11 Agri-Nanotechnology for Sustainable Agriculture

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Contents

Abstract

An interdisciplinary field like nanotechnology is exhaustively being explored for its benefits for the welfare of society. The encouraging outcomes in various fields paved a new scope for utilization of nanotechnology in the agri-sector also. The green revolution led to the uncontrolled use of agrochemicals, which on the one hand resulted in an increase in the productivity, but on the other hand has severe adverse effects on soil diversity and aquatic ecosystems and has negative impacts on the health of people growing and consuming these chemical-laden agriproducts. Nanotechnology emerges as a resourceful front in current agri-

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practices and is expected to become a key strength through new inventions. As a result, the amalgamation of nanotechnology with agriculture results in enhanced productivity, better pest and weed management, and reduced health implications to soil, water, and people, though a lot of safety, toxicity, risk assessment, and risk management issues still remain unsettled lagging behind the broad application of nanotechnology in agriculture. This chapter will talk about the green synthesis, applications of nanotechnology in agriculture and agro-economy, uncertainties, risks, and ethical concerns related to agri-nanotechnology.

Keywords

Green synthesis · Agro-economy · Risks and ethical concerns · Agri-nanotechnology

11.1 Introduction

The development of the agri-sector is an indispensable factor of economic growth in developing countries. Currently, the ever-increasing global population is leading to a decline in the ratio of demand and supply of agriproducts. To meet this issue, it is necessary to employ new tools in the agriculture sector (Abbas et al. 2016). The inclusion of biotechnology and nanotechnology in agricultural practices can play a vital role in increasing the production rate with improved food processing and packaging. Nanotechnology is extensively influencing the society through its vast applications in our day-to-day life, and from the year 2003, it has embarked into the agriculture and food industry, and over the span of the last few years, the researches in the area of agri-nanotechnology has skyrocketed (Agrawal and Rathore 2014). It influences almost all the areas of the agri-sector, including soil and plant health, irrigation management, water filtration, food processing, food packaging, and vector and pest management. Nanotechnology lets us construct nanoscale structures through modifications at the atomic level (Aouada and de Moura 2015). The objective of using nanomaterials and nanotechnology in the agri-sector is to increase the yield, manage the nutrient loss, and minimize the usage of chemicals, through pest and nutrient management. It is being approximated that by the year 2020, the worldwide economic impact of nanotechnology will be more than 3 trillion US dollars, employing around six million workers (Aziz et al. 2016). This involved people engaged in improving the production and promotion of nano-based goods, quality assessment, efficiency enhancement, and safety measurements of foodstuffs. Due to poor assessment and management of associated risks, most of the nano-based products used in food industry are not directly being induced in human food. Majority of them are the surface materials only contacting the food except the nano-oxide of iron and titanium which are being used as food color and food pigment (Baker et al. 2017).

11.2 Synthesis of Nanoparticles

The exceptional physical, chemical, mechanical, electronic, and optical characteristics of nanoparticles are continuously drawing the attention of scholars towards sustainable methods of their synthesis. To facilitate this, researchers are focusing on the green synthesis methods to lessen the environmental hazards (Baligar and Fageria 2015). The cost-efficiency, environmental affability, decreased toxicity, and rapid reaction rate are the characteristic features of green synthesis (Berekaa 2015; Bhagat et al. 2015). The use of noxious solvents, intense temperature and pressure, and endothermic nature of reactions are all non-eco-friendly and can cause grave impacts to the environmental equilibrium. In the green synthesis of nanoparticles, plant extracts and appropriate metal ions are being mixed in a fixed ratio under the required physical parameters (Camilli et al. 2014; Chhipa 2016; Cox et al. 2017). There are various chemical, physical, biological, and cross-synthesis routes to construct nanoparticles with a chosen character. The various procedures for synthesizing NPs are listed in Fig. 11.1. The extensively used physical techniques are extremely pricey, whereas the chemical methods are disadvantageous to the society and the environmental health. In addition to the environmental impacts, there are several other issues like insufficient growth rate and imprecise structures of synthesized nanoparticles and toxicity of synthesized substance (Das et al. 2015; De Matteis 2017; de Oliveira et al. 2014).

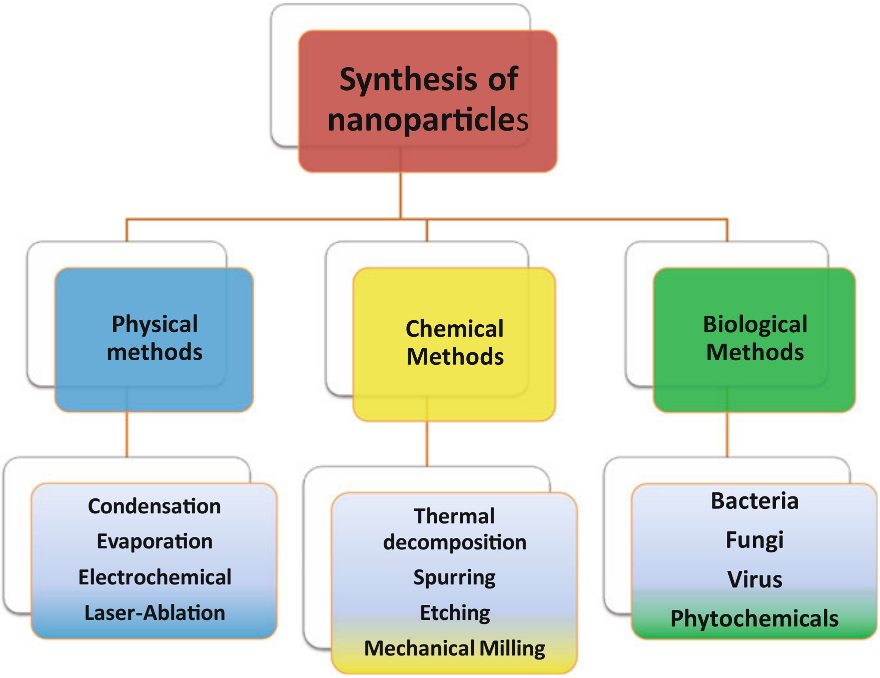


Fig. 11.1 Synthesis of nanoparticles

11.2.1 Green Synthesis of Nanoparticles

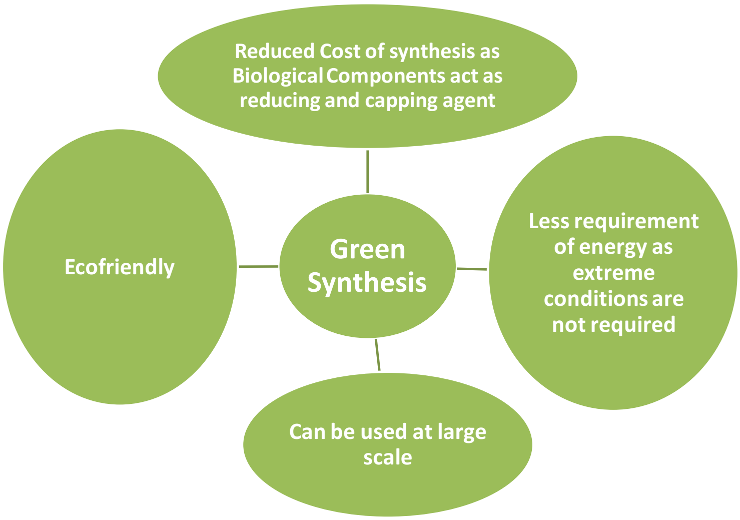
The green synthesis of nanomaterials avoids the creation of unnecessary or detrimental by-products by using sustainable, consistent, and environment-friendly synthesis routes (Ditta and Arshad 2016). The green synthesis of metal nanoparticles has been implemented to use diverse organic resources such as plant extracts, microorganisms, yeast, etc.

11.2.1.1 Nanoparticles from Plants

For the purpose of green synthesis of metallic nanoparticles, a broad biodiversity of plants and availability of various phytochemicals like terpenoids, ascorbic acids, aldehydes, flavones, ketones, amides, etc. in different plant extracts are being explored to a great extent (Ezz El-Din and Manjaiah 2017; Fraceto et al. 2016; Glenn and Florescu 2016). These phytochemicals have the capability to reduce metallic salts into their corresponding metallic nanoparticle. The green synthesis of nanoparticles is a single-step environment-friendly and economically efficient biological reduction process which involves comparatively little amount of energy to kick off in contrast to the chemical and physical methods (Hajirostamlo et al. 2015) (Table 11.1).

Table 11.1 Nanoparticles from plants (Pandey 2018c)

Name of plant	Metal nanoparticle
Macrotyloma uniflorum, *Aloe vera*, *Sinapis arvensis*, *Artemisia nilagirica*, *Semen cassia*, *Zea mays*, *Nerium oleander*, *Magnolia kobus*, *Oryza sativa*, *Helianthus annuus*, *Saccharum officinarum*, *Sorghum bicolour*, *Basella alba*, *Capsicum annuum var. aviculare*, *Medicago sativa*, *Callicarpa maingayi*, *Ficus benghalensis*, *Pinus eldarica*, *Sesbania drummondii*, *Pithophora oedogonia*, *Allium sativum*, *Hovenia dulcis*	Silver nanoparticles
Zingiber officinale, *Abelmoschus esculentus*, *Hamamelis*, *Mentha*, *Eucalyptus*, *Terminalia chebula*, *Morinda citrifolia*, *Anacardium occidentale*, *Jatropha waste*, *Stevia rebaudiana*, *Diospyros kaki*	Gold nanoparticles
Carica papaya, *Aloe vera*, *Green tea*, *Sorghum bran*, *Dodonaea viscosa*, *Azadirachta indica*, *Eucalyptus tereticornis*, *Sargassum muticum*	Iron nanoparticles
Ricinus communis, *Calotropis gigantean*, *Ocimum tenuiflorum*, *Ocimum sanctum*, *Nerium oleander*, *Tabernaemontana divaricata*, *Ficus religiosa*, *Punica granatum*, *Carica papaya*	Copper nanoparticles
Ixora coccinea, *Limonia acidissima*, *Parthenium hysterophorus*, *Pongamia pinnata*, *Trifolium pratense*	Zinc nanoparticles
Solanum trilobatum, *Moringa oleifera*, *Trigonella foenum-graecum*, *Nyctanthes arbor-tristis*	Titanium nanoparticles



11.2.1.2 Nanoparticles from Microbes

Microbes do have the prospective of reducing metal ions into pure nanoparticles through the extracellular enzymes. Their unique metal affinity to bacteria and fungi make them useful for the green synthesis of metal nanoparticles. The microbial scheme of creating metal nanoparticles is relatively time-consuming in comparison with the plant extracts; still their easy handling, growth and culture methods, and the

Table 11.2 Nanoparticles from microorganism (Pandey 2018c)

Name of microorganism	Metal nanoparticle
Staphylococcus aureus, *Streptomyces naganishii*, *Trichoderma reesei*, *Brevibacterium casei*	Silver nanoparticles
Klebsiella pneumoniae, *Streptomyces viridogens*, *Nocardia farcinica*, *Rhodopseudomonas capsulata*, *Penicillium brevicompactum*, *Neurospora crassa*, *Thermomonospora* sp., *Aspergillus oryzae*, *Aspergillus clavatus*	Gold nanoparticles
E. coli, *Shewanella oneidensis*, *Pleurotus* sp., *Klebsiella oxytoca*	Iron nanoparticles
Stereum hirsutum, *Shewanella oneidensis*, *Streptomyces* sp., *Penicillium aurantiogriseum*, *Hypocrea lixii*	Copper nanoparticles
Candida albicans, *Lactobacillus*, *Streptomyces* sp.	Zinc nanoparticles
Aspergillus tubingensis, *Bacillus amyloliquefaciens*, *Fusarium oxysporum*	Titanium nanoparticles

low investment and lesser environmental risks make them beneficial for biosynthesis (Handford et al. 2015; Jayaseelan et al. 2011).

Fungi: Fungi are comparatively new in their utilization for synthesizing nanoparticles but are advantageous than bacteria because of their easy management, huge enzyme secretion, and hassle-free downstream process, though eukaryotic genetic alterations in fungi are not so easy (Karpachev et al. 2016).

Bacteria: Bacteria being prokaryotes easily go through genetic alteration for synthesizing nanoparticles. Nanoparticles of Ag, Au, Zn, Pb, Fe, and iron sulfide and Cd quantum dots are generally being synthesized by bacteria (Khan and Fulekar 2016) (Table 11.2).

11.3 Application of Nanotechnology in Agriculture

In developing countries agriculture is the spine of economic development. The primary test which the agri-sector faces is the uncertain climatic conditions, bioaccumulation, and rapid rate of industrialization along with the mounting demand for food to feed a projected population of six to nine billion people by the year 2050 (Kouhkan et al. 2019). The world of agriculture is facing a large array of challenge of stagnant harvest yield, nutrient deficit, declining soil organic matters, weather alterations, diminishing cultivable area, water scarcity, GMO resistance, and dearth of manual labor. The agriculture of India is yet not out of the effects of the green revolution reflecting an exponential rise in the consumption of fertilizers from 0.5 tons in the year 1960 to 23 million tons in 2008 (Kumar et al. 2015; Liu and Lal 2015; Mabe et al. 2017). Even though the crop productivity rose up to four times, still it led to decrease in the organic content of soil resulting into the stagnant yield of some crops. Due to the dependency on various natural factors like soil, water, climate, etc., the agricultural sector is very unpredictable (Mani and Mondal 2016;

Milewska-Hendel et al. 2016). Therefore, in order to meet the challenges of environmental sustainability with food managing the demands of food quality and quantity, it is very necessary to sense, record, manipulate, and store the consistent and accurate statistics of all abiotic and biotic components of the environment (Monreal et al. 2016). To fulfill this, it is very necessary to combine agriculture with technological advances and infusing the principles of nanotechnology in agricultural practices has shown to achieve enhanced outcomes. Nanotechnology has enormous potential and benefits in the agri-sector. Nanoparticles when infused in plants in precise amounts make various structural and physiological changes in them reflecting effective results in plant growth and seed germinations and rate of production (Morales-Díaz et al. 2017; Mufamadi and Sekhejane 2017). The benefits of nanotechnology comprise of pest management through nanoformulations of pesticides, amplifying the productivity through nanoencapsulation for sustained release of nutrients, developing pest resistance through nano-mediated gene transfer, creating nanobiosensors for precision farming, etc. Nanoparticles capture medicine, nutrient, and genes of concern and facilitate their sustained release for better solubility, assimilation, permanence, and diffusion of herbicides through plant cells (Nima et al. 2014).

11.3.1 Precision Farming

Precision agriculture or precision farming is the method that makes agricultural practices more precise and managed in terms of crop growth and raising of cattle. The chief constituent of precision farming is the inclusion of a broad range of objects such as GPS-based soil sampling and control systems, robotic systems, sensors, drones, and self-governing means of transportation, automatic software, and hardware tools. Precision farming is the ultimate aim to make the most of crop yield with minimum efforts (Nuruzzaman et al. 2016; Ozdemir and Kemerli 2016). For precision farming, the efficient crop yield is ensured by precise identification and location of agriculture issues with the help of technical aids like sensing devices, computers, and satellite positioning systems. With the help of technical interventions, the physiographic factors like soil health, nutrient status, and water level can be accurately assessed and managed to improve agricultural productivity (Pandey 2018a). Precision farming techniques are enabled with advanced monitoring tools and minuscule sensors help in monitoring soil conditions, crop growth, and agricultural waste management. The use of wireless nanosensors in various countries is being reported by the *Forbes Magazine*, e.g., small nanosensors are being used by Honeywell, a Tech R and D company using small nanosensors for monitoring requisition and expiry status of food articles in grocery stores in Minnesota. By using nanosensors, the requirement for herbicides, pesticides, and nutrients can precisely be estimated for every single corner of farm resulting into maximum efficiency with optimal inputs (Pandey 2018b). Smart delivery systems and sensors based on nanotechnology help in the proficient exploitation of natural agro-resources like soil, water, and the environment along with chemical nutrients and medicines through precision farming as well as help farmers detect weeds, pests, or environmental stress like drought. Once the issue is being sensed, nanosensors will make automatic adjustments for irrigation, or pesticide application. Nanosensors dispersed in the field can also sense the existence of a microorganism in soil and plants to manage them. Precision farming can as well facilitate management of agricultural wastes and thus help keep the environmental pollution to a bare minimum (Parisi et al. 2015).

11.3.1.1 Delivery of Fertilizers

A huge amount of fertilizers used to increase crop production has led to a lot of detrimental effects on the valuable microflora of the soil. Apart from this, a large amount of fertilizer gets wasted due to runoffs and cause pollution. Nanoencapsulated fertilizers can resolve this issue as they have the property of getting rapidly absorbed by plants completely. Nanoencapsulation facilitates the strong hold of nutrients and their sustained release and surface protection (Patra and Baek 2017). Inorganic fertilizers like diammonium phosphates, urea, etc. used to supplement the requirements of nitrogen, phosphorus, and potassium in soil get wasted into the environment resulting in economical loss and environmental pollution as well (Prasad et al. 2016, 2017). The approach of using more stable and efficiently absorbed nano-coated chemical nutrients helps in reducing the dissolution rate of the fertilizer and leading to its sustained release for efficient absorption by plant roots.

This nano coating of nutrients facilitate sustainability by trimming down the wastage and minimizing environmental pollution. These slow-releasing encapsulated fertilizers are exceptional substitutes to the conventionally used soluble fertilizers. Researchers performed various studies to administer the controlled-release model of 22 essential nutrients by using nanoclays and nanocomposites (Raliya and Tarafdar 2014). Nano-coated sulfur fertilizers are being used for sulfur-scarce soils. Eco-friendly kaolin and chitosan nanoparticles have shown excellent results for sustained release of N-P-K fertilizers. Nanoencapsulation of fertilizers helps in the improved absorption of nutrients from the soil. Nanosilica and SiO_2 films help protect plants from infections and unfavorable environmental conditions and enhance the growth of roots and seedlings. Nontoxic titanium oxide nanoparticles are being used as an additive to increase crop productivity. To overcome the issues of high rate of water solubility, leaching, and denitrification of N fertilizers, various slow- and controlled-release fertilizers are being designed by using nanoclay-like montmorillonites, bentonites, halloysites, and zeolites (Rossi et al. 2014; Saharan et al. 2013; Schmid and Stoeger 2016).

11.3.1.2 Nanobiosensors

Nanosensors when immobilized with a range of bio-receptors are called nanobiosensors and are designed for detecting and analyzing data on atomic scales for detection and sensing of various chemicals, pathogens, enzymes, pollutants, infections in crops, and water level of soil. The pathogenic bacteria *E. coli* can be sensed by using a nanobiosensor made up of antibodies coated on fiber-optic nanosensors (Sekhon 2014). Nanobiosensors made up of antibodies conjugated with fluorescent Si nanoparticles can help in detecting the gram(−) bacteria *Xanthomonas axonopodis*, responsible for bacterial infections in Solanaceae plants. The peculiar optical properties of gold nanoparticles make them a potential biosensor for sensing pathogens; for example, the karnal bunt disease in wheat crop can be detected by using gold nanobiosensors. Though the applications of nanobiosensors for detecting plant pathogens is still in its primitive stage, still various nanobiosensors made up of CNTs, Si nanoparticles, and various nanowires are being reported to detect and report plant pathogens very precisely (Sertova 2015).

11.3.1.3 Nanopesticides and Nanoherbicides

In a broader aspect, pesticides and herbicides enhance crop yield and plant growth either by killing the unwanted weeds, grasses, insects, or microorganisms or by making the plants resistant to them (Shweta et al. 2016). The increased usage of pesticides may lead to decline in N_2 fixation, resistance in pest and pathogens, bioaccumulation of pesticides, and reduced biodiversity of soil. The use of nanopesticides may help resolve these issues to some extent. But a major fraction of pesticides applied to plants and soils gets wasted through leaching and runoff (Siddiqui et al. 2015). Therefore, it is necessary to enclose these pesticides in some coating to have their controlled and precise release and increased solubility. Various nanoparticles made up of silver, zinc, and titanium oxides have shown promising results in controlling infections and pests in rice and silkworms (Subramanyam and Siva 2016). Citric acid and multiwalled carbon nanotube encapsulated pesticides, Mancozeb and Zineb, have shown promising results in controlling the fungi *Alternaria alternata*. The exploitation of nanoformulations opens new ways to boost the strength and constancy of natural substances. This is achieved with the help of the anti-pathogenic behavior of nanoparticles and because of specific defense mechanisms inside the plants (Tarafdar et al. 2013; Wang et al. 2017) (Table 11.3).

One more area of concern in agri-practices is when weeds are grown in between and along with the standing crops. Herbicides are used to get rid of these weeds, but usually herbicides when sprayed might have an effect on the standing crop, sourcing a considerable loss of crop production. The nanoscale dimensions and target-based

Table 11.3 Effects of nanopesticides (Wang et al. 2017)

Nanopesticides	Effect
Essential oil-filled glycol-coated polyethylene nanoparticles	Against red flour beetle (*Tribolium castaneum*)
Silver nanoparticles	Protects oak trees from Raffaelea Cucurbit family against powdery mildew
Ag NPs by *Tinospora cordifolia*	Against *Pediculus humanus*, *Anopheles subpictus*, *Culex quinquefasciatus*
Hydrophobic aluminum-silicate nanoparticles as phenolic suspension	Protects *Bombyx mori* from grasserie disease
Hydrophobic nanosilica	Controls the spread of highly resistant species *Spodoptera littoralis*

precise delivery of nanoherbicides make them easy to blend with soil particles to wipe out the weeds without distressing the major crops. Nanoencapsulation is also useful in achieving sustained delivery and controlled solubility of herbicides. For example, herbicides containing atrazine, ametryn, and triazine are being nanoencapsulated using carbon nanotubes and silver, zinc oxide, and titanium oxide nanoparticles to attain more than 80% efficiency in precise and sustained release to plants (Yang et al. 2017; Zhang et al. 2016).

11.3.1.4 Nanofiltration in Agriculture

The dearth of water has become a serious issue for agricultural practices in various regions of the world. To deal with this, it is very much essential to opt for some economically competent and sustainable methods for irrigation and to check water wastage by making apt amendments in irrigation techniques, though these modifications might be time-consuming and inapt in areas with continual lack of water. Nanotechnology can be helpful to resolve the issues related to water availability. The applications of nanofilters have shown to be a very effective tool for managing irrigation water by water treatment methods (Amin 2018). The pore dimensions of 0.5 nm to 1 nm make nanofilters highly useful for water softening and wastewater treatment methods. It is recommended in agriculture that the irrigation water should be free from particles greater than 50 μm, toxic salts, and heavy metals and should have low salinity (Yan et al. 2019). Therefore, it is necessary to treat water to remove every unwanted substance which may lead to decrease in productivity, quality, and diversity of crops. In a number of dry and hot places in some countries, solar-powered nanofilters are being used for managing desalinated water for irrigation as it is being shown by the requirement shows 25% less demand for irrigation and fertilizers, with a substantial increase in crop yield (Quist-Jensen et al. 2015).

11.3.1.5 Micronutrient Supply

Though the appropriate requirement of micronutrients is less than 100 ppm, still they have a key role in plant metabolism as activators to various enzymes. Chitosan nanoparticles have been found to be helpful in the slow release of some plant growth hormones like 1-naphthylacetic acid (Dayarathne et al. 2019). Iron oxide nanoparticles have positive effects on the growth of plants in soils rich in calcium and high in pH. It is been observed that iron nanoparticles have enhanced effects on the yield, protein content, grain weight, and spike weight when directly being applied on the leaves of wheat plant (Hans and Jana 2018). Symptoms of iron deficiency in soya bean plants can be overcome by applying nanoemulsion of iron nanoparticles. Micronutrients like Mn, Fe, Cu, B, Zn, Mo, etc. are very vital for the proper growth of plants (Feregrino-Perez et al. 2018). The mammoth increase in the crop production during the green revolution has led to a drastic change in the micronutrient balance of soil. To enhance the micronutrient availability to plants, nanoformulations of zinc, iron, molybdenum, etc. can either be infused through soil or sprayed on the plants. With the help of nanotechnology, smart seeds are being developed by making seeds absorb the nanoemulsions, which can be programmed in such a way that they only germinate when the conditions are adequate to them (Singh et al. 2018; Sun-Waterhouse and Waterhouse 2016). Nano-coated smart seeds have the ability to sense water and appropriate conditions for germination, to detect adequateness of moisture during storage. It was reported that application of nanosilicon dioxide ($nSiO_2$: size 12 nm) significantly enhanced the characteristics of tomato seed germination. Germination in tomato seeds was reported to enhance when applied with SiO_2 nanoparticles (Cushen et al. 2012).

11.3.1.6 Nanogenetic Manipulation of Agricultural Crops

Nanotechnology proffers innovative tools for manipulating plant genes using nanofibers, particles, and capsules. Appropriately designed nanomaterials work as carriers and might hold plant genes and substances controlling the movement of genetic materials. Nanofibers find their use in crop engineering, drug delivery, and environment monitoring via quick and efficient delivery of genetic material to cells. A mesoporous Si nanoparticle is shown to successfully transport foreign DNA into cells (Wakeil et al. 2017; Liu and Lal 2015). Starch nanoparticles are being reported to bind and transport genetic material through plant cells through the instant pore channels in the cell wall. Nanobiosensors can help protect crop field by sensing and releasing alerts for pollen grain contamination originating from genetically modified crops. The amalgamation of nanotechnology with biotechnology led to the breakthrough designing of three-dimensional molecular structures through constructing self-assembling synthetic DNA sequences as crystals. This method can well be used for enhancing vital crops by connecting and categorizing desired essential organic compounds like nucleic acids, protein, lipids, and carbohydrate molecules to these crystals (Liu and Lal 2015). Nanoparticles loaded with agrochemicals or genetic materials are capable of functioning as a magic bullet or gene gun, resulting in target-based precise delivery of these products. This method has given effective result in using mesoporous nanosilica or gold-capped nanoparticles for introducing specific DNA strands to corn and tobacco plants (Wang et al. 2019) (Table 11.4).

Table 11.4 Advantages of nanoformulations over conventional formulations (Nasrollahzadeh et al. 2019)

Desirable characteristics	Examples of nanofertilizer-enabled technologies
Formulation with controlled-release characteristics	The nano-designed formulations may allow the fertilizers to cleverly manage the discharge rate of the nutrients as per requirement patterns of the crops
Dispersion and solubility management of micronutrients	Nanoformulations of micronutrients might enhance the solubility and help in diffusion of non-dissolvable micronutrients in soil
New methods for controlled release	The rates and patterns of release of water-soluble nutrients can be accurately controlled by encapsulating the fertilizers in resins or polymer coatings
Affectivity of nutrient release	Nanoformulations might help in widening the period of effectivity of fertilizers in the soil
Leaching of nutrients	Nano-designed formulations help in reducing the loss of nutrients from soil through leaching

11.4 Nanotechnology in Agribusiness

11.4.1 Sustainable Water Use

Nanotechnology can be a boon in desiccated and drought-affected regions, as water scarcity leads to a great loss in crop production and agri-economy as well. Nanohydrogels can optimize the water consumption and increase the sustainability of agricultural practices by periodic absorption and discharge of water and nutrients (Kundu et al. 2019). It has been observed that soils laden with nanosilver-coated hydrogel has 7.5% more capacity to hold water. Hydrogels have the capacity to store water more than 150 times their weight (Rai et al. 2018).

11.4.2 Treatment of Seeds

Nanotreatment of seeds contributes towards the increase in the numbers and weight and weather resistance. Around 75% increase in dry weight, more than 15% increase in shelf-life, more than 85% increase in drought resistance, and three times increase in vitamin content are being observed in seeds when treated with nanosolutions which results in improved productivity and revenue generations (Baker et al. 2017; Kumar et al. 2019).

11.4.3 Pest and Disease Detection

The spread of disease, contaminants, pests, and microorganisms results into relentless harm to the agribusiness. The accurate and selective sensing of such serious threats by nanobiosensors helps in managing agricultural practices in a more healthy way through preventing outbreaks of diseases, pests, infections, and monitoring soil health resulting into the increased productivity and enhanced characteristics of food grains (Sozer and Kokini 2009; Rienzie et al. 2019).

11.4.4 Enhanced Delivery of Nutrients and Plant Protection Products

The smart delivery systems based on nanotechnology help in enhancing the reach of nutrients and precise delivery of protection products, resulting into the improvements in the quality, quantity, and life span of agriproducts (Corsi et al. 2018; Martinho 2018).

11.4.5 Decreased Pollution and Reduced Runoff

Nano-applications in agriculture help in reducing the pollution caused by chemical fertilizers and medicines and help in remediation of heavy metal polluted soils. This makes the discarded soils to be used again. Nanosolutions help in controlling the loss of agrochemicals caused by leaching and runoff which saves revenue loss as well (Dahabieh et al. 2018; Dudo et al. 2011).

11.5 Risks, Toxicity, Co-Contaminant Effects, and Impacts of Nanomaterials

The general properties and risks associated with nanoparticles are analyzed with the help of various articles being published. The characteristic properties of nanoparticles are directly or indirectly associated with their synthesis. The characteristics of nanoparticles and the challenges and risks associated are summed up in Table 11.5.

The environment and human beings are exposed to nanomaterials when these are released in the environment during their manufacture, usage, clearance, and management of harvests containing nanoproducts. The tiny dimensions of nanoparticles

Table 11.5 Properties of nanomaterials and associated risks (He et al. 2019)

Properties of nanomaterial	Risk associated
Aggregation	The agglomeration and high solubility and fusion of nanoparticles pose substantial risks by decreasing the resistance to corrosion, leading to phase change and weakening of infrastructure
Reactivity	The specific properties of agrochemicals based on the function groups might get altered due to the unprompted degradation of nanoparticles
Impurity	Owing to their highly reactive nature, nanoparticles are very prone to react with external impurities which may alter their properties and outcomes of their applications. Therefore, it becomes necessary to encapsulate them with some nonreactive substance
Contaminants	During their synthesis, most of the nanoparticles get contaminated by the precursors used for their synthesis which alters the actual properties of the nanomaterial. For example, CNTs get contaminated by metals like Rb, Yt, or Ni, and iron nanoparticles by sulfur
Size	The agglomeration and aggregation of nanoparticles hinder in retaining the size of nanoparticles. Therefore, it becomes necessary to encapsulate the synthesized nanoparticles
Clearance and recycling	There are no very clear clearance policies for the management of nanomaterials because not much data related to their exposure and applications issues is available for studies
Shape effects	Nanoparticles show specific toxic behavior at a particular aspect ratio, i.e., their toxicity is shape dependent. For example, 10-μm fiber of asbestos can cause cancer, and fibers having a length ranging 5–10 μm may cause mesothelioma, whereas fibers with length of 2 μm can cause asbestosis

make possible their translocation within the body causing organ damage, cancer, asthmatic attacks, irreversible oxidative stress, organ enlargements, organ dysfunctions, denaturation of protein, etc. (Di Sia 2017). The shape and the chemical composition of nanoparticles are the key reason for nanoparticle toxicity, and because of this, there are various nontoxic or less toxic nanoparticles, with some having positive effects.

11.6 Nanomaterial Regulations

The exceptional characteristics of nanomaterials like high biochemical activity, tissue penetration capacity, and better bioavailability make them a better resource for biomedical purposes. These virtues of nanomaterials might also bring possibilities for toxic effects on the environment and living being. Therefore, various laws, regulations, rules, and legislations are being formulated and implemented by government and nongovernment organizations to reduce or curb the risks associated (Justo-Hanani and Dayan 2015). However, there are no definite globally accepted protocols, norms, and regulations for the manufacture, management, testing, categorization, and evaluation of environmental influences of nanoparticles. Presently, the European Union and the United States have designed strong regulatory guidelines and legislations to manage the probable hazards of nanomaterials (Amenta et al. 2015). The current developments in the areas of nano-based formulations for agriculture bring along biosafety issues with them. The scientists at IFDC-USA (International Fertilizer Development Center) have highlighted that the pros and cons of broad manufacturing of nanoformulations are yet to be recognized (Coles and Frewer 2013). The most intricate and under-researched areas of nano-based agriproducts are risk assessment and management. In fact, the lacuna in the substantiation of permissible doses of nanoproducts for agriculture has deferred their broad market acceptance as compared to various other common technologies. Furthermore, there are not much statistical data available to understand the exploitation of nanonutrients from plants and the management of the metal residues. Risk assessment and management of a nano-based product corresponds to the pertinent risks and hazards that arise from that product all through its voyage from creation to consumption (Steinhäuser and Sayre 2017).

11.6.1 Existing Regulations of Agri-Nanoproducts at the World Level

As per the records maintained by NAAS (National Academy of Agricultural Sciences), more than 80% of the products, publications, and patents come from countries like United States, Japan, Germany, Switzerland, South Korea, France, and among Asian countries like China, whereas the rate of advancements and the investments being made in India are not satisfactory enough (Sayre et al. 2017) (Table 11.6).

Table 11.6 Existing regulations for nanoproducts (Radad et al. 2012)

Country	Regulating body/regulations
USA	FDA (Food and Drug Administration) US EPA (US Environmental Protection Agency)
Canada	CFIA (Canadian Food Inspection Agency) PHAC (Public Health Agency of Canada)
European Union	Regulation number1169/20119 (Provision of Food Information to Consumers) Regulation number 450/2009 (Active and Intelligent Materials and Articles) Regulation number 528/2012 (The Biocidal Products Regulation) Regulation number 1907/2006 (Registration, Evaluation, Authorisation and Restriction of Chemicals) Regulation number 1107/2009 (Plant Protection Products) Regulation number 1223/2009 (The Cosmetic Products Regulation)
Non-European countries	FOPH (Federal Office of Public Health of Switzerland) The Ministry of Environment and Urban Planning Russian Corporation of Nanotechnologies Food Standards Australia New Zealand (FSANZ)
Asian countries	Presently, there are no precise rules and legislations for regulating the applications of nanoproducts in agriculture The National Centre for Nanoscience and Technology (NCNST) In China, the application of nano-based products in food and agriculture is not permitted by regulatory bodies

11.7 Future Research

Nanotechnology has vast potential in the agriculture sector. Enhancing the crop production by precision farming governed by nanoprinciples is highly desirable to get maximum output with reduced inputs through superior sensing and by precise actions. Nanotechnology gives control to crops to make use of soil, water, fertilizers, herbicides, and pesticides in a more effective way. The future applications of nanotechnology comprise of exploiting nanoporous zeolites for sustained release of fertilizers and water in efficient amounts for plants, use of improved nano-capsules for delivering agrochemicals, production of biofuel, and better genetic manipulations in plants together with keeping the sustainability of the environment and health of living beings at first priority. This will comprise of defining the effects of nanomaterial behavior on the physiochemical and biological characteristics of the environment throughout their life cycle. Every part of all these experimental statistics is required to be shared among industries and government as well as nongovernment regulating bodies sequentially to evidently characterize the actual profile of concerned nanomaterial under changeable exposure circumstances and to design and execute an appropriate risk management strategy for sustainable development. In general, synchronized execution of all these facets may show the way for the development of an extensive regulatory consensus integrating various aspects of ethical studies and public engagement in decision making. These are essential for flourishing the applications of nanotechnology for achieving a long-lasting sustainable role of this emerging technology in the agri-sector, and we can convincingly be confident and hopeful for a brighter future of agriculture in amalgamation with nanotechnology.

11.8 Conclusion

In this chapter, a few fresh ideas related to the potential offerings of nanotechnology in agriculture are being examined. Out of those, some are very concrete, and for some, the primary investigational statistics are already existing, whereas quite a few have a strong futuristic approach. However, there are a range of apprehensions associated with the applications of nanomaterials in agri-sector that need to be dealt: how to handle nanoformulations in actual field conditions; what precautions should be taken; what are the best nano structures, instruments, and equipment to be used; and what are the safety precautions to be taken for the people working in the environment of nanostructures, etc. These and various other issues need to be regulated.

It can be concluded that the exploitation of nanomaterials in the agri-sector is still an underdeveloped area with the hope of being taken over by successful results and broad acceptance worldwide. The constant utilization of chemicals for enhancing agricultural efficiency has led to the contagion of soil crest, groundwater, and food resources, and in this reverence, nanotechnology is emerging as a broadly accepted technique for the development of agriculture in a sustainable manner. Promising results are already being recognized in the area of nutrients, medicines, herbicides, pesticides, and genetic materials by using the principles of nanotechnology. Consequently, with the exploitation of nanoprinciples, a controlled, precise, and target-oriented delivery of agrochemicals can be achieved. The employment of nanotools can tackle up the critical question of maintaining sustainable plant growth and plant protection. Apart from this, nanotechnology might potentially aid to offer more efficient methods for sensing, detecting, and remediation of environmental problems.

References

Abbas SS, Haneef M, Lohani M, Tabassum H, Khan AF (2016) Nanomaterials used as a plants growth enhancer: an update. Int J Pharm Sci Rev Res 5:17–23

Agrawal S, Rathore P (2014) Nanotechnology pros and cons to agriculture: a review. Int J Curr Microbiol Appl Sci 3:43–55

Amenta V, Aschberger K, Arena M, Bouwmeester H, Moniz FB, Brandhoff P, Gottardo S, Marvin HJP, Mech A, Pesudo LQ, Rauscher H, Schoonjans R, Vettori MV, Weigel S, Peters RJ (2015) Regulatory aspects of nanotechnology in the agri/feed/food sector in EU and non-EU countries. Regul Toxicol Pharmacol 73(1):463–476. https://doi.org/10.1016/j.yrtph.2015.06.016

Amin M (2018) Nanofiltration systems and applications in wastewater treatment: review article. Ain Shams Eng J 9:3077. https://doi.org/10.1016/j.asej.2018.08.001

Aouada FA, de Moura MR (2015) Nanotechnology applied in agriculture: controlled release of agrochemicals. In: Rai M, Ribeiro C, Mattoso L, Duran N (eds) Nanotechnologies in food and agriculture. Springer, Cham, pp 103–118. https://doi.org/10.1007/978-3-319-14024-7_5

Aziz N, Pandey R, Barman I, Prasad R (2016) Leveraging the attributes of *Mucor hiemalis*-derived silver nanoparticles for a synergistic broad-spectrum antimicrobial platform. Front Microbiol 7:1984. https://doi.org/10.3389/fmicb.2016.01984

Baker S, Volova T, Prudnikova SV, Satish S, Prasad MNN (2017) Nanoagroparticles emerging trends and future prospect in modern agriculture system. Environ Toxicol Pharmacol 53:10–17. https://doi.org/10.1016/j.etap.2017.04.012

Baligar VC, Fageria NK (2015) Nutrient use efficiency in plants: an overview. In: Rakshit A, Singh HB, Sen A (eds) Nutrient use efficiency: from basics to advances. Springer, New Delhi, pp 1–14. https://doi.org/10.1007/978-81-322-2169-2_1

Berekaa MM (2015) Nanotechnology in food industry; advances in food processing, packaging and food safety. Int J Curr Microbiol App Sci 4:345–357

Bhagat Y, Gangadhara K, Rabinal C, Chaudhari G, Ugale P (2015) Nanotechnology in agriculture: a review. J Pure App Microbiol 9:737–747

Camilli L, Pisani C, Gautron E, Scarselli M, Castrucci P, D'Orazio F et al (2014) A three-dimensional carbon nanotube network for water treatment. Nanotechnology 25:065701. https://doi.org/10.1088/0957-4484/25/6/065701

Chhipa H (2016) Nanofertilizers and nanopesticides for agriculture. Environ Chem Lett 15:15–22. https://doi.org/10.1007/s10311-016-0600-4

Coles D, Frewer LJ (2013) Nanotechnology applied to European food production – a review of ethical and regulatory issues. Trends Food Sci Technol 34(1):32–43. https://doi.org/10.1016/j.tifs.2013.08.006

Corsi I, Winther-Nielsen M, Sethi R, Punta C, Della Torre C, Libralato G, Lofrano G, Sabatini L, Aiello M, Fiordi L, Cinuzzi F, Caneschi A, Pellegrini D, Buttino I (2018) Ecofriendly nanotechnologies and nanomaterials for environmental applications: key issue and consensus recommendations for sustainable and ecosafe nanoremediation. Ecotoxicol Environ Saf 154:237–244. https://doi.org/10.1016/j.ecoenv.2018.02.037

Cox A, Venkatachalam P, Sahi S, Sharma N (2017) Reprint of: Silver and titanium dioxide nanoparticle toxicity in plants: a review of current research. Plant Physiol Biochem 110:33–49. https://doi.org/10.1016/j.plaphy.2016.08.007

Cushen M, Kerry J, Morris M, Cruz-Romero M, Cummins E (2012) Nanotechnologies in the food industry – recent developments, risks and regulation. Trends Food Sci Technol 24(1):30–46

Dahabieh MS, Bröring S, Maine E (2018) Overcoming barriers to innovation in food and agricultural biotechnology. Trends Food Sci Technol 79:204–213. https://doi.org/10.1016/j.tifs.2018.07.004

Das S, Wolfson BP, Tetard L, Tharkur J, Bazata J, Santra S (2015) Effect of N-acetyl cysteine coated CdS:Mn/ZnS quantum dots on seed germination and seedling growth of snow pea (*Pisum sativum* L.):imaging and spectroscopic studies. Environ Sci 2:203–212. https://doi.org/10.1039/c4en00198b

Dayarathne HNP, Jeong S, Jang A (2019) Chemical-free scale inhibition method for seawater reverse osmosis membrane process: air micro-nano bubbles. Desalination 461:1, 1–9

De Matteis V (2017) Exposure to inorganic nanoparticles: routes of entry, immune response, biodistribution and in vitro/in vivo toxicity evaluation. Toxics 5:29. https://doi.org/10.3390/toxics5040029

de Oliveira JL, Campos EVR, Bakshi M, Abhilashi PC, Fraceto LF (2014) Applications of nanotechnology for encapsulation of botanical insecticides for sustainable agriculture and promises. Biotechnol Adv 23:1550–1561

Di Sia P (2017) Nanotechnology among innovation, health and risks. Procedia Soc Behav Sci 237:1076–1080. https://doi.org/10.1016/j.sbspro.2017.02.158

Ditta A, Arshad M (2016) Applications and perspectives of using nanomaterials for sustainable plant nutrition. Nanotechnol Rev 5:1–22. https://doi.org/10.1515/ntrev-2015-0060

Dudo A, Choi D-H, Scheufele DA (2011) Food nanotechnology in the news. Coverage patterns and thematic emphases during the last decade. Appetite 56(1):78–89. https://doi.org/10.1016/j.appet.2010.11.143

Ezz El-Din H, Manjaiah DH (2017) Internet of nano things and industrial internet of things. In: Acharjya D, Geetha M (eds) Internet of things: novel advances and envisioned applications. Studies in big data. Springer, Cham, pp 109–123. https://doi.org/10.1007/978-3319-53472-5_5

Feregrino-Perez AA, Magaña-López E, Guzmán C, Esquivel K (2018) A general overview of the benefits and possible negative effects of the nanotechnology in horticulture. Sci Hortic 238:126–137

Fraceto LF, Grillo R, de Medeiros GA, Scognamiglio V, Rea G, Bartolucci C (2016) Nanotechnology in agriculture: which innovation potential does it have? Front Environ Sci 4:20. https://doi.org/10.3389/fenvs.2016.00020

Glenn JC, Florescu E (2016) Millennium project team. 2015-16 state of the future. J Socialomics 5:1–6. https://doi.org/10.4172/2167-0358.1000168

Hajirostamlo B, Mirsaeedghazi N, Arefnia M, Shariati MA, Fard EA (2015) The role of research and development in agriculture and its dependent concepts in agriculture [Short Review]. Asian J Appl Sci Eng 4. https://doi.org/10.1016/j.cocis.2008.01.005

Handford CE, Dean M, Spence M, Henchion M, Elliott CT, Campbell K (2015) Awareness and attitudes towards the emerging use of nanotechnology in the agri-food sector. Food Control 57:24–23

Hans KB, Jana T (2018) Micronutrients in the life cycle: requirements and sufficient supply. NFS J 11:1–11

He X, Deng H, H-min H (2019) The current application of nanotechnology in food and agriculture. J Food Drug Anal 27(1):1–21. https://doi.org/10.1016/j.jfda.2018.12.002

Jayaseelan C, Rahuman AA, Roopan SM, Kirthia AV, Kim S-K, Iyappan M, Siva C (2011) Synthesis of pediculocidal and larvicidal silver nanoparticles by leaf extract from heartleaf moonseed plant, *Tinospora cordifolia* Miers. Parasitol Res 109(1):185–194. https://doi.org/10.1007/s00436-010-2242-y

Justo-Hanani R, Dayan T (2015) European risk governance of nanotechnology: explaining the emerging regulatory policy. Res Policy 44(8):1527–1536. https://doi.org/10.1016/j.respol.2015.05.001

Karpachev VV, Spiridonov JJ, Voropaeva NL, Tkachev AG, Shachnev NV, Figovsky OL (2016) Pre-sowing seed treatment nanotechnology with environment-friendly nanotube-based nanochips. Int Lett Nat Sci 58:29–34

Khan R, Fulekar MH (2016) Biosynthesis of titanium dioxide nanoparticles using *Bacillus amyloliquefaciens* culture and enhancement of its photocatalytic activity for the degradation of a sulfonated textile dye Reactive Red 31. J Colloid Interface Sci 475:184. https://doi.org/10.1016/j.jcis.2016.05.001

Kouhkan M, Ahangar P, Babaganjeh LA, Allahyari-Devin M (2019) Biosynthesis of copper oxide nanoparticles using *Lactobacillus casei* subsp. casei and its anticancer and antibacterial activities. Curr Nanosci 16:101. https://doi.org/10.2174/1573413715666190318155801

Kumar S, Bhanjana G, Sharma A, Sarita MC, Sidhu Dilbaghi N (2015) Herbicide loaded carboxymethyl cellulose nanocapsules as potential carrier in agri nanotechnology. Sci Adv Mater 7:1143–1148

Kumar S, Nehra M, Dilbaghi N, Marrazza G, Hassan AA, Kim K-H (2019) Nano-based smart pesticide formulations: emerging opportunities for agriculture. J Control Release 294:131–153. https://doi.org/10.1016/j.jconrel.2018.12.012

Kundu M, Krishnan P, Kotnala RK, Sumana G (2019) Recent developments in biosensors to combat agricultural challenges and their future prospects. Trends Food Sci Technol 88:157–178

Liu R, Lal R (2015) Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. Sci Total Environ 514(Suppl C):131–139. https://doi.org/10.1016/j.scitotenv.2015.01.104

Mabe FN, Talabi K, Danso-Abbeam G (2017) Awareness of health implications of agrochemical use: effects on maize production in Ejura-Sekyedumase municipality, Ghana. Adv Agric 11:7960964. https://doi.org/10.1155/2017/7960964
Mani PK, Mondal S (2016) Agri-nanotechniques for plant availability. In: Kole C, Sakthi Kumar D, Khodakovskaya MV (eds) Plant nanotechnology. Principles and practices. Springer, Cham, pp 263–303. https://doi.org/10.1007/978-3-319-42154-4_11
Martinho VJPD (2018) Interrelationships between renewable energy and agricultural economics: an overview. Energ Strat Rev 22:396–409. https://doi.org/10.1016/j.esr.2018.11.002
Milewska-Hendel A, Gawecki R, Zubko M, Stróż D, Kurczynska E (2016) Diverse influence of nanoparticles on plant growth with a particular emphasis on crop plants. Acta Agrobot 69 (4):1694. https://doi.org/10.5586/aa.1694
Monreal CM, DeRosa M, Mallubhotla SC, Bindraban PS, Dimkpa C (2016) Nanotechnologies for increasing the crop use efficiency of fertilizer-micronutrients. Biol Fertil Soils 52:423–437. https://doi.org/10.1007/s00374-015-1073-5
Morales-Díaz AB, Ortega-Ortíz H, Juárez-Maldonado A, Cadenas-Pliego G, GonzálezMorales S, Adalberto Benavides-Mendoza A (2017) Application of nanoelements in plant nutrition and its impact in ecosystems. Adv Nat Sci 8:1–13. https://doi.org/10.1088/2043-6254/8/1/013001
Mufamadi MS, Sekhejane PR (2017) Nanomaterial-based biosensors in agriculture application and accessibility in rural smallholding farms: food security. In: Prasad R, Kumar M, Kumar V (eds) Nanotechnology. Springer, Singapore, pp 263–278. https://doi.org/10.1007/978-981-10-4573-8_12
Nasrollahzadeh M, Sajadi SM, Sajjadi M, Issaabadi Z (2019) Applications of nanotechnology in daily life. Interface Sci Technol 28:113–143
Nima AZ, Lahiani MH, Watanabe FXY, Khodakovskaya MV, Biris AS (2014) Plasmonically active nanorods for delivery of bio-active agents and high-sensitivity SERS detection in planta. RSC Adv 4:64985–64993. https://doi.org/10.1039/C4RA10358K
Nuruzzaman M, Rahman MM, Liu Y, Naidu R (2016) Nanoencapsulation, nano-guard for pesticides: a new window for safe application. J Agric Food Chem 64:1447–1483. https://doi.org/10.1021/acs.jafc.5b05214
Ozdemir M, Kemerli T (2016) Innovative applications of micro and nanoencapsulation in food packaging. In: Lakkis JM (ed) Encapsulation and controlled release technologies in food systems. Wiley, Chichester
Pandey G (2018a) Challenges and future prospects of agri-nanotechnology for sustainable agriculture in India. Environ Technol Innov 11:299–307
Pandey G (2018b) Nanotechnology for achieving green-economy through sustainable energy. Rasayan J Chem 11(3):942–950
Pandey G (2018c) Prospects of nanobioremediation in environmental cleanup. Orient J Chem 34 (6):2838–2850. https://doi.org/10.13005/ojc/340622
Parisi C, Vigani M, Rodríguez-Cerezo E (2015) Agricultural nanotechnologies: what are the current possibilities? Nano Today 10:124–127
Patra JK, Baek K-H (2017) Antibacterial activity and synergistic antibacterial potential of biosynthesized silver nanoparticles against foodborne pathogenic bacteria along with its anticandidal and antioxidant effects. Front Microbiol 8:167. https://doi.org/10.3389/fmicb.2017.00167
Prasad R, Pandey R, Barman I (2016) Engineering tailored nanoparticles with microbes: quo vadis. WIREs Nanomed Nanobiotechnol 8:316–330. https://doi.org/10.1002/wnan.1363
Prasad R, Bhattacharyya A, Nguyen QD (2017) Nanotechnology in sustainable agriculture: recent developments, challenges, and perspectives. Front Microbiol 8:1014. https://doi.org/10.3389/fmicb.2017.01014
Quist-Jensen CA, Macedonio F, Drioli E (2015) Membrane technology for water production in agriculture: desalination and wastewater reuse. Desalination 364:17–32. https://doi.org/10.1016/j.desal.2015.03.001

Radad K, Al-Shraim M, Moldzio R, Rausch W-D (2012) Recent advances in benefits and hazards of engineered nanoparticles. Environ Toxicol Pharmacol 34(3):661–672. https://doi.org/10.1016/j.etap.2012.07.011

Rai PK, Kumar V, Lee SS, Raza N, Kim K-H, Ok YS, Tsang DCW (2018) Nanoparticle-plant interaction: implications in energy, environment, and agriculture. Environ Int 119:1–19. https://doi.org/10.1016/j.envint.2018.06.012

Raliya R, Tarafdar JC (2014) Biosynthesis and characterization of zinc, magnesium and titanium nanoparticles: an eco-friendly approach. Int Nano Lett 4:1. https://doi.org/10.1007/s40089-014-0093-8

Rienzie R, Ramanayaka S, Adassooriya NM (2019) Nanotechnology applications for the removal of environmental contaminants from pharmaceuticals and personal care products. In: Pharmaceuticals and personal care products: waste management and treatment technology, pp 279–296

Rossi M, Cubadda F, Dini L, Terranova ML, Aureli F, Sorbo A, Passeri D (2014) Scientific basis of nanotechnology, implications for the food sector and future trends. Trends Food Sci Technol 40:127–148

Saharan V, Mehrotra A, Khatik R, Rawal P, Sharma SS, Pal A (2013) Synthesis of chitosan based nanoparticles and their in vitro evaluation against phytopathogenic fungi. Int J Biol Macromol 62:677–683. https://doi.org/10.1016/j.ijbiomac.2013.10.012

Sayre PG, Steinhäuser KG, Teunenbroe T-V (2017) Methods and data for regulatory risk assessment of nanomaterials: questions for an expert consultation. Nano Impact 8:20–27. https://doi.org/10.1016/j.impact.2017.07.001

Schmid O, Stoeger T (2016) Surface area is the biologically most effective dose metric for acute nanoparticle toxicity in the lung. J Aerosol Sci 9:133–114

Sekhon BS (2014) Nanotechnology in agri-food production: an overview. Nanotechnol Sci Appl 7:31–53. https://doi.org/10.2147/NSA.S39406

Sertova NM (2015) Application of nanotechnology in detection of mycotoxins and in agricultural sector. J Cent Eur Agric 16:117–130. https://doi.org/10.5513/JCEA01/16.2.1597

Shweta TDK, Singh S, Singh S, Dubey NK, Chauhan DK (2016) Impact of nanoparticles on photosynthesis: challenges and opportunities. Mater Focus 5:405–411. https://doi.org/10.1166/mat.2016.1327

Siddiqui MH, Al-Whaibi MH, Firoz M, Al-Khaishany MY (2015) Role of nanoparticles in plants. In: Siddiqui MH, Al-Whaibi MH, Mohammad F (eds) Nanotechnology and plant sciences: nanoparticles and their impact on plants. Springer, Cham, pp 19–35. https://doi.org/10.1007/978-3-319-14502-0_2

Singh R, Glick BR, Rathore D (2018) Biosurfactants as a biological tool to increase micronutrient availability in soil: a review. Pedosphere 28(2):170–189

Sozer N, Kokini JL (2009) Nanotechnology and its applications in the food sector. Trends Biotechnol 27(2):82–89. https://doi.org/10.1016/j.tibtech.2008.10.010

Steinhäuser KG, Sayre PG (2017) Reliability of methods and data for regulatory assessment of nanomaterial risks. Nano Impact 7:66–74. https://doi.org/10.1016/j.impact.2017.06.001

Subramanyam SG, Siva K (2016) Bio-synthesis, characterization and application of titanium oxide nanoparticles by *Fusarium oxysporum*. Int J Life Sci Res 4:69–75

Sun-Waterhouse D, Waterhouse GIN (2016) Recent advances in the application of nanomaterials and nanotechnology in food research. In: Grumezescu A (ed) Novel approaches of nanotechnology in food. Elsevier, London, pp 21–66

Tarafdar A, Raliya R, Wang W-N, Biswas P, Tarafdar JC (2013) Green synthesis of TiO_2 nanoparticle using *Aspergillus tubingensis*. J Adv Sci Eng Med 5:943–949

Wakeil NE, Alkahtani S, Gaafar N (2017) Is nanotechnology a promising field for insect pest control in IPM programs? In: Grumezescu A (ed) New pesticides and soil sensors. Academic, London, pp 273–309

Wang L, Hu C, Shao L (2017) The antimicrobial activity of nanoparticles: present situation and prospects for the future. Int J Nanomed 12:1227–1249. https://doi.org/10.2147/IJN.S121956

Wang P, F-Jie Z, Kopittke PM (2019) Engineering crops without genome integration using nanotechnology. Trends Plant Sci 24(7):574–577. https://doi.org/10.1016/j.tplants.2019.05.004

Yan L, George C, Xiuli Y, Huining D (2019) Preparation of layer-by-layer nanofiltration membranes by dynamic deposition and crosslinking. Membranes 9:20. https://doi.org/10.3390/membranes9020020

Yang Y, Qin Z, Zeng W, Yang T, Cao Y, Me C, Kuang Y (2017) Toxicity assessment of nanoparticles in various systems and organs. Nanotechnol Rev 6(3):279–228

Zhang Q, Han L, Jing H, Blom DA, Lin Y, Xin HL, Wang H (2016) Facet control of gold nanorods. ACS Nano 10:2960–2974. https://doi.org/10.1021/acsnano.6b00258