18 Nanotechnology for Agricultural and Environmental Sustainability

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Abstract

Nanotechnology provides answer for sustainable agriculture by enhancing nutrient utilization efficacy, improving efficiency of pest control, mitigating impact of climate change, and reducing harmful environmental impacts of agriculture food production. A lot of auspicious nanotechnologies have been anticipated and needed to be checked for their beneficial role. Here we explore nanotechnology in relation to agriculture and environmental aspects. We have discussed how nanotechnology can be applied to enhance plant growth and development, and provided comprehensive overview about nanofertilizers, nano-pesticide, and applications in field of food sector.

Keywords

Nanotechnology · Agriculture · Nanoparticles · Soil fertility

18.1 Introduction

Nanotechnology is the alteration of material at range of 1–100 nm in one dimension. Definition of nanotechnology varies across the globe; hence there is no universal definition of nanotechnology (Thakur and Shirkot 2017). Nanotechnology has been utilized to increase plant growth and protection including nanocarriers for fertilizers

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and nanopesticides and help to develop plants with enhanced photosynthetic capability and sensors for plant health monitoring. In vivo and in vitro studies show tremendous promises of nanotechnology in making agriculture more sustainable, efficient, and resilient. Agriculture puts huge pressure on earth's environment and is a big contributor for biodiversity loss. The current agriculture practices are not meant for meeting production goal of 2050 (Prasad et al. 2017). Crop yield plateau is getting flattened and race is increasing for natural resources such as water, energy, and arable land. Before the formal start of agriculture by *Homo sapiens*, the predators like lifestyle supported about four million people globally. Today agriculture provide food for up to six million people. Total cereal production of the world has increased significantly in the past 40 years. Major contributors for yield increase are fertilizers, water, pesticides, and new variety with disease resistance power. This has led to reduced hunger, improving nutrition, and preventing ecosystems from conversion. In 2050, world population is estimated to be 50% greater than at present, and world grain production is projected to increase by 2.4 fold. If we have to increase production of cereals and grains, we need much more precise and pinpointed target delivery of fertilizers, pesticides, and insecticides and require super green revolution variety (Kah and Tufenkji 2019). Half of the world's land is already used for intensive agriculture, it causes loss of ecosystems, and adds significant and environmentally damaging amounts of nitrogen and phosphorous to land ecosystem. A threefold increase in nitrogen and phosphorous quantity is required if we have to meet challenges to achieve 2050 or 2030 UN goals. Sustainable agriculture are methods or techniques that help us to meet present and future needs of people for food and fiber for ecosystem service and for healthy lives. Nanotechnology can up to some extent fulfill some needs in the future through nano-enabled pesticides and by converting plants into sensors. Only 0.1% of pesticides applied to the field reach their target, that is, target locations of desired product. Hence nanocarriers and nanoformulations have potential to improve the efficacy of existing pesticides by improving the accuracy of preexisting pesticides by accurate delivery (Giraldo 2014). The concept of sustainable release of an active compound from nanocarriers has existed since the 1960s: nanotechnology can produce smart pesticides which can release active compounds when plants are in stress like pathogen, water, temperature, pH, redox conditions, light, and plant biochemicals (Fig. 18.1).

18.2 Nanotechnology in Agriculture

There were many efforts to use nanotechnology in agriculture which started after the advent of new field of science, namely, nanotechnology. Age-old farming practices are neither able to increase productivity nor will restore damage caused by existing technology back to Darwin time. Nanotechnology became popular with plenty of public funding, but the growth is not like as desired from this technology (Thakur and Shirkot 2017). Developing countries and least developed countries lacked foresight; infrastructure-wise, they are unwilling to spent money on innovation

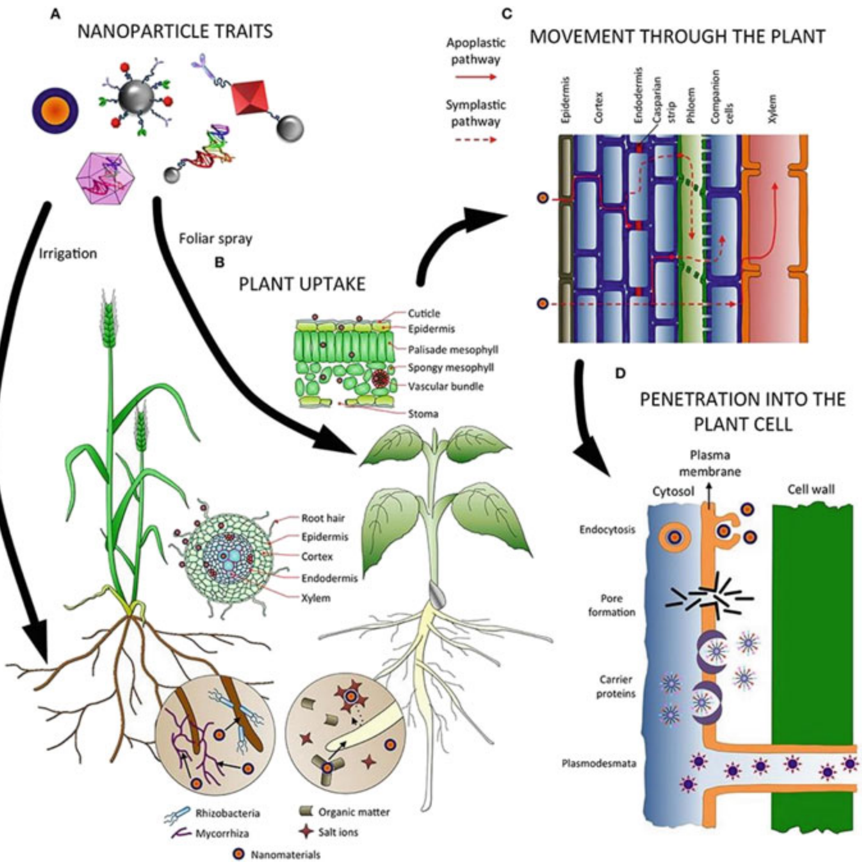

Fig. 18.1 (**a**) Picture represent how nanoparticles are translocated and their application. (**b**) represents nanoparticle interaction with microorganisms and other chemicals in soil, (**c**) represents nanoparticle traffic pathways (apoplastic/symplastic), (**d**) mechanisms for the transport of nanoparticles within cell

(research and development project). With advances in technology and increased awareness about production and quality, nowadays consumers not only want to eat food but also want a nutrient-balanced diet. Nanotechnology certainly can reduce millions of tons of chemical which are poured into the soil in the name of fertilizers and pesticides and can reduce about 70–80% chemical fertilizer which are used currently by farmers. Nanotechnology in farming has optimistic future for increasing the efficiency of nutrient use through nanoformulations of fertilizers, removing yield barriers using high-throughput phenotyping and control of pest and diseases (Thakur et al. 2018). Knowing more about mechanisms of host-pathogen interaction at molecular level will greatly help to increase production for increasing populations. Nanotechnology gets much awaited hype because of its large numbers of applications in field of nano-pesticide and nano-insecticide and in sustainable delivery of chemicals in field/soil for long-term effect of these chemicals. Biosensor is an area which needs miniaturizations, and nanotechnology can greatly benefit through small and smart devices (Fraceto et al. 2016) such as nanosensors and other nanosystems that are very important in biochemical analysis (Viswanathan and Radecki 2008). Nanosensors can detect mycotoxin present in various foods and their products (Sertova 2015). Agriculture sector always benefitted from various techniques and tools which are developed by different branches of sciences, like hybrid varieties, fertilizers, and pesticides.

18.2.1 Soil Fertility

To achieve high production in various crops like cereals and others, we have to supply synthetic fertilizer. Ancient methods of applying fertilizer cause losses of macronutrients and micronutrients, due to which very minute concentration reach to target sites and about 40–70% N, 80–90% P, and 50–90% potassium of conventionally applied fertilizers are lost in the environment (Tilman et al. 2002). Nanomaterial supplies single or various nutrients to plants ensuring better yield of crops and reduced environmental degradation (Liu and Lal 2015) (Chinnamuthu and Boopathi 2009). Encapsulation of nanofertilizer is ensured by three ways: (1) nanoporous materials, (2) film polymer, and (3) nanoparticle or nanoemulsions. Nanomaterial trapping on fertilizer sticks more strongly material of high surface area (Brady and Weil 1999). Nanofertilizer possesses qualities like solubility, stability, sustainable release, less toxicity with ease, and safe distribution and disposal (Torney et al. 2007 and Green and Beestman 2007).

18.2.2 Plant Growth

Nanoparticles of various metals have shown good potential for increasing crop yield and health by better nutrient uptake (Khot et al. 2012). True effectiveness of nanomaterials only depends on nanomaterial size, concentration, surface, and chemical properties other than susceptibility of the plant species (Ma et al. 2010). Use of advanced technology largely helps to understand interaction between plants and nanomaterials (Table 18.1).

18.2.3 Plant Growth and Development

Nanomaterial interplay causes many physiological changes in the plants depending upon the property of nanoparticles. Efficiency of nanomaterials is determined through numerous factors most importantly the dose at which these are applied (Khodakovskaya et al. 2012). Nanomaterials induce different effects on plant growth and development; their impact on plants is controlled by nanomaterial composition, size, shape, other properties, and plant species (Ma et al. 2010). Khodakovskaya

Table 18.1 Effects of nanomaterials on plant growth and development

Active element	Effects	Particle size and concentration	References
Calcium	Helps in management of insect pests in *Z. mauritiana*	26%	Hua et al. (2015)
Magnesium	Increased growth and yield in *T. aestivum* and *V. unguiculata*	0.25–0.5 g L^{-1}	Delfani et al. (2014)
Zinc	Increased carbohydrate, fat, and fiber content in *S. oleracea*	10 ppm	Burman et al. (2013)
Iron	Increased carbohydrate content in *O. basilicum*	1–3 mg L^{-1}	Elfeky et al. (2013)
Silicon	Increased protein and chlorophyll content in pea	15 mg L^{-1}	Suriyaprabha et al. (2014)
Titanium	Increased nitrogen and protein content in *S. oleracea*	0.25%	Yang et al. (2007)
Silver	Increased growth and development of *B. juncea* and *V. unguiculata*	50–75 ppm	Pallavi et al. (2016)
Gold	Enhanced growth in *Brassica juncea*	10–25 ppm	Arora et al. (2012)
Carbon	Reduction of oxidative stress in *B. vulgaris*	0.01 and 0.001 nmol	Kaphle et al. (2018)

et al. (2012) reported that application of gold nanoparticles enhances the redox status of the treated plants. Germination of *Brassica. juncea* seedlings improves when inoculated with 25 ppm gold nanoparticles; 19% improvement has been found when 10 ppm of gold nanoparticles were inoculated.

Christou et al. (1988) transferred a gene into soybean genome through DNA-coated gold particles. The optimistic results of gold nanoparticles were identified. Shah and Belozerova (2009) studied effects of gold nanoparticles within plants which inhibited aquaporin function, a group of transmembrane proteins that help in the transportation of wide range of molecules including water. Krishnaraj et al. (2012) investigated effect of silver nanoparticles on *Bacopa monnieri*. Morphological study showed minimal reduction in root and shoot lengths. Seed germination rate has been increased in case of lettuce and cucumber (Barrena et al. 2009), *Brassica juncea* (Arora et al. 2012), and *Gloriosa superba* Gopinath et al. (2014). It has been noted that increase in number of leaves, leaf area, plant height, and chlorophyll content led to better crop yield. Kumar et al. (2010) found that 24 nm-sized gold nanoparticles increased the seed yield three times than control in case of *Arabidopsis thaliana*. It was further noted that inoculum of 10–80μg/ml concentrations increases shoot growth and free radical scavenging activity. Gunjan et al. (2014) observed that exposure of gold nanoparticles led to increase in shoot length from 6.81 to 7.36 cm in seedlings of *Brassica juncea*, and at 100 ppm average root length increased up to 1.62 cm due to gold nanoparticle exposure. As gold nanoparticle concentration increased, there was an increase in antioxidative enzyme activity, H_2O_2, and proline content. Siddiqi and Husen (2016) reported that plants exposed to gold nanoparticles showed mixed effects on growth and yield of different crops. Toxicity of gold nanoparticles depends on the size and shape of nanomaterials. It has been observed through several studies that lower concentration of nanomaterials helps in increase in growth and yield of fruit/seed.

18.2.4 Fertilizer Release

In the past few decades, the application of nanoparticles in the agricultural sector has increased, accompanied by the creation of fertilizers, which have improved product performance and quality. The current trend is to incorporate nutrients through nanostructure in order to facilitate their availability to plants. Different encapsulation techniques including nutrient encapsulated inside nanomaterials such as nanotubes or nanoporous materials have been developed to improve fertiliaer avilability for crop plants. The nutrients can be coated with a thin protective polymer film and delivered as particles or emulsions of nanoscale dimensions. Several studies focus on the use of artificial fertilizers such as nitrogen, phosphorus, and potassium, so-called NPK fertilizers for various crops and under various growing conditions (Solanki et al. 2015). Therefore, studies are underway for encapsulations, in which NPK fertilizers are entrapped within chitosan nanoparticles (Hasannen et al. 2014). On the other hand, urea is utilized as a model fertilizer to access fertilizer loading and the controlled release behavior of nanoparticles (Wanyika et al. 2012). Castro-Enriquez et al. (2012) reported use of nanomembranes of wheat gluten to release urea. These membranes provided a potential solution to the problem of loss by leaching of these fertilizer into agricultural crops. A similar objective was obtained by employing gold nanoparticles supported on TiO_2 or titanate nanotubes. Thus, nano fertilizer gives high surface area relative to the number of nanomaterials.

18.2.5 Pesticide, Herbicide, and Insecticide Release

Various plant pathogens and pest reduce the crop production by 20–40% globally per year. Currently farmers employ various chemical formulations to manage pest and insect problem. There are various reasons that lead to vast application of these chemicals into the field, but keeping in mind environmental safety and sustainability of agriculture, we need to shift toward nanoformulation choice. It has been observed that 90% of applied pesticide are degraded after application. So, we have to move toward development of eco-friendly nanopesticides and insecticides.

Nanotechnology is being explored toward delivery of agrichemicals (insecticide, pesticides), nanobiosensors, and others. Technology enabled scientist and researchers to craft nanomaterials with desired shape, size, and surface property, so that they can be utilized as surface-coating materials for efficient delivery of agrochemicals. There are two different mechanisms by which nanomaterial can protect plant or crop from diseases, pest, insect, and other predators. Nanomaterials by their own provide crop protection. Nanomaterials can be used as delivery agent for agrochemicals or other active bioagents such as dsRNA. Nanomaterials as delivery agents provide benefits like large shelf life, more solubility, less toxicity, and precise delivery of chemicals. Nanopesticide is much more stable under environmental conditions such as rain and UV. De-Oliveira et al. (2015) reported that nanomaterials can be used as a delivery agent for combination of atrazine and simazine to control vegetation. Herbicidal activity was determined through pre- and post-emergent treatment of *Raphanus raphanistrum*. The formulation showed growth inhibition at concentrations ten times lower than those of the commercial formulation. Atrazine was also studied in gel beads of chitosan, obtaining an extended-release period of the compound up to 7 months. Nanoemulsions are useful for the formulation of pesticides, and the latter can be effective against various insect pests in agriculture.

18.3 Antimicrobial Activity of Nanoparticles

Microorganisms play an important role in agriculture; however some bacteria and fungi are playing the major role to crop contamination and degradation, which leads to huge economic losses worldwide. Nanotechnology provides a wide avenue to antimicrobial compounds. Gold, zinc oxide, and silver nanoparticles are the prime metals on considering antimicrobial activity. Nanotechnology is emerging as a new tool to mitigate plant diseases and helps in disease management. Nanoparticles are found to be effective for inhibiting growth of broad range of pathogenic microorganisms such as bacteria, fungi, viruses, and yeasts (Nirmala and Pandian 2007).

18.4 Psychrophiles' Role in Agriculture

Psychrophiles are microorganisms which live in extremely low temperature (−20 to 8^0C) conditions. About 70% of earth area comes under temperature zone of 1–5°C, which is permanently cold (Feller and Gerday 2003). Psychrophilic enzyme offers lucrative application for different industries such as textile, brewing food, and dairy industry. Psychrophiles are the excellent source of polyunsaturated fatty acids, which are used by pharma industry for the development of novel therapeutic agents. Mukhopadhyay et al. (2015) studied the effect of nanoparticles on the stability of pectate lyase at a temperature 4 °C; they have found 70% activity after repeated freezing and thawing at 25 °C.

18.5 In Food Sector

Applications of nanotechnology in the food sector offer great benefits in biosensing, detection of food pathogens and toxins, food packaging, delivery systems, delivery of bioactive compounds, and protection of functional ingredients. This technology may completely revolutionize the food sector because the application of nanotechnology improves the safety and the nutritional value of food products. In recent years, there has been an increasing interest in nanotechnology in the food industry, in which nanotechnology has grown enormously, as well as the creation of new food products to satisfy the needs for food quality, sensory appeal, texture, taste, improving supplements, other sensory attributes, coloring, strength, processability, stability during shelf life, and safety while simultaneously being a good source of nutrients. Prakash (2012) reported that nanotechnology could be used in quality control, food additives, and the detection of bacterial and fungal contamination in food products. It was reported that the application of nanoparticles in food is primarily focused on optimizing the use of dispersion systems and release of the bioactive compounds of liposomes and micelles, thereby increasing the bioavailability of food. Lopes and colleagues conducted experiments on other functional food ingredients in order to develop new functional material and the design of methods such as nanofiltration and instrumentation (nanosensors). The different applications of nanoparticles in the food sector will be described in the following sections.

The development of nanostructured food ingredients and of delivery systems for nutrients and supplements are the main focus of nanotechnology applications in foods. Numerous bioactive agents intended for oral ingestion are nonpolar compounds with high melting points, low water solubility, and poor oral bioavailability. Thus certain bioactive compounds are difficult to incorporate into commercial products, such as functional foods and beverages; therefore it is necessary to incorporate these into particles that facilitate their bioavailability. Moreover, micelles, liposomes, and nanoemulsions can be good options due to their high stability under moderate conditions, such as pH value, temperature, or salt concentration. Popov et al. (2010) have proposed the use of nanoemulsion technology in order to obtain aromatized beverages, juices, and milk enriched with controllably released vitamins, minerals, and functional components. The use of nanoemulsion technology has been reported for the manufacture of encapsulating systems for functional compounds, in order to prevent their degradation and to improve their bioavailability, such as nutraceuticals, drugs, flavors, antioxidants, and antimicrobial agents. Nutraceuticals are utilized in food to provide health benefits. The efficacy of nutraceuticals in disease prevention depends on the preservation of bioactive bioavailable ingredients until their release at target sites, taking into account that nanoparticles in food can be used as additives or supplements, for example, zinc oxide nanoparticles have been employed in nutritional supplements such as multivitamins. Lopes et al. (2013) used liposomes containing functional food ingredients to protect these from oxygen and water. Nanoencapsulation aids in solving certain difficulties such as loss of functionality during processing or storage and the loss of activity of enzymes. Nanoencapsulation comprises a promising technique to protect bioactive compounds from environmental damage and to mask their unpleasant properties. Microorganisms such as *Lactobacillus acidophilus*, *Lactobacillus casei*, *Lactobacillus rhamnosus*, and *Bifidobacterium* spp. have been nanoencapsulated for the protection and controlled release of these beneficial, live probiotic species to promote healthy gut function.

Table 18.2 Products developed through nanotechnology

Product	Application	Institution
Nano-biosensors	Used in checking of contamination of packaged food	Nestle, USA
Precision farming	Nano sensors give real-time access to monitoring of crop growth and soil health	US Department of Agriculture, USA
Livestock and fisheries	Nano-veterinary medicine used for nano-vaccines, drug delivery, smart herds	NanoVic, Dingley, Australia
Use of agricultural waste	Cotton waste used for improving strength of cloth through nanofiber	Cornell University, USA
Nanoparticles	*Campylobacter jejuni* removed from poultry through nanoparticles	Clemson University, USA
Buckyball fertilizer	Ammonia from buckyballs	Kyoto University, Japan
Nanocides	Nanoparticles were used to encapsulated pesticides	BASF, Germany

Nanotechnology in the food industry exerts a great impact on the development of novel food packaging materials that can help to control the oxidation of foodstuffs and to prevent the formation of off flavors and undesirable-textured foods. For example, edible films, edible coating, and polymer nanocomposites are effective, but their application depends on the level of adherence between the materials involved. Campos et al. (2011) reported that edible coatings or films could be used as a vehicle for incorporating functional ingredients such as antioxidants, flavor colors, antimicrobial agents, and nutraceuticals. Natamycin-loaded poly (*N*-isopropylacrylamide) nanohydrogels are used to aid controlled release of active compounds. It was reported that this compound does not cause changes in the main properties. The most important characteristic of food packaging compounds is that they should maintain their bioactivity. In case of nanocomposites, these exhibit good characteristics, such as augmented barrier properties, increased mechanical strength, and improved heat resistance. Cellulose nanocomposites have been employed in mango pulp to improve tensile properties and water vapor permeability. Moreover, nanoparticles are also being currently used in edible coatings and films in a wide variety of foods, including fruits, vegetables, meats, and seafood. In food packaging, nanotechnology offers huge opportunities that can benefit both consumers and the food industry (Table 18.2).

18.6 Conclusion and Future Prospects

Progress of nanotechnology is impressive in agriculture; it has been noted that it takes 20 years for any technology to move from lab to field. Surely nanotechnology or nanobiotechnology will boom in the near future or may be in the next decade. It is well known that applying new technologies to agriculture sector could bring big breakthrough in improving our current terrible nutrient usage effectively by use of nanoformulation of fertilizers, breaking yield, and nutritional quality barrier through bionanotechnology, surveillance, and control of pest and diseases. Presently we are better enabled by technology to know more about host parasite interactions at molecular level. These technologies has helped in generation of safe nanopesticides, safe carriers, better preserving and packing materials for food and food additives. Nanotechnology can improve shelf life of vegetables and flowers and also help in better water management practices, restoring soil fertility, retrieval of salinity of soil problem. Implementation of theories like theory of chaos and string theory opens a Pandora box for agriculture production system. Nanotechnologist needs more understanding in material technology, in conjunction with knowledge of the agriculture production system.

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