NANOTECHNOLOGY IN PLANT GROWTH PROMOTION AND PROTECTION

RECENT ADVANCES AND IMPACTS

EDITED BY **AVINASH P. INGLE**

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Nanotechnology in Plant Growth Promotion and Protection

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Recent Advances and Impacts

Edited by

Avinash P. Ingle

Biotechnology Centre
Department of Agricultural Botany
Dr. Panjabrao Deshmukh Agricultural University
Akola, Maharashtra
India

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Contents

List of Contributors

Bilal Haider Abbasi
Department of Biotechnology
Quaid-i-Azam University
Islamabad
Pakistan

Heba Mahmoud Mohammad Abdel-Aziz
Botany Department
Faculty of Science
Mansoura University
Mansoura
Egypt

Nadeesh Adassooriya
Department of Chemical and Process Engineering
Faculty of Engineering
University of Peradeniya
Peradeniya
Sri Lanka

Sumaira Anjum
Department to Biotechnology
Kinnaird College for Women
Lahore
Pakistan

Tatiana Bauer
Federal Research Center the Southern Scientific Center of the Russian Academy of Sciences
Rostov-on-Don
Russia

Adalberto Benavides-Mendoza
Department of Horticulture
Autonomous Agricultural University Antonio Narro
Saltillo
Mexico

Rahul Bhagat
Department of Biotechnology
Government Institute of Science
Aurangabad
Maharashtra
India

Hao Chen
Department of Agriculture
University of Arkansas
Pine Bluff
AR
USA

Svetlana Deneva
Institute of Biology of Komi Scientific Centre of the Ural Branch of the Russian Academy of Sciences
Nalchik
Russia

Pavel Diviš
Faculty of Chemistry
Brno University of Technology
Brno
Czech Republic

Laura Olivia Fuentes-Lara
Department of Animal Nutrition
Autonomous Agricultural University
Antonio Narro
Saltillo
Mexico

Nobuhide Fujitake
Graduate School of Agricultural Sciences
Kobe University
Kobe
Japan

Olga Gorobtsova
Institute of Mountain Ecology of Russian
Academy of Science
Nalchik
Russia

Yolanda González-García
Department of Horticulture
Autonomous Agrarian University
Antonio Narro
Saltillo
Mexico

Magín González-Moscoso
PhD Program in Protected Agriculture
Autonomous Agricultural University
Antonio Narro
Saltillo
Mexico

Indarchand Gupta
Department of Biotechnology
Government Institute of Science
Aurangabad
Maharashtra
India

Christophe Hano
Laboratoire de Biologie des Ligneux et
des Grandes Cultures (LBLGC)
INRA USC1328
Université d'Orléans
France

Mohammed Nagib Abdel-ghany Hasaneen
Botany Department
Faculty of Science
Mansoura University
Mansoura
Egypt

Hipólito Hernández-Hernández
Institute of Agro-engineering
Papaloapan University
Oaxaca
Mexico

Avinash P. Ingle
Biotechnology Centre
Department of Agricultural Botany
Dr. Panjabrao Deshmukh Agricultural
University
Akola
Maharashtra
India

Antonio Juárez-Maldonado
Departament of Botany
Autonomous Agrarian University
Antonio Narro
Saltillo
Mexico

Marek Kolenčík
Nanotechnology Centre
VŠB Technical University of Ostrava
Ostrava
Czech Republic
Department of Soil Science and Geology
Faculty of Agrobiology and Food Resources
Slovak University of Agriculture in Nitra
Nitra
Slovakia

Amna Komal
Department to Biotechnology
Kinnaird College for Women
Lahore
Pakistan

Pradeep Kumar
Department of Forestry
North Eastern Regional Institute of Science and Technology
Nirjuli, Arunachal Pradesh
India

A. Lakshmanan
Department of Nano Science & Technology
Tamil Nadu Agricultural University
Coimbatore
Tamil Nadu
India

Alonso Méndez-López
Departament of Botany
Autonomous Agrarian University
Antonio Narro
Saltillo
Mexico

Tatiana M. Minkina
Southern Federal University
Rostov-on-Don
Russia

Dámaris Leopoldina Ojeda-Barrios
Laboratory of Plant Physiology
Autonomous University of Chihuahua
Chihuahua
Mexico

Harris Panakkal
Department of Biotechnology
Government Institute of Science
Aurangabad
Maharashtra
India

C. Sharmila Rahale
Department of Nano Science & Technology
Tamil Nadu Agricultural University
Coimbatore
Tamil Nadu
India

Vishnu D. Rajput
Southern Federal University
Rostov-on-Don
Russia

Illa Ramakanth
Department of Chemistry
Rajiv Gandhi University of Knowledge Technologies
Nuzvid
India

Ryan Rienzie
Agribusiness Centre
Faculty of Agriculture
University of Peradeniya
Peradeniya
Sri Lanka

Martin Šebesta
Institute of Laboratory Research on Geomaterials
Faculty of Natural Sciences
Comenius University in Bratislava
Bratislava
Slovakia

Martin Šeda
Department of Applied Chemistry
Faculty of Agriculture
University of South Bohemia
České Budějovice
Czech Republic

Anna Sindireva
University of Tyumen
Tyumen
Russia

Abhishek Singh
Sardar Vallabhbhai Patel University of Agriculture and Technology
Meerut
Uttar Pradesh
India

Garima Shandilya
Nanotechnology Unit
Department of Mechanical Engineering
Bharati Vidyapeeth Deemed University
College of Engineering
Pune
Maharashtra
India

Sudhir S. Shende
Southern Federal University
Rostov-on-Don
Russia

Sant Gadge Baba Amravati University
Amravati
Maharashtra
India

Tahsin Shoala
Environmental Biotechnology
Department
College of Biotechnology
Misr University for Science and
Technology
6th of October City
Egypt

K. S. Subramanian
Department of Nano Science & Technology
Tamil Nadu Agricultural University
Coimbatore
Tamil Nadu
India

Anita Tanwar
Department of Chemistry
GDC Memorial College
Bahal
Haryana
India

Kirtan Tarwadi
Nanotechnology Unit
Department of Mechanical Engineering
Bharati Vidyapeeth Deemed University
College of Engineering
Pune
Maharashtra
India

Anil Timilsina
Department of Agriculture
University of Arkansas
Pine Bluff, AR
USA

Martin Urík
Institute of Laboratory Research on
Geomaterials
Faculty of Natural Sciences
Comenius University in Bratislava
Bratislava
Slovakia

Krishan K. Verma
Sugarcane Research Institute
Chinese Academy of Agricultural Sciences
and Guangxi
Academy of Agricultural Sciences
Nanning
Guangxi
China

Ondřej Zvěřina
Department of Public Health
Faculty of Medicine
Masaryk University
Brno
Czech Republic

Preface

Agriculture is the backbone of several developing countries because their economy is directly relying on agriculture; moreover, developed countries are also depending on agriculture for their food. However, a continuous increase in the worldwide population and currently available agricultural practices has led to major global concerns such as production and supply of good quality food, and food security. To date, various advancements have been made in agriculture through the discovery of effective agrochemicals and other farming technologies. Despite all these developments, agriculture is still facing several severe challenges like crop loss due to plant pathogens, soil fertility issues due to extensive use of synthetic agrochemicals, soil pollution, imbalance of beneficial microflora, resistance in microbial pathogens, etc. Unfortunately, the extensive use of synthetic agrochemicals like pesticides, fungicides, and fertilizers, are mostly responsible for all these problems. Therefore, it is need of the hour to develop effective farming technologies in addition to the development of potent, economically viable, and eco-friendly products that can sustainably manage the plant pathogens and enhances crop production.

In this context, nanotechnology can be used as the most innovative solution for such issues and has the great potential to rapidly take forward the agriculture and allied sectors with the help of modern tools. The nanomaterials can be effectively used in the development of various nano-based products like nanoantimicrobials and nanofertilizers. Moreover, various nanoparticles can also be used as nanoscale carriers for the delivery of agrochemicals and other nutrition. Besides, modern nano-based tools can be promisingly used in precision farming for the detection of plant pathogens, nutrient deficiencies, etc. The use of above-mentioned nano-based products helps to enhance plant growth, protect plants through the management of plant pathogens, and also reduces soil pollution. Considering these facts, the editor attempted to discuss the recent advances and role of nanotechnology in plant growth promotion and protection through this book.

In this book there are total 15 chapters, which are broadly focused on the recent advances and the role of nanotechnology in plant growth promotion and protection. Chapter 1 is mainly focused on effective application of nanotechnology in agriculture, particularly, in plant growth promotion and control of plant diseases through the management of plant pathogens. Chapter 2 is about the application of titanium-based nanomaterials such as titanium dioxide nanoparticles in plant growth. In this chapter, various aspects like the interaction of nanoparticles with plants and their pathways and the effects of different concentrations of titanium dioxide nanoparticles on plant growth have been discussed.

In Chapter 3, authors reviewed the role of different zinc-based nanoparticles in plant growth promotion and protection. The focus has been given on the effects of nanoparticles when used through different modes of application like foliar application, soil, and hydroponic application. Chapter 4 specifically focused on the application of nanomaterials in the form of nanofertilizers as an effective alternative to chemical fertilizers. Further, uptake, translocation, and fate of nanofertilizers in plants have been also elaborated. Chapter 5 discusses the role of nanobiotechnology in sustainable agriculture through the applications of various nanomaterials in plant nutrition and protection. In Chapter 6, the authors discussed how nanotechnology can be useful in enhancing the immunity of plants through its application in seed and soil. Chapter 7 is focused on the effects of natural organic matter on the bioavailability of elements from inorganic nanomaterials. Particularly, the emphasis has been given on the effects of organic matter on different properties of nanoparticles such as aggregation and agglomeration, dissolution, and bioavailability. Chapter 8 emphasizes on different biotic and abiotic stresses in plants and the induction of tolerance against such stresses in crops after application of nanomaterials. In Chapter 9, the authors reviewed the role of different nanoparticles as elicitors of biologically active ingredients in plants. Moreover, various other aspects like routes of exposure, uptake, and interaction of nanoparticles into plant cells, elicitation of different bioactive molecules like polyphenols, alkaloids, and terpenoids, essential oils have been thoroughly explained. Chapter 10 is dedicated to the use of various nanoparticles in plant growth promotion and the management of a variety of plant pathogens. Besides, the influence of nanoparticles on plant photosynthesis, enhancement of root and shoot growth, phytopathogen suppression, etc. has been briefly discussed. Chapter 11 focused on the application of metal-based nanoparticles in plant protection. In this chapter, the authors discussed role of different metal-based nanoparticles like silver, copper, zinc, titanium, and magnesium in plant protection. Apart from this, various possible antimicrobial mechanisms for metal-based nanoparticles have been also briefly elaborated. Chapter 12 is dedicated on the role of zinc-based nanoparticles in the management of plant diseases. Chapter 13 emphasizes on effects of different metal oxide nanoparticles on plant growth. In this chapter, authors presented the positive and negative effects of different metal oxide nanoparticles in a variety of plants. Chapter 14 is focused on the most important and relevant aspects, i.e. biostimulation and toxicity of nanomaterials in plants. This chapter explained how nanoparticles can stimulate the biological response and toxicity in plants. However, final Chapter 15 is completely dedicated to toxicological concerns of nanomaterials in agriculture. Moreover, special emphasis has been given on various important aspects like uptake and translocation of nanomaterials in plants, various factors affecting the uptake and translocation of nanomaterials, etc. In addition, how nanomaterials affect the defense mechanisms of plants and generate phytotoxicity has been also discussed.

Overall, this book covers very informative chapters written by one or more specialists, experts in the concerned topic. Hence, I would like to offer a very rich guide for researchers in this field, undergraduate or graduate students of various disciplines like agriculture, biotechnology, and nanotechnology and allied subjects. In addition, this book is useful for people working in various agriculture and food-based industries, regulatory bodies, and agriculture-related organizations.

I would like to thank all the authors for their outstanding efforts to provide state-of-the-art information on the subject matter of their respective chapters. Their efforts will

definitely enhance and update the knowledge of the readers about the role of nanotechnology in agriculture particularly, in plant growth promotion and protection. I also thank everyone in the Wiley team for their constant help and constructive suggestions particularly to Rebecca (Senior Editor), Kerry, Nivetha and other team members. I am highly thankful to Science and Engineering Research Board (SERB), Department of Science and Technology, Government of India, New Delhi for providing financial assistance in the form of "Ramanujan Fellowship".

I hope that the book will be useful for all the readers to find the relevant information on the latest research and advances in effective use of nanotechnology in agriculture.

Avinash P. Ingle

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Nanotechnology as a Smart Way to Promote the Growth of Plants and Control Plant Diseases: Prospects and Impacts

Heba Mahmoud Mohammad Abdel-Aziz and Mohammed Nagib Abdel-ghany Hasaneen

Botany Department, Faculty of Science, Mansoura University, Mansoura, Egypt

1.1 Introduction

Nanotechnology is a modern and creative science which involves the designing, manipulation, and use of nanoscale materials (Ali et al. 2014; Agrahari and Dubey 2020). The term "nano" is a Greek word which actually means "dwarf," and when it is used to describe materials, it is supposed to have at least one dimension of 100 nm or less. Today, nanotechnology has entered in every aspect of day to day life (Zulfiqar et al. 2019). In medicine, nanotechnology has made breakthrough improvements as a means of smart drug delivery systems and many other applications. When it comes to agriculture field, research is still under way to discover the applications of nanomaterials to improve plant growth and control plant diseases (Ali et al. 2014; Zulfiqar et al. 2019; Agrahari and Dubey 2020).

Nanomaterials or nanoparticles can be manufactured using different ways, such as top-down and bottom-up approach. The production of nanomaterials through top-down approach involves the breaking down of bulk materials into nanosized structures or particles. The disadvantage of this method is low control on the size of nanoparticles and a greater amount of impurities. On the contrary, bottom-up approach of nanoparticles synthesis involves building up of a material from the bottom, i.e. atom-by-atom, molecule-by-molecule, or cluster-by-cluster. It is usually a chemically controlled synthesis process, so this method has better control on particle size and also reduces impurities. In addition, nanoparticles can be biologically manufactured which is also called as biomanufacturing method. Different biological systems such as plants, fungi, and bacteria can be used for this purpose. The advantage of this method is the greater control over the toxicity and size of the particle (Heikal and Abdel-Aziz 2020). The global population is rapidly increasing and is supposed to reach 9.6 billion by 2050 leading to many concerns (Zhang et al. 2015). The major problem will be how to provide food to such growing mass population (Zulfiqar et al. 2019). On the one hand, concerns related to soil fertility are getting worse year after year and the development of urban activities continuously decreasing the cultivated areas.

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On the other hand, problems related to plant pathogens and their control are also major issues in current scenario (Chhipa 2017). Therefore, question arises that how to produce more food when there are less cultivated lands and nonfertile soils? One of the recent approaches proposed by scientists all over the world is the introduction of nanotechnology in agriculture to solve these problems. The introduction of nanotechnology to agriculture may provide solutions to improve plant growth through the applications of various nano-based agrochemicals such as nanofertilizers, nanoherbicides, and nanoantimicrobials. In addition, utilization of smart Nanodevices like nanosensors can also help in the detection of pathogens and heavy metals in soil. Thus, nanotechnology converted conventional farming into precision farming (Raliya et al. 2018).

Different nanoformulations like nanofertilizers composed of either macronutrients or micronutrients have been tested in many research works. Some studies showed positive effects on growth and productivity of tested plants and some showed negative impacts especially when used in higher concentrations. Considering these facts, the present chapter is focused on detail review of all such studies. The use of nanotechnology in the management of plant diseases showed promising results having significant impacts on different plant pathogens such as insects, bacteria, fungi, or even viruses. Like every new technology, nanotechnology also has its merits and demerits. The concerns of the use of nanotechnology in agriculture arise from toxicity issues, and their hazardous effects to human health and environment are also discussed in this chapter.

1.2 Nanofertilizers

Nanofertilizers being used in agriculture to increase the efficiency of nutrient uptake by plants. The term nanofertilizer means any nanomaterials which has potential to enhance the nutrient uptake in plants. They can be nanoforms of different fertilizers like nitrogen (N), phosphorus (P), and potassium (K) with other macro- or micronutrients (Singh et al. 2017; Bajpai et al. 2020). There are three proposed types of nanofertilizers: (1) nanofertilizers (nanoparticles of fertilizers), (2) nanocoatings (traditional fertilizers being loaded on nanoparticles), and (3) nanoadditives (traditional fertilizers with additives in the nano form) (Naderi and Danesh-Shahraki 2013).

1.2.1 Methods for Application of Nanofertilizers

Nanofertilizers can be applied by three different methods discussed below:

1.2.1.1 Seed Priming

In this method, seeds are soaked in an emulsion containing nanoparticles before being put in soil. This method was found to be best suited for dormant seeds (Abdel-Aziz et al. 2019).

1.2.1.2 In Soil

Incorporation of nanofertilizers in soil can be done in two ways: either by mixing solid nanoparticles with soil before cultivation or through addition of nanofertilizers to irrigation water and being given to the plant at times of irrigation (Hasaneen et al. 2016).

1.2.1.3 Foliar Application

Nanoemulsions of nanofertilizers are being used as sprays to foliar products of plants either in seedling or early vegetative stages (Abdel-Aziz et al. 2019).

From several studies, it was suggested that foliar application is the best method to apply nanofertilizers to plants. Seed priming with nanofertilizers could be toxic to embryo cells of seeds and therefore seeds abort to germinate. On the other hand, soil incorporation of nanofertilizers fails to give the desired target because of the presence of soil microflora which could easily degrade and decompose the tiny nanofertilizers in soil (Abdel-Aziz et al. 2019).

1.2.2 Possible Ways for Uptake and Translocation of Nanofertilizers in Plants

When nanofertilizers are introduced in soil, they are supposed to come in contact with root hairs and get absorbed by them. Further, thus absorbed nanofertilizer is expected to reach root epidermal tissues and then move deep to reach xylem vessels, followed by their transport to every part of the plant (Tripathi et al. 2017). When nanofertilizers are applied through foliar spray, they are supposed to come in contact with stomatal openings and tiny pores in the epidermal tissue. From where they enter and move deep into the leaves tissue to reach to the phloem tissue. Then, from the phloem they are being translocated to every part of the plant (Abdel-Aziz et al. 2016, 2019).

1.2.3 Macronutrient Nanofertilizers

Macronutrient nanofertilizers are fertilizers which provide the nutrients that the plant needs in large amounts such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) (Ditta and Arshad 2016; Zulfiqar et al. 2019). It is proposed that the need to apply macronutrient fertilizers will increase by the year 2050, and it may reach to 265 million tons (Chhipa 2017; Adisa et al. 2019). The high ability of penetration and the high surface area of nanoparticles make them more efficient to release the nutrients in controlled manner compared to traditional fertilizers. Considering these facts, nanofertilizers with potential of slow or controlled release of nutrients being developed from macronutrients. For example, nitrogen slow release nanofertilizer was developed from urea-modified hydroxyapatite by Kottegoda et al. (2017) and evaluated their efficacy. The results obtained showed that initially nitrogen release from the developed nanofertilizer (urea-hydroxyapatite nanocomposite) is rapid; however, later its slow release was continued till the 60th day from its application. This application of nitrogen nanofertilizer reported to increase rice yield even at 50% lower concentrations than traditional urea fertilizer (Kottegoda et al. 2017).

Liu and Lal (2015) synthesized a phosphorus (P) nanofertilizer of 16 nm particles using carboxymethyl cellulose-stabilized hydroxyapatite nanoparticles and studied its effect on soybean growth. They applied the developed P nanofertilizer in soil in a greenhouse experiment and found that growth was increased by 33% and yield by 18% as compared with soybean treated with traditional P fertilizer. Mechanically, the hydroxyapatite nanoparticles have low interaction with soil particles than ionic P thus making uptake of P nanofertilizer easier than traditional P fertilizer. However, further studies are required to test the availability of P nanofertilizer under different soil types, pH, ionic states, organic carbon, and water content (Raliya et al. 2018). In another study, a biosafe P nanofertilizer was developed as a nano water phosphorite suspension (particle size: 60–120 nm) and tested on corn in greenhouse, field, and farm level. The results obtained showed that fresh yield, fruit yield, and production quality of corn plants increased several folds with the use of this P nanofertilizer as compared to traditional P fertilizer (Sharonova et al. 2015).

Hasaneen et al. (2016) and Abdel-Aziz et al. (2019) used two types of NPK nanofertilizers: nanochitosan loaded with NPK and carbon nanotubes (CNTs) loaded with NPK for fertilization of French bean plants in greenhouse conditions. They used three different methods of application of nanofertilizers, i.e. seed priming, soil incorporation, and foliar application. The results obtained revealed that, foliar application was the best method of application for both the nanofertilizers. For foliar application treatment, the life cycle of the plant was shortened by 37.5% (80 days) as compared with other nano treatments or nontreated plants (110 days). Also, nanochitosan-NPK showed better improvement in the crop plants than CNTs-NPK (Hasaneen et al. 2016; Abdel-Aziz et al. 2019). Abdel-Aziz et al. (2016) reported that foliar application of nanochitosan loaded with NPK (10–100%) to wheat plants grown in sandy soil in greenhouse conditions improved the crop productivity and shortened the lifecycle of the plant by 40 days as compared with traditional NPK fertilizers. The lowest concentration of NPK nanofertilizer (10%) recorded to have best effects on wheat growth and productivity. This study lacks comparison of the results of nanochitosan-NPK with pure nanochitosan. The nanochitosan used in these studies was produced by polymerization of methacrylic acid with chitosan.

Similarly, Ha et al. (2019) produced nanochitosan from ionic gelation of chitosan with tripolyphosphate and then loaded NPK on nanochitosan particles. They applied the nanochitosan-NPK fertilizer to the leaves of coffee plants in greenhouse conditions. It was observed that application of this developed nanofertilizer enhanced the rate of photosynthesis, increased the rate of uptake of nutrients and growth of coffee plants as compared with untreated plants. The results obtained from the above-mentioned studies were reported in greenhouse conditions, and field trials are important to validate the approach of using NPK nanofertilizers.

In groundnut, foliar application of nanocalcium oxide (CaO) fertilizer reported to increase Ca accumulation and root development in plants as compared with normal CaO and calcium nitrate ($CaNO_3$) (Deepa et al. 2015). This study showed that CaO nanoparticles were transported through phloem, but the mechanism of its action is still not known. In another study, Mg nanoparticles (500 mg/L) in combination with normal Fe (500 mg/L) were used to treat black-eyed pea (*Vigna unguiculate*) and showed an increase in seed mass (10%) as compared with plants treated with normal Fe (Delfani et al. 2014). Nano-S was also shown to enhance root and shoot growth of tomato and pumpkin plants as compared with untreated plants (Salem et al. 2016a,b). Both these studies showed that the effect of nano-S was concentration-dependent and higher concentrations caused deleterious effects on the growth of both plants. This suggested that further studies are needed to adjust the suitable concentrations of applied nano-S.

1.2.4 Micronutrient Nanofertilizers

Micronutrient nanofertilizers are those fertilizers which provide micronutrients to the plants (the elements which are needed in small amounts by the plant but are essential for plant growth and metabolism) (Adisa et al. 2019; Zulfiqar et al. 2019). The most important micronutrients are zinc (Zn), boron (B), iron (Fe), manganese (Mn), and copper (Cu). It was reported that cucumber seedlings grown in nutrient solution containing Zn nanoparticles (synthesized from waste tire rubber) showed an increase in shoot and fruit yield as compared with other cucumber seedlings grown in commercial zinc sulphate ($ZnSO_4$) solution (Moghaddasi et al. 2013). Adhikari et al. (2015) reported that maize plants treated with zinc oxide (ZnO) nanoparticles showed increased shoot dry weight and shoot height as compared with untreated plants. Also, Subbaiah et al. (2016) applied ZnO nanoparticles (particle size: 25 nm) as foliar spray on maize which resulted in enhancement of maize growth, yield, and Zn content in the produced grains as compared with maize plants treated with normal $ZnSO_4$. Application of Zn nanofertilizer in pearl millet (*Pennisetum americanum*) caused significant increase in shoot and root growth, increase in chlorophyll content and leaf protein. Moreover, enhanced crop production as compared with control plants over a period of six weeks was also recorded (Tarafdar et al. 2014). Foliar application of micronutrient nanofertilizers of Zn or B to pomegranate trees resulted in an increase in fruit yield (30%). The magnitude of increase was most pronounced with low concentrations of nanofertilizers (34 mg/ tree for B and 636 mg/ tree for Zn) (Davarpanah et al. 2016). Dimkpa et al. (2017a) showed that micronutrient nanocomposites (ZnO, B_2O_3, and CuO, at 2.8 mg Zn/kg soil, 0.6 mg B/kg soil and 1.3 mg Cu/kg soil, respectively) when applied to soybean plants under drought stress improved the growth and yield of treated plants as compared with untreated plants.

There are few studies performed demonstrating the foliar spray application of iron oxide nanoparticles, results recorded easy uptake of these nanoparticles and improved growth in different plants such as corn (Li et al. 2016), pumpkin (Zhu et al. 2008), and watermelon (Li et al. 2013; Wang et al. 2013). In addition, some of other studies on the use of iron oxide nanoparticles on crops plants such as wheat (Ghafari and Razmjoo 2013), lettuce (Zahra et al. 2015), soybeans (Alidoust and Isoda 2013; Ghafariyan et al. 2013), clover (Feng et al. 2013), peanut (Rui et al. 2016), rice (Alidoust and Isoda 2014), and *Citrus maxima* (Hu et al. 2017) showed that Fe nanofertilizer improved several traits of these plants including increased biomass, grain yield, Fe fortification, and improved biochemical parameters such as nutrients uptake, chlorophyll content, and photosynthesis (Raliya et al. 2018). But it should be mentioned that the effect of Fe nanoparticles was relatively concentration-dependent which implies the need for future studies to adjust the suitable concentrations of Fe nanoparticles and further application to a variety of crops (Zulfiqar et al. 2019).

Foliar application of Mn nanoparticles (0.05 mg/L) to mung bean (*Vigna radiata*) resulted in improvement of root growth, shoot growth, and biomass as compared to plants treated with $MnSO_4$ (Pradhan et al. 2013). In another study, Dimkpa et al. (2018) showed that application of Mn nanoparticles (6 mg/Kg) did not affect wheat grain yield but enhanced nutrient uptake by the plant. Adhikari et al. (2016) showed that exposure of maize plants to CuO nanoparticles (10 mg/L) resulted in significant increase in growth as compared with untreated plants. Nanocomposites of CuO, ZnO, and B_2O_3 caused significant increase in the uptake of N, K, Zn, and B in soybean as compared with untreated plants under drought stress (Dimkpa et al. 2017a). Dimkpa et al. (2017a,b, 2019) revealed that root or foliar exposure of soybean or sorghum to the nanocomposites of Cu, Zn, and B or to Zn nanoparticles increase N and K accumulation. These findings indicate the possible role of using nanomicronutrients in fortifying accumulation of macronutrients in plants to achieve better nutrient use efficiency (Adisa et al. 2019).

1.2.5 Non-nutrient Nanofertilizers

There are other nanoparticles which are not classified as plant nutrients but potentially have positive impact on plants. These nanoparticles mainly include CNTs, chitosan (Cs), cerium(IV) oxide (CeO_2), silicon dioxide (SiO_2), and titanium dioxide (TiO_2). Although they are not of nutritional need to the plant, but they can improve growth and yield (Adisa et al. 2019). CNTs were found to increase shoot length of date palm (*Phoenix dactylifera*) at 0.05–0.1 mg/L (Taha et al. 2016) and promote growth of tobacco plants at 5–500 mg/L (Khodakovskaya et al. 2012). Studies have showed that Cs nanoparticles improve seed germination, enhance plant growth, increase photosynthesis, and improve crop yield (Adisa et al. 2019). Van et al. (2013) treated Robusta coffee plants with nanochitosan under greenhouse conditions which resulted in increased chlorophyll content and photosynthetic rate as well as increased nutrient accumulation as compared with untreated plants. Cu-chitosan nanoparticles increased seedling growth, fresh, and dry mass of tomato plants as compared with untreated plants (Saharan et al. 2015). Pretreatment of maize seeds with Cu-chitosan nanoparticles improved seed germination and growth parameters as compared with untreated control (Saharan et al. 2016).

In a similar manner, CeO_2 nanoparticles reported to increase shoot biomass, growth, and grain yield of wheat plants relative to untreated plants (Rico et al. 2014). A similar finding was recorded for shoots of barley with CeO_2 nanoparticles (Rico et al. 2015). Foliar application of SiO_2 to cucumber (*Cucumis sativus*) resulted in increased plant height, biomass, growth and yield as compared with untreated control (Yassen et al. 2017). Application of SiO_2 to strawberry (*Fragaria × ananassa*) increased macronutrients and micronutrients uptake (K, Ca, Mg, Fe, Mn, and Si) in plants as compared with untreated plants (Yousefi and Esna-Ashari 2017). TiO_2 nanoparticles have been tested on various crops such as spinach (Hong et al. 2005), lettuce (Zahra et al. 2015), tomato (Tiwari et al. 2017), *Lemna minor* (Song et al. 2012), watermelon (Wang et al. 2013), wheat (Feizi et al. 2012), and mung beans (Raliya et al. 2015). These studies conclude that TiO_2 nanoparticles were able to increase plant growth and yield, increase chlorophyll content, enhance photosynthetic rate, and improve germination rate. But the plant responses depend on plant type, nanoscale properties, and concentrations and the method of application (Raliya et al. 2018).

1.2.6 Advantages of Nanofertilizers

The following are a list of advantages of using nanofertilizers as described by León-Silva et al. (2018) and presented in Bajpai et al. (2020):

i) Decreases the need for fertilizers and production costs.
ii) When applied in soil, reduces nutrient loss by leakage and soil drainage.

iii) Synthesis can be done eco-friendly.
iv) Improvement of nutrient uptake and controlled release of plant nutrients
v) Improve condition and bioavailability of essential nutrients in soil.
vi) Less negative effects and toxicity especially when used in low concentrations.
vii) The ability to improve product quality.

1.2.7 Limitations of Nanofertilizers

The successful use of some nanofertilizers for improved crop productivity was demonstrated. But the deliberate introduction of this technology in farming could lead to unintended nonreversible results. In this scenario, the use of this technology in farming productivity can be restricted by new environmental and unintentional health issues. Phytotoxicity of nanomaterials is also a problem because many plants react in a dose-dependent manner to different nanomaterials. Consequently, before market implementation, it is extremely necessary to look at the advantages of nanofertilizers and their limitations (Zulfiqar et al. 2019).

Especially because of their small size with enhanced surface area, nanomaterials are very reactive. Often of importance are the reactivity and volatility of these materials. This raises safety concerns for farm workers who may be exposed to the use of xenobiotics during application (Nair 2018). Given the anticipated benefits, the efficacy and effectiveness of these new fertilizers must therefore be examined. Indeed, their acceptance of sustainable agriculture is limited to their acceptance in terms of transport, toxicity, and availability and unintended environmental consequences on the exposure to biological systems (Nair 2018; Zulfiqar et al. 2019).

Risk assessment and the risk identification of nanomaterials including the assessment of the life cycle of nanomaterials or fertilizers is critical and to the prioritization of toxicological research. This is particularly valid with regard to nanoparticles accumulation in plants and potential health issues. In addition, the use of nanofertilizers made of nanomaterials created serious concerns about human and food safety (White and Gardea-Torresdey 2018). Some of the studies have shown the phytotoxic effects of nanoparticles on plants, the phytotoxicity of nanoparticles is dependent on the type of plant species, mode of application, time of exposure, and concentration and type of the applied nanoparticles. It is important to study the degree of toxicity of each nanoparticle to any given crop so as to understand translocation and accumulation of nanofertilizers and possible interactions with soil or plant compounds and also the accumulation of nanoparticles in different plant tissues (White and Gardea-Torresdey 2018; Zulfiqar et al. 2019).

1.3 Nanopesticides and Nanoantimicrobials

Plant pests and pathogens are among the biotic factors which contributed a yearly loss of about 20–40% in crop plants. The strategies available for the management of plant diseases predominately involve the use of toxic pesticides which are harmful to humans and the environment. Nanotechnology can provide advantages over conventional pesticides because of their ability to reduce toxicity, the improvement of shelf-life, and the increase of solubility of poor water-soluble pesticides, all of this could have positive impacts on the environment (Worrall et al. 2018). There are two directions through which nanoparticles can be used for plant disease managements either as nanoparticles alone or as nanocarriers for insecticides, bactericides, fungicides, or antivirals (Worrall et al. 2018).

1.3.1 Nano-Insecticides

Insecticides may be used against insects' larvae, large, or adult insects and can kill insects in different stages of their growth and development. Insects are a class of invertebrates, including insect pests that kill crops and infect stored grains. Applying nanoscale pesticides can therefore be helpful for managing insect pests in farming, without damaging nature (Jampílek and Král'ová 2017). Kah and Hofmann (2014) pointed out that aluminum nanoparticles acted as an insecticidal dust against two insect species, i.e. *Sitophilus oryzae* (L.) and *Rhyzopertha dominica*, (F.) which are major pests of stored grains. Chitosan nanoparticles have shown effectiveness against cotton leafworm (*Spodoptera littoralis*), oleander aphid (*Aphis nerii*), nymphs of the spear psylla (*Cacopsylla pyricola*), and the root-knot nematode (*Meloidogyne javanica*) (Malerba and Cerana 2016). Kumar et al. (2014) used a nanoformulation of imidacloprid – sodium alginate to Bhendi plants and managed to control leafhoppers and Jassids (sucking pests). EL-bendary and El-Helaly (2013) used silicon nanoparticles to control the neonates of *S. littoralis* (leaf worm) in tomato plants.

1.3.2 Nanobactericides

Metal nanoparticles such as silver (Ag), copper (Cu), zinc oxide (ZnO), and titanium dioxide (TiO_2) have been studied for their antibacterial activities (Kah and Hofmann 2014). Nano TiO_2 either alone or with zinc or silver was used against *Xanthomonas* sp., the causal agent of bacterial spot disease in roses (Paret et al. 2013a) and tomatoes (Paret et al. 2013b). Field (Paret et al. 2013a) and greenhouse (Paret et al. 2013b) studies showed that the severity of bacterial spot disease in rose plants was significantly reduced – in case of plants treated with TiO_2/Zn as compared to untreated control plants. Furthermore, TiO_2 nanoparticles present in nanofertilizers reported to provide protection from bacteria (Sadeghi et al. 2017). In an *in vitro* study performed by Mondal and Mani (2012), it was observed that copper nanoformulation could reduce the growth of bacterial blight on pomegranate at 0.2 mg/L, a concentration which is much lower than the recommended dose of copper oxychloride (2500–3000 mg/L).

1.3.3 Nanofungicides

Different metal nanoparticles have been studied for their antifungal properties (Gogos et al. 2012). Silver nanoparticles have shown antifungal inhibition of *Sclerotinia sclerotiorum*, *Alternaria alternata*, *Rhizoctonia solani*, *Macrophomina phaseolina*, *Curvularia lunata,* and *Botrytis cinereal* by well diffusion assay causing infections in plants (Krishnaraj et al. 2012). Also, Silver nanoparticles showed antifungal activity against *Aspergillus flavus*, *Aspergillus parasiticus*, *Fusarium solani*, *R. solani*, *Candida albicans*, *Candida glabrata,* and *Candida tropicalis* (Asghar et al. 2018; Khatami et al. 2018). Chitosan nanoparticles have shown antifungal activities, such as controlling *Botrytis* bunch rot in grapes, *Fusarium* crown, root rot in tomato, and *Phyricularia grisea* in rice (Kashyap et al. 2015).

1.3.4 Nano-Antivirals

Metal nanoparticles such as Ag, Cu, ZnO, and TiO_2 have been studied for their antiviral properties (Kim et al. 2018). Foliar application of silver nanoparticles on bean leaves caused complete suppression of sun-hemp rosette virus (Jain and Kothari 2014). In another study, Elbeshehy et al. (2015) have shown that *Vicia faba* plants treated with the bean's yellow mosaic virus and sprayed with silver nanoparticles have achieved surprisingly better results 24 hours after infection compared with spray applications before or at the time of inoculation. Nanofertilizers which contained TiO_2 nanoparticles were found to cause inactivation of viruses (Sadeghi et al. 2017). Gold nanoparticles were shown to dissolve the Barley yellow mosaic virus particles conferring resistance to the plant (Alkubaisi et al. 2015). Chitosan nanoparticles were found to increase viral resistance against the mosaic virus in snuff, alfalfa, potato, cucumber, and peanut (Malerba and Cerana 2016).

1.3.5 Advantages of Using Nanopesticides

From the results obtained by using nanopesticides in laboratory and field trials, the following advantages can be summarized (Bajpai et al. 2020):

i) Reduction of the required pesticide amounts and application rates, thus reducing costs of cultivation.
ii) Enhanced efficiency due to controlled or slow release of active ingredients.
iii) The availability of active ingredients for prolonged time which offers better control of insects and pests.
iv) The biodegradable nature nanopesticides reduce environmental pollution.

1.3.6 Risks of Using Nano-based Agrochemicals

Current research has revealed that the absorption, translocation, and accumulation of nanoparticles depend on various factors including the control of the microbial pathogen, plant parts, plant species and size, chemical composition, functionality, and stability of nanoparticle used (Raliya et al. 2015). Because the guidelines or protocols for quantification of nanoparticles within tissues are not yet clearly defined, the bulk of the data is generated for germination and cell culture. The present research discussion is more focused on the effect of nanoparticles on plants. But, the effect of application of nanoparticles to the next generation of plants exposed to nanoparticles is still not known (Mohamed and Abd-Elsalam 2018).

On the other hand, the antimicrobial activity of nanoparticles against different microbes and plant pathogens is undeniable fact, but the effects of these nanoparticles on soil microflora are less documented, which attracts much attention from scientists. There are many gaps in our knowledge with regards to the toxicity of these nanoparticles to the environment and different ecological systems. The negative effects of nanoparticles were recorded on denitrifying bacteria which disrupts the process of denitrification in soil (Bajpai et al. 2020).

There is also an urgent need to feel safe about the nanomaterials' phytotoxicity when applied to crop plants, in addition to understanding the potential benefits of using the nanotechnology in agriculture. Therefore, the first step should be related to analysis of penetration of those particles into plant cells and the way in which they are transported. For the biosafety of nanomaterials, formulation stability is also an important feature (Adisa et al. 2019).

1.4 Conclusions

The increasing challenges for humanity and food security clearly demonstrate that there is a growing demand for more production with less input in agriculture. One of the main problems in food safety is the application of large quantities of microbial pesticides together with the presence of new microbial-resistant strains. Also, the increased application of chemical fertilizers. That means the conventional farming practices are not able to control such threats adequately without putting human health at serious risk. Therefore, adoption of modern agricultural techniques and innovative technology is necessary so that such threats can more wisely and precisely controlled. In fact, nanotechnology is among the most advanced scientific methods in the area of agriculture and plant diseases management. Nanotechnology has a leading role in remodeling farming, and in the fight against plant microbes. The research of nanotechnology is already in its premature growth process after recent decades. All the action, however, is very wide and become popular day by day.

The rapid development and implementation of marketable formulations involving artificially designed plant protection nanoparticles has been driven by nanotechnologies in combination with biotechnology. Nanoparticles have proved to be a talented tool in this era to reduce indiscriminate use of unnecessary chemicals and toxins in plants. Specific nanomaterials with high antimicrobial/antiviral potential against pathogens have found to be advantageous and practical, whereas other nanoparticles have a deleterious effect in terms of plant reactivity and phytotoxicity. Therefore, we should be very careful when examining the type of nanomaterial needed for their implementation considering the concentration, physical, chemical, and accumulation properties. Otherwise, they could be a potential serious threat to the entire ecosystem. The effect of nanoparticles depends on several factors, and if their conditions vary, their results can easily and completely change. These factors mainly include type and concentration of the nanomaterials used, the chemical/biological surface coating agent, the age and type of the plant, and the target portion of tissue. Nanobiotechnological industries are now growing very quickly, and new nanofertilizers and antimicrobial nano-based systems have been developed, but a long way to go to manufacture comparatively cost-effective, safe, and environmentally friendly and stabilized nanomaterials; however, further extensive studies are also required on these issues. Moreover, it is important to make a broad-based assessment of these nanomaterials within the food and agri-food industry to gain public acceptance. In this way, the unlike challenges which faced genetically modified organisms worldwide will be avoided.

The unique impact of nanotechnology and its applications in the agricultural sector is only at its infancy, but the anticipations of this science are still very high in terms of eradicating challenges related to plant disease control, food production, environmental sustainability, and even fossil fuels.