled release of pesticides around the roots or within plants without efficacy (Nuruzzaman et al., 2016). Nanoformulations can circumvent the problems of water-insolubility and environmental leaching of conventional formulations of pesticides (Dwivedi et al., 2016). Crop yields can be greatly increased through the use of nano-formulated pesticides that increase pesticide efficacy by altering their permeability, stability, biodegradability and inoculation load (Khan and Rizvi, 2014) (Haq and Ijaz, 2019; Petosa et al., 2017). Clay nano-tubes called halloysites are efficient pesticide carriers that enable slow release of the active ingredient (pesticide) and are environmentally safe (Dwivedi et al., 2016). Hydrophobic nanosilica can be used directly against insect pests, achieveing killing after ready absorbing into the insects' cuticle layers (Nair et al., 2010). Nanoformulations have also been shown to increase plant immunity, called systemic acquired resistance against pests. After penetration of the pesticides in nanoformulations, such as silica nanospheres into plant and sap tissues, sap sucking insects are effectively targeted and the pesticides are protected from photodegradation (Li et al., 2007; Hou et al., 2016). Metallic bioactive Au NPs fabricated in latex are known to inhibit insect protease trypsin, thus aiding in the biocontrol of insect pests (Patil et al., 2016). Similarly, synthetic nanomaterials, such as ZnO, CuO, SiO2, TiO2, CaO, MgO, AgO and MnO are also effective against plant microbial pathogens such as bacteria and fungi (Servin et al., 2015; Vanathi et al., 2016; Gilbertson et al., 2020; Role of Nanotechnology, 2020). Nanoformulations of herbicides, such as SiO_2 and metsulfuron-methyl-loaded pectin NPs, are significantly more toxic to weeds than non-nanoherbicide formulations (Sharifi-Rad et al., 2018). Increasing evidence indicates that nanoformulations of pesticides, herbicides, and fungicides may become indispensable in sustainable modern agri-

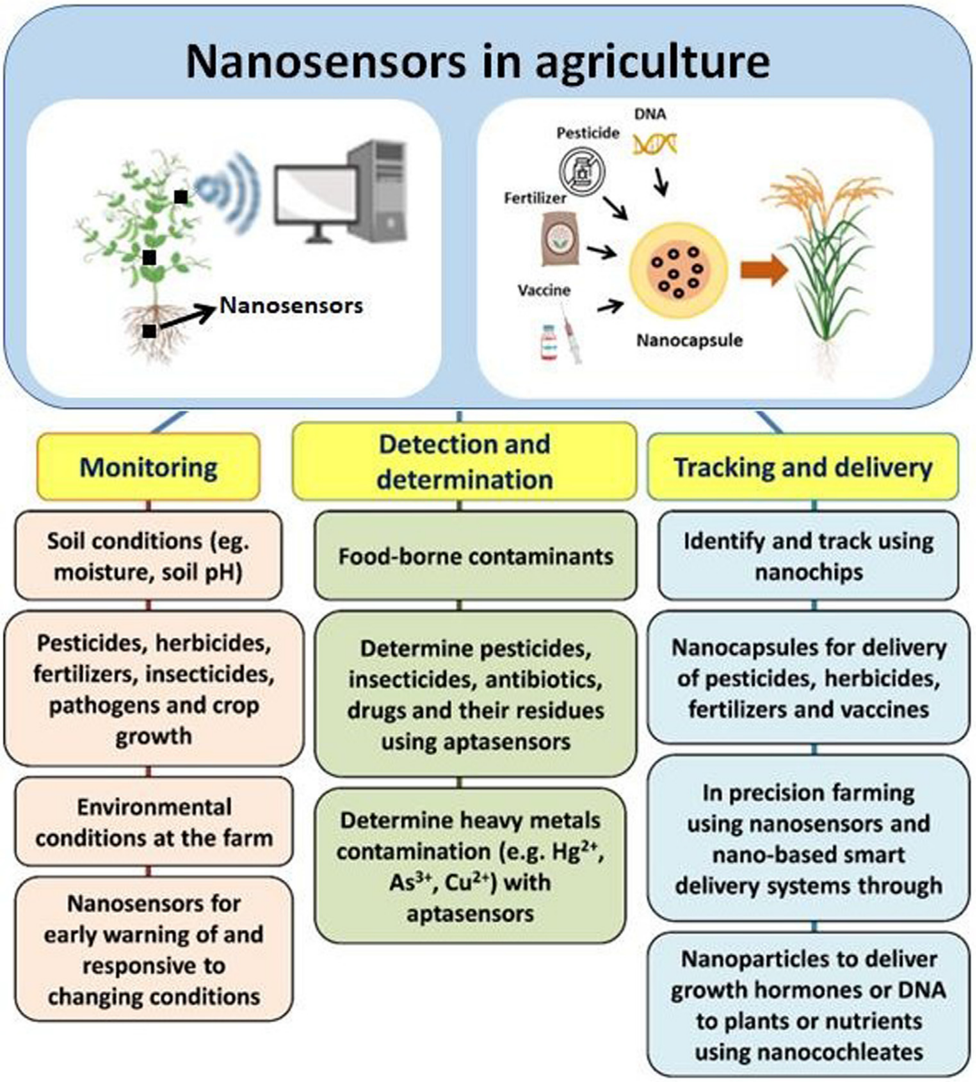

Fig. 3. Overview of the applications of nanosensors in agriculture. The potential applications of various nano-based sensors in agriculture can be broadly grouped into three categories- monitoring of environmental and plant conditions; detection and determination of organic and inorganic contaminants; and tracking and delivery of nutrients, growth and pest control agents (Gogos et al., 2012) (Dubey and Mailapalli, 2016) (Fang et al., 2017).

culture. Hydrogels are polymers that absorb aqueous solutions through hydrogen bonding with water molecules (Narjary et al., 2013). These hydrogels are used in agriculture because they aid in water retention, thus facilitating crop production and increasing yields by decreasing water stress, increasing water holding capacity, decreasing fertilizer leaching, and enhancing water permeability (Narjary et al., 2013). In contrast, hydrogels can also be used to load the desired fertilizers and to facilitate root diffusion throughout the plant, thereby enhancing crop productivity (Ghobashy, 2020)·

Nanofertilizers in agriculture

The growth of the human population has increased the global food demand, thereby requiring the development of a more efficient agricultural system. Although chemical fertilizers enrich the soil and provide nutrients for better plant growth. However, excessive and prolonged use of fertilizers poses detrimental environmental problems such as soil, water, and air pollution (Congreves and Van Eerd, 2015). Another fundamental drawback of conventional fertilizers is fertilizer loss due to high release in soil and low bioavailability to plants (Chhipa, 2017). Consequently, large amounts of fertilizers are used in agriculture with very low nutrient use efficiency less than 40% of fertilizers ever reach the target plants (van Dijk and Meijerink, 2014; Solanki et al., 2015). Most applied fertilizers are lost through leaching, runoff, drifting, hydro- or photolysis, evaporation or biodegradation (Sabir et al., 2014). Given these challenges, the search for new technologies with a focus on nutrient use efficiency and sustainable agriculture has gained new momentum. The emergence of nanotechnology and nanomaterials has shown excellent potential for overcoming the constraints of modern conventional use of fertilizers (Raliya et al., 2017; Yogendra kumar, 2021). Engineered nanofertilizers can deliver plant nutrients in a sustained manner, thus increasing fertilizer use efficiency and decreasing fertilizer loss and environmental contamination (Chhipa, 2017) (Solanki et al., 2015). Nanofertilizers can be specifically engineered to release nutrients to meet requirements specific to crop plants in pastures and grasslands (Yogendra kumar, 2021). Nanofertilizers minimize the loss of nutrients through leaching or evaporation or degradation, and increase the bioavailability to plants. For example, the nanoformulations of nitrogen fertilizers are released synchronously with the rate of plant uptake of nitrogen, thereby significantly decreasing loss and increasing efficiency (Dwivedi et al., 2016) (Panpatte et al., 2016). Some such formulations include nanomaterials of clay, zeolite, and chitosan (a polysaccharide), which are highly porous environment-friendly materials (Panpatte et al., 2016) (Aziz et al., 2016). The solubility, optimum release, and efficient uptake of fertilizers such as phosphate and potassium nitrate can be greatly enhanced by formulations with NH_4^+-charged zeolites and graphene oxide films, respectively[1, 40]. Similarly, plant uptake of nutrient fertilizers such as calcium, magnesium, iron, phosphorus, zinc, and manganese is increased with the use of nanoformulations of nanocalcite with NPs of SiO_2, MgO, and Fe_2O_2 (Sabir et al., 2014). Nanofertilizers can be classified into different types and forms such as controlled/slow-release fertilizers, controlled loss, magnetic or nanocomposite fertilizers (Panpatte et al., 2016). These nanofertilizers are synthesized by encapsulation of fertilizer ingredients with nanomaterials, which are synthesized through“top-down” and “bottom-up” processes (Subramanian et al., 2015). Although balanced use of fertilizers, elite seeds and irrigation systems can increase crop productivity by as much as 40%, the application of nanofertilizers can potentially enhance agricultural productivity (Mohamed et al., 2021). Formulations of fertilizers with carbon NPs have been shown to significantly increase the yield of rice, wheat, maize, soybean, and vegetable crops (Liu et al., 2009). NPs greatly facilitate the entry of nutrients into plants through the nanopores in the roots and leaves, thereby stimulating a range of plant biological processes (Eichert and Goldbach, 2008). This property of NPs also enables efficient uptake of micronutrients, such as Mn, B, Cu, Fe, Cl, Mb and Zn, which are essential for healthy plant growth. Human health is indirectly promoted because consuming micronutrient-enriched food helps prevent deficiency associated health problems (Monreal et al., 2016). Thus, studies have shown that nanoformulations of micronutrients such as ZnO NPs, enable controlled release of elemental micronutrients for plant uptake, thereby facilitating growth and productivity (Kale and Gawade, 2016; Ali et al., 2019). Similarly, the application of NPs such as TiO_2, Fe/SiO_2 and Fe_3O_4 significantly enhances the growth, yield and nutritive values of spinach (Zheng et al., 2005); maize, barley (Najafi Disfani et al., 2017) and sweet basil (Joshi et al., 2018), respectively. The quest for sustainable agriculture and better quality of life can be potentially fulfilled in part by the application of nanofertilizers to enhance crop productivity in an environment-friendly manner. Table 1 provides details of technology transfer of different NPs in the agricultural field.

Table 1
Technology transfer of various nanoparticles used in sustainable agriculture.

Commercial Product Name	Company	Composition/content
TAG NANO (NPK, PhoS,Zn,Cal, etc.) fertilizers	Tropical Agrosystem India (P) Ltd., India	Probiotics,seaweedextracts, humicacidchelatedwith proteino-lacto-gluconate
Master Nano Chitosan Organic Fertilizer	Pannaraj Intertrade, Thailand	Chitosan with organic acid, salicylicacidandphenolic Compounds
Nano-Gro™	Agro Nanotechnology Corp., FL, USA	Plant immunity enhancer and growth regulator
Nano Green	Nano Green Sciences, Inc., India	Extracts of corn grain,soybeans potatoes, coconut and palm
Nano-Ag Answer®	UrthAgriculture,CA,USA	Microorganisms, sea kelp and mineral electrolytes
BiozarNano- Fertilizer	Fanavar Nano-Pazhoohesh Markazi Company, Iran	Organic materials, micronutrients, and macromolecules

Necessity of post-harvesting management of fruits

Diverse agroclimatic areas worldwide, together with distinct soil forms, enable the production of many varieties of fruits. Maintenance of fruits before harvesting and post-harvesting is highly important. After harvesting, fruit crops must be protected until marketing. The shelf-life of fruits is decreased by physical damages during their collection, transport and packaging. In addition, a major reason for the loss of harvests is diseases caused by microorganisms, such as bacteria, viruses and fungi. Fruits, owing to their soft texture, are highly susceptible to microbial infections. Citrus fruits are susceptible to several diseases caused by microorganisms, including *Penicillium* and Fusarium decay, *Rhizopus* and *Aspergillus.* For example, sor rot diseases and green, blue, and whisker decay, are caused by *Penicillium digitatum* (Youssef et al., 2010; Youssef et al., 2012; Youssef et al., 2012; Youssef and Roberto, 2014). Fungal infections are prevalent in grapefruits after harvesting. *Botrytis cinerea* causes the common gray mold disease of grapes and leads to an immense loss of grapefruit crops (Youssef and Roberto, 2014; Ladaniya, 2008). Crown rot, blossom end rot and anthracnose are common diseases affecting banana. Several fungal infections occur in apple and lead to large losses worldwide. Blue mold (*Penicillium expansum*), gray mold (*Botrytis cinerea*), speck rot, *Sphaeropsis* rot, *Mucor* rot, powdery mildew and bull’s eye rot are diseases affecting apple crops. Mango fruits are highly susceptible to diseases including anthracnose (*Colletotrichum gloeosporioides*), stalk end rot, or stem end rot (*Botrytis theobromae*), aspergillus rot (*Aspergillus niger*), and rhizopus rot. These are common diseases affecting many fruits including guava, papaya, avocado, dragonfruit and apricot worldwide, thus causing substantial losses to the fruit industry. Therefore, systematic organization of post-harvesting of fruits is required (Youssef and Roberto, 2014; Ladaniya, 2008).

Present post-harvest management approaches

Fungicides such as thiabendazole, pyrimethanil, fludioxonil, imazalil and other chloride-based chemicals are used for the post-harvest management of fruits. These chemicals are highly expensive and their use poses several health risks to consumers and causes environmental pollution (Palou, 2018). Several studies have investigated eco-friendly and non-hazardous methods for the post-harvest management of fruits in the past two decades. The alternative control measures of post-harvest fruits involve use of natural compounds, biocontrol agents, irradiation, boiling water or air application, and salt application. Biological control has been performed by using yeast antagonists and bacterial antagonists. Physical treatments include ozone treatment, electrolyzed water, UV irradiation, heating and changing atmospheric conditions. Chitosan and oligochitosan natural compounds, and essential oils including thyme oil, tea tree oil, lemongrass oil, and oregano oil, are used to manage fruits after harvesting (Ruffo Roberto et al., 2019).

Nanomaterials as an effective means of post-harvest management of fruits

A wide variety of nanomaterials in many forms have been developed and used to control the damage to fruits in the food and agriculture industry including those based on lipids, carbon, inorganic metals and their oxides (Khot et al., 2012; Bajpai et al., 2018). The applications of nanotechnology are very helpful in controlling post-harvest diseases, developing advanced packaging methods using nano-bio films, decreasing the effects of gases and harmful rays, and developing nano-biosensor chips for labeling fresh products. Nanomaterials are also used as antifungal agents for various fungal infections of fruits. In this context, several nanomaterials have been designed and developed as post-harvest management tools to control diseases in many fruits including citrus, grapes, banana, apple, mango, papaya and guava (Ruffo Roberto et al., 2019; Tarun Kumar Upadhyay, xxxx).

Packaging is an important task for fruit transport. Maintaining the quality and freshness of fruits during the period of marketing until the fruits reach consumers is critical. However, complete blocking of packaging leads to gas impermeability which is not desirable for fresh fruits. This challenge in fruit packaging has been overcome with nanopolymers (Hariram, 2020). Nanomaterials often used as packaging materials include AgNPs, which show antimicrobial activity against many microorganisms. Chitosan/silica nanocomposites and chitosan NPs (CNPs) have successfully protected "Italia" grapes from bunch loss, without any adverse effects to the grapes (Rubentheren et al., 2015). Moreover, thyme (*Thymus vulgaris* L.) containing pullulan and polymeric nanocapsule coatings of grapes (153.9 nm) have been found to increase shelf-life and to maintain the color, durability and acidity for longer periods than observed in uncoated fruits. The coating of grapes with formulated nanocapsules also prevents the evaporation of volatile compounds from the fruit surface, thus delaying ripening and increasing the shelf-life of grapes (Piña-Barrera et al., 2019). Grapes wrapped with a nanocomposite hybrid film synthesized from chitosan/gelatin and AgNPs (25–45 nm) show a fresh appearance with no leakage of juice from the surfaces of the grapes, and extend shelf-life for 2 weeks. Moreover, CNPs have shown many beneficial effects on grapes (Rubentheren et al., 2015). CNPs decrease the bulk loss of fruits by delaying ripening time, and maintaining sufficient moisture and acidity. Additionally, the decay percentage is decreased when chitosan-coated grapes are stored under refrigerated conditions. AgNPs made up of banana peel extracts showed potent inhibition of *E. coli, Klebsiella* species, *and Shigella* species (Siddiqi et al., 2018). Banana fruits coated with CNPs (102.4–370 nm) at a concentration of 0.2% show decreased loss of humidity and aroma, inhibited penetration of oxygen and infection control after harvest (Esyanti et al., 2019). Post-harvest loss of banana decreases with the use of chitosan at 1.25% and CNPs (121.2 nm). Chitosan in combination with CNPs maintains a normal pulp to peel ratio, starch, soluble solid levels, and sensory quality. Consequently, banana shelf-life increases by delaying the ripening period (Lustriane et al., 2018). A familiar inorganic nanomaterial synthesized from soybean protein isolate/cinnamaldehyde/ZnO nanocomposite has potent antimicrobial activity, and excellent barrier and mechanical properties (Ruffo Roberto et al., 2019). This inorganic nanocomposite film coating preserves banana firmness and sensory quality, and prevents early ripening, increasing quality and freshness. A film of CNPs comprising of pectin and glycerol as a plasticizer has shown prolonged film firmness. The water vapor permeation is 21% for films containing pectin but is 38% without pectin (Piña-Barrera et al., 2019) (Esyanti et al., 2019; Lustriane et al., 2018). Various nanomaterials used for post-harvest management of fruits and vegetables are shown in Fig. 4. However, further studies are required to develop nanomaterial use strategies.

Nanotechnological applications in the post-harvest management of vegetables

Substantial population growth and urbanization have increased the demand for high-value fruits, vegetables, meat and dairy. Vegetables are the most important food, owing to their excellent nutritional value: they are low in fat and calories, have large amounts of dietary fiber and supply essential vitamins, minerals and trace elements. Many factors influence the post-harvest losses of vegetables, because they have short shelf-lives, thus resulting in considerable loss between harvest and reaching consumers (Yahaya et al., 2017). This loss can be due to several reasons, including improper handling, processing, transportation, storage and marketing. The damage caused by insects, mites and pathogenic microorganisms is also responsible for substantial post-harvest loss of vegetables. Diseases render vegetables prone to mechanical damage, loss of appearance and decreased quality thus, resulting in large losses to producers (Linling et al., 2013). Additional major factors affecting vegetable shelf-life and quality include environmental factors such as relative humidity, temperature and the availability of oxygen during storage of vegetables (Arah et al., 2015). All these factors are responsible for large losses of fresh produce of vegetables worldwide every year. Traditional and currently used methods and approaches in post-harvest management of vegetables are not adequately controlling the loss of vegetables. Thus, innovative technologies, particularly nanotechnology, may be valuable in managing the post-harvest losses of vegetables more effectively, through eco-friendly approaches. Various nanoformulations, including nanoemulsions, nanocomposites, nanospheres, nano-bubbles and nanocapsules, are used for the post-harvest management of vegetables (de Oliveira Filho et al., 2022; Kumera et al., 2021). These nanomaterials have major advantages in safety, decreasing flow of gases, maintenance of optimum moisture and increased shelf-life of vegetables (Watson et al., 2011). The ultimate target of using nanotechnology in designing packaging materials is to promote successful and efficient management of post-harvesting losses of vegetables. For example, during storage, the moisture content of vegetables is significantly retained when

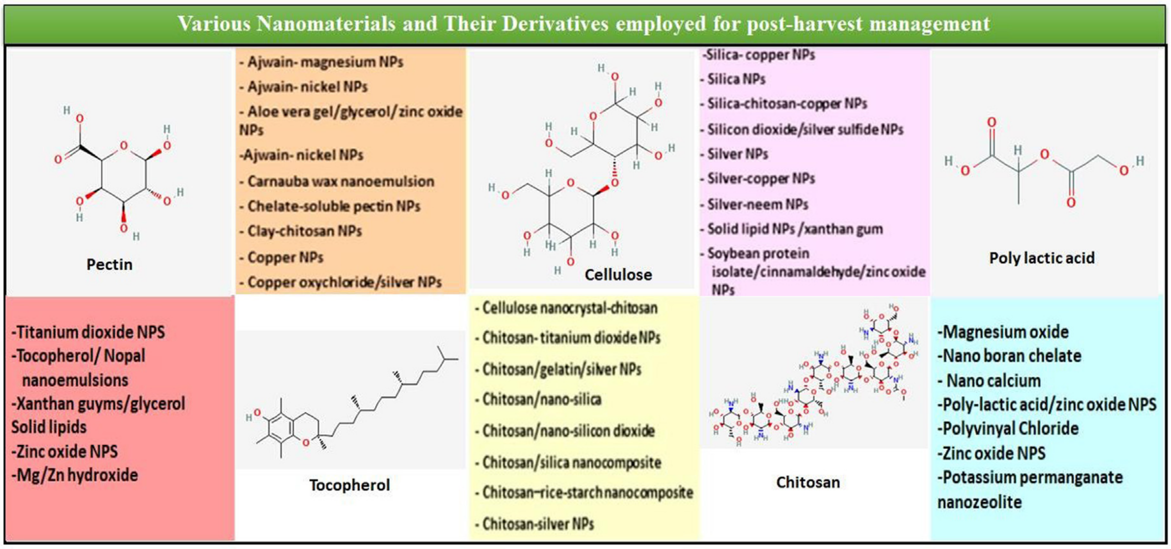

Fig. 4. Various nanomaterials and their derivatives used for post-harvest management of vegetables and fruit (Lustriane et al., 2018) (Xing et al., 2019).

AgNPs impregnated packets are used, whereas a considerable loss of moisture is observed without these NPs (Xing et al., 2019). Thus, NPs impregnated packets can be used to manage the permeability of vegetables. Chitosan film with incorporated sulfur NPs improves the mechanical strength, water vapor barrier, hydrophobicity and antimicrobial activity (Xing et al., 2019). The moisture content of vegetables is not lost after packaging in NPs impregnated packets, whereas considerable loss of moisture is observed when normal packets are used. This property of NPs is due to controlling of the cell permeability of the vegetables. Coating films made up of NPs showed decreased antimicrobial activity and respiration rates by acting as protective barriers, and additionally control the texture and color, and maintains freshness by stopping the decaying process, thereby increasing the shelf-life of vegetables. Silver-chitosan nanocomposite coatings successfully retain firmness and vitamin C content, and promote good sensory characteristics during storage. Therefore, this coating may be used for maintaining the shelf-life of fresh produce during storage post-harvesting (Ortiz-Duarte et al., 2019). Singh et al. have studied the biochemical properties of vegetables after cellulosic packaging and observed maintenance of freshness during the storage period. Smart packaging of vegetables has been developed for storing vegetables for longer periods in supermarkets: this packaging is used for detecting food spoilage and arresting the growth of microorganisms (Singh et al., 2010). Many combinations of nanomaterials are used as antimicrobial agents against diverse diseases affecting vegetables after harvesting. Some of the potent nanomaterials showing antimicrobial activities discussed herein have been used in the successful post-harvest management of vegetables. AgNPs with electrocatalytic properties provide significant antimicrobial activity; edible polymers have also been used for active packaging of food to control vegetable loss post-harvest (Liu et al., 2009). ZnO NPs, beyond conferring antibacterial activity, act as a permeable barrier when used as coating films (Shahabi-Ghahfarrokhi et al., 2015). A composite coating of graphene oxide, chitosan and TiO_2 NPs at a ratio of 1:20:4 shows potent antimicrobial activity against *Bacillus subtilis* and *Aspergillus niger*, through rupturing the cell membranes (Xu et al., 2017). Moreover, β-chitosan coated AgNPs have been found to control more than 99 % of *E. coli* and *Pseudomonas aeruginosa* (Andrade et al., 2014). In addition, whey protein isolate in combination with cellulose nanofiber films synthesized from rosemary essential oil in combination with TiO_2 have shown high antimicrobial activity against gram-positive *S. aureus* and *L. monocytogenes* (Alizadeh-Sani et al., 2018). Similarly, soybean polysaccharide/TiO_2 NPs bio-nanocomposite films have shown potent antibacterial activity against *S. aureus* and *E. coli*. Photocatalytic TiO_2 inorganic NPs are widely used as an antimicrobial agent in various coatings of food products (Alizadeh-Sani et al., 2018). The antimicrobial activity of nanomaterials remains unclear and under debate. Their mechanism involves formation of pits on the bacterial surface, thereby leading to membrane rupture and structural changes leading to death (Babu et al., 2018). Another hypothesis involves generation of reactive oxygen species by nanomaterials. These reactive oxygen species are potentially produced through the inhibition of a respiratory enzyme by nanomaterials, and act on the cells in which they are produced, thus damaging them (Babu et al., 2018). Therefore, nanomaterials play an important role in the post-harvest management of both fruits and vegetables. However, the toxicity of the NPs on crops is an area of research that must be explored further. The major factors affecting nanomaterial toxicity are their size, surface area and fabrication type (Rienzie and Nadeesh, 2018). Other extrinsic factors causing toxicity to the crops, include the pH of the environment to which the NPs are exposed, and plant life cycle stages and species (Rienzie and Nadeesh, 2018). Some of the NPs causing toxicity to certain plants include the TiO_2 NPs, which decrease root length in Lactuca sativa (Song et al., 2013); SiO_2 NPs which decrease plant height, shoot and root biomass in cotton (Le et al., 2014); silica NPs which decrease plant growth and transpiration (Hawthorne et al., 2012); and graphene-based NPs, which decrease the active photosynthetic tissue area (leaves) and cause plant death at higher concentrations (Begum et al., 2011). Despite being very beneficial, using nanomaterials for post-harvest management applications, in edible coating films and antimicrobial agents incorporated in coating films and packaging materials pose challenges that remain to be addressed.

Future perspectives and conclusion

In summary, we described various applications of nanotechnology in diverse fields of agriculture, including seed storage, seed germination, plant growth, stress tolerance, plant adaptation, priming, fertigation, and delivery systems for crop productivity. Moreover, the nanomaterials used as sensors for precision agriculture and crop protection are discussed in detail. Importantly, we discussed nanomaterials used as fertilizers to replace chemical fertilizers for sustainable agriculture. Additionally, various synthetic nanomaterials used for the post-harvest management of fruits and vegetables, in the forms of edible coating films, packaging materials and effective antimicrobial agents against many pathogenic organisms, are discussed. For the effective, convenient, and economically simple post-harvest management of vegetables and fruits, nanotechnological applications have an edge over conventional methods. In conclusion, farmers worldwide, can apply the applications of nanotechnology in various fields of agriculture and food, including crop production, soil resource management, forest preservation, agrochemicals, farm animal breeding, water resource management, agricultural diagnostics, reestablishment of agricultural resources after natural disasters, organic agriculture, food processing aquaculture, fishery development, wastewater treatment, soil conservation, nutraceuticals, drug delivery and poultry farming. Simplification of land ownership, correction of land maps, and infrastructure development are necessary for the efficient application of nanotechnology for sustainable agriculture. Nanotechnology is expected to expand its potential in providing viable alternative agricultural solutions and to play a major role in achieving sustainable agriculture. However, further research and deeper understanding are needed to enable the use of these nanomaterials in successful post-harvest management of vegetables to provide fresh, healthful and highly nutritious food to humans.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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