Approaches, Challenges, and Prospects of Nanotechnology for Sustainable Agriculture

Garima Pandey, Smriti Tripathi, Sangeeta Bajpai, and Monika Kamboj

1 Introduction

The growth of agriculture is a necessary aspect of the economic development in nearly all the developing nations. The current status of escalating worldwide population graph is resulting into a decline in the demand–supply ratio of agri-products (Ali et al. 2014; Contado 2015). The amalgamation of nanotechnology and biotechnology in agricultural sector would play an imperative part in increasing the productivity rate with better packaging and processing of agri-products. Nanotechnology is expansively influencing the globe with enormous applications in almost every field, and in last few years, work in the area of agri-sector has skyrocketed (Corradini et al. 2010; Cui et al. 2010; Dhawan et al. 2011). It pervades nearly every region of agri-sector, ranging from soil health, irrigation and filtration management, sensing and monitoring of biological host-molecules, food processing and packaging, and pest, vectors, and rodent management (http://www.nanotec.org.uk/; Fraceto et al. 2016). Nanotechnology constructs nanoscale materials by making changes at the atomic level. The purpose of utilizing nanotechnology in agriculture is to boost the agricultural yield, to curtail the usage of hazardous chemicals, to deal with the loss of nutrients, and pest and vector management. This also involves enhancing the creation and the promotion of nano-based agri-products, their efficiency improvement, and quality and safety assessment of the agricultural goods.

G. Pandey (✉)
SRM-IST, Delhi-NCR Campus, Ghaziabad, UP, India
e-mail: garimap@srmist.edu.in

S. Tripathi
United College of Engineering and Research, Knowledge Park III, Greater Noida, UP, India

S. Bajpai · M. Kamboj
Amity School of Applied Sciences, Amity University, Lucknow, UP, India

F. Fernandez-Luqueno, J. K. Patra (eds.), *Agricultural and Environmental Nanotechnology*, Interdisciplinary Biotechnological Advances,
https://doi.org/10.1007/978-981-19-5454-2_3

However, all the nano-based agri-products also bring in risk issues like contamination of air, soil, and water, or threats to plant, human, and animal health, along with them (Gehrke et al. 2015; Gour and Jain 2019). Owing to the poor information, assessment, and management of the risks associated, it is still not apparent how the environmental sustainability of agriculture will be achieved through nanotechnology in future. Over 1300 commercial nanomaterials (NMs), with prospective applications in various fields, are presently available in the market. The synthesis of nanomaterials with precise dimensions, composition, and property has extended their efficient applications in agriculture (Handy et al. 2008; Hegde et al. 2016). Nanomaterials being used in agriculture could be from natural sources or engineered ones synthesized in the laboratories. Nanomaterials are synthesized by the top-down and the bottom-up approaches of synthesis and are generally grouped into organic, inorganic, and composite nanomaterials (such as surface-modified clays). The applications of biologically synthesized nanomaterials pave the way for sustainability in agriculture sector. The biosynthesis of nanomaterials from green reducing agents without consuming high amount of energy and lethal chemicals has engrossed the attention from the researchers globally (Hochella Jr et al. 2019; Joseph and Morrison 2006; Mukhopadhyay 2014).

2 Green Synthesis of Nanomaterial

In recent years, research has been concentrated on evolving innovative environmental means as an alternate to the conventional mode in order to cut the reaction times, refining the degree of pureness of the products, and increasing the reaction yields. These innovative technologies are incrementally taking modern society toward safer and more sustainable practices and are environmentally friendly. It serves the purpose of protecting human health and environment from hazardous waste. Nanotechnology is an emergent branch of science that involves synthesis of nano-sized particles (less than 100 nm) by physical and chemical processes or from natural resources (green approach) as green agents. Nanomaterials possess fabulous physical and chemical properties with ample of applications. The green nanoparticles (NPs) have numerous applications. They play a significant role in the development of novel and effective drugs, catalysts, sensors, pesticides, optics, photo-thermal therapy, and medicine (Narayanan and El-Sayed 2005; Eychmuller 2000; Salata 2004). So, researchers have focused in developing nanomaterials by green methods.

The synthesis of nanomaterials is usually achieved via chemical and physical methods. These traditional methods require the use of extremely toxic, expensive chemicals and are havoc for the ecosystem. As a need of the hour, to reduce the risk of toxicity in the environment from the different chemicals used in the physical and chemical methods, researchers have moved toward more environment-ally friendly process called “green synthesis.” Nowadays, green methodology is adopted to integrate the particles at nanoscale in which compounds derived from natural resources such as microbes, animals, and plants are used. Such green tools to produce NMs are cost effective with low waste generation.

Significant rules to be considered for green synthesis at nanoscale (Darroudi et al. 2011) include:

1. Use of the green solvents in the synthesis.
2. Use of an eco-friendly benign reducing agent.
3. Use of a nontoxic stable material.

The natural biodegradable resources such as enzymes, vitamins, bacteria, actinomycetes, yeasts, fungi, algae, plant extracts, and phytochemicals are the common green systems/vehicles utilized to synthesize highly stable, well characterized, and safer nanomaterials instead of the chemical methods (Machado et al. 2013; Huang et al. 2014; Luo et al. 2016). Among these methods, synthesis via plant extracts is beneficial since it lessens the peril of further adulteration by lessening the reaction time and upholding the cell structure (Ajitha et al. 2015). Some of the systems used by researchers to synthesize nanomaterials by green route are described as follows.

2.1 Bacteria-Mediated Green Synthesis

The defense machinery of bacteria plays a crucial route in the biosynthesis of nanoparticles. When the concentration of ions is high, bacterial cells do not survive and are under stress. To overcome this stress, their cell mechanism, that is, enzymes in cell walls, converts toxic and reactive ions into stable nontoxic nanoparticles. The only drawback in this case is that high concentration of nanoparticles can damage the cell structure of bacteria as they require ambient conditions of pH, temperature, and pressure to survive. Also, rate of synthesis is slow. Researchers reported bioreduction of silver ion to bactericidal Ag NPs by using cell-free culture supernatants of psychrophilic bacteria and silver nitrate as precursor (Shivaji et al. 2011). Different bacteria were utilized by researchers (Du et al. 2017; Singh et al. 2016a, b; Wang et al. 2016) to synthesize intracellular or extracellular Ag NPs of different size using silver nitrate as substrate.

2.1.1 Algae-Mediated Green Synthesis

Algae are most primitive, aquatic photoautotrophic, eukaryotic microorganisms. In recent years, they have been explored for synthesis of nanoparticles. Algae belonging to the Class Cyanophyceae (blue green), Chlorophyceae (green algae), Phaeophyceae (brown algae), and Rhodophyceae (red algae) have been used as bio-tools for synthesis of nanoparticles (Khanna et al. 2020). Algae-mediated biosynthesis of nanoparticles is shown in Fig. 1 (Chaudhary et al. 2020). They have the ability to produce nanoparticles by accumulating heavy metals (Castro et al. 2013).

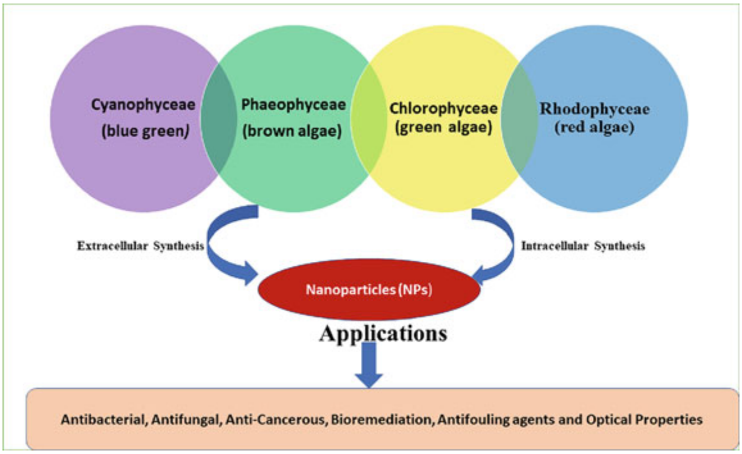

Fig. 1 Algae-mediated biosynthesis of nanoparticles

Cell walls of algae are rich source of bioactive components that make them attractive bio-machinery for the production of diverse nanomaterials by capping and stabilizing the precursors. Brown algae from marine are the rich source of fucoidans, a polysaccharide secreted from their cell walls, utilized for the production of gold nanoparticles (Lirdprapamongkol et al. 2014). Brown algae have the capability to uptake the heavy metals through complex cell walls, laden with mucilaginous polysaccharides and carboxyl groups (Venkatesan et al. 2014). *Chlorella* spp. and *Sargassum* spp. have been expansively reconnoitered for the production of nanoparticles. Singaravelu et al. (2007) synthesized gold nanoparticles from the marine algae *Sargassum wightii* in a short span.

2.1.2 Fungus-Mediated Green Synthesis

Fungus is another widespread bio-machinery to produce nanoparticles as it is easy to handle, affordable, and secretes enzymes that are responsible for synthesis of nanomaterials for mass production. A variety of fungi are being exploited for nanomaterial production due to their ability to tolerate and bio-accumulate the metal. They can withstand laboratory conditions (Fayaz et al. 2011), so have been the first choice of nano scientists for the synthesis of nanoparticles. The active bio-compounds released by the fungus are the bio-tools for production of nanoparticles, which can be controlled to alter the composition, shape, and size of nanomaterial (Menon et al. 2017). Suganya et al. synthesized stable gold nanoparticles by using blue green alga *Spirulina platensis* protein and studied the Au NP potency against the bacterial cell. These gold NPs damage the bacterial cell by penetrating their peptidoglycan layer (Suganya et al. 2015). Extracellular synthesis of metallic nanoparticles is rapid than the intracellular synthesis (Mukherjee et al. 2001; Bhainsa and D’Souza 2006). The major shortcoming of this approach is occurrence of the genetic manipulation of enzymes in fungus recognized for synthesis of metallic NPs (Thakkar et al. 2010). Also, fungus-mediated synthesis process is slow.

2.1.3 Plant-Mediated Green Synthesis

Scientists' community is continually trying to adopt the synthetic route that is eco-friendly and less hazardous to mankind. Based on this strategy, variety of plants and their extracts are being frequently explored recently to synthesize nanoparticles. Plant-mediated green synthesis resulted in stable and less contaminated pure nanoparticles with uniform shape and size. The reaction time was much more reduced (as compared to using bacteria or fungus) without the consumption of toxic reagents. The biosynthesis of NP from plant extract of different plants has been reported (Mohan Kumar et al. 2013; Kuang et al. 2013; Thakur and Karak 2014; Njagi et al. 2010; Wang et al. 2014; Senthil et al. 2012). Mechanism of nanoparticle synthesis involves three stages: activation, growth, and termination (Kalpana-Sastry et al. 2009). Metal ions are reduced to atoms that nucleate to form new entities in the first phase. These new forms will grow to stable NPs in the second phase. Termination stage ends with the formation of NPs of desired shape and size.

2.1.4 Advantages of Green Synthesis Routes of Nanomaterial

Green synthesis routes of nanomaterial have many advantages, including:

- Ease of synthesis and characterization
- Economic viability
- Bioavailability of resources
- Eco-friendliness (Awwad et al. 2020)
- Cost effectiveness
- Environmental sustainability
- Fabrication of nano-objects with controlled size and shape
- Less chances of failure (Garg et al. 2020)

3 Advantages and Usefulness of Nanotechnology in Agriculture

Agriculture is a backbone of economic development for any developing country. The basic challenges that the agriculture industry is facing are: unpredictable weather conditions, industrial development, and biological accumulation, with an increasing food demand due to population explosion (Amin 2018). Global agriculture is facing lots of problems in recent times like lack of nutrients, degradation in soil quality, climate change, reduction in agricultural land area, biomagnifications, limited production of crops, low moisture content in soil, lack of manual labors, and genetically modified crops (the deoxyribonucleic acid [DNA] of which is immune to certain diseases and pests). The escalation in the consumption of chemical fertilizers (from 0.5 to 23 million tons) shows that, till today, we are not overcome from the repercussions of green revolution (Baker et al. 2017; Corsi et al. 2018; Cushen et al. 2012). There is no doubt that the production of our crops has increased manifolds, but it is also true that the amount of required organic nutrients in them has decreased, which has limited the production of some crops. The continuous reliance on uncertain natural factors like climate, soil, and rain in agriculture makes it very unpredictable (Dahabieh et al. 2018; Dayarathne et al. 2019). Consequently, to overcome the obstacle of sustainability, and to fulfill the demands of quality food, it is essential to maintain the database of living and nonliving constituents of the environment (Dudo et al. 2011). To accomplish this, agriculture has to be technically developed and nanotechnology has an important role in it. The promotion of nanotechnology principles in agricultural practices has helped in achieving advanced results. Nanotechnology has immense possibilities and profits in agriculture. When correct amounts of nanoparticles suffuse in plants, it shows so many physical and biological changes in them and indicates quality results in their growth and growth of plants and the rate of seed germination and production (Feregrino-Perez et al. 2018; Hans and Jana 2018). Nanoformulation of insecticides, enhanced crop production via nanocapsules for controlled release of nutrients, pest control through nano-arbitrated genetic transformations, and developing nanobiosensors for site-specific crop management are the few advantages of nanotechnology. The drugs containing nanoparticles deliver its continuous release of nutritional materials, and genes of concern give their continued release through plant cell to improve their absorption, and proliferation of herbicides (Kouhkan et al. 2019).

3.1 Precision Farming

Precision farming is basically an approach to manage the agriculture process with the help of information technology. It makes agricultural practices additionally effective and manageable with regard to crop production and livestock rearing. The main components of precision farming include all artificial intelligence (AI) devices like robotic system, drones, and global positioning system (GPS)-based soil sampling. It also includes sensors, automated means of transport, latest software, and hardware tools. The prime objective of precision farming is to enhance the yield of crops by minimum inputs (Kumar et al. 2015, 2019). Initial technological survey of agricultural land is actually very helpful in precision farming; this survey includes soil quality, and location identification with the aid of technology like sensors, satellite, and computers. Mediation of technology measures all geomorphology accurately—for example, soil quality or required nutrients and moisture in soil and climate—

which can be managed further to enhance and improve quality and quantity of the crop (Kundu et al. 2019).

Precision farming is empowering with modern equipment and technology, like minuscule sensors, that actually helps in supervising soil quality, growth of specific crop, and management of agricultural trash. As reported by the *Forbes*, nanosensors are being used by various countries—for example, R&D Company using nanosensors to monitor sell by date and use by date in stores in Minnesota. Use of nanosensors can optimize the need of chemicals to inhibit the growth of unwanted plants; insecticides and nutritional constituents can be estimated, which can result in maximum farming output in terms of crop production and quality by putting minimum inputs (Liu and Lal 2015). Technological advancement in delivery system and use of nanosensors help in reducing unethical exploitation of agricultural resources like soil, moisture, and soil nutrients. Precision farming with nanotechnology plays a vital role in agriculture by predicting environmental problems like drought and soil moisture as well as detection of seeds and pests, which is very helpful in making agriculture actually sustainable. As soon as the nanosensors understand the edaphic factors, they automatically adjust the irrigation or pesticides. The dispersed nanosensors in the field also understand the existence of microorganisms spread in the fields and then work accordingly. Precision farming plays an important role in managing the farming waste materials and hence is very significant to reduce the environmental pollution at its minimum level (Mabe et al. 2017).

3.2 Delivery of Fertilizers

The continuous use of chemical fertilizers for the purpose of enhancement of production has led to many adverse effects like depleted nutrient level in the soil and degrading of soil quality. Runoff and pollution are also responsible for the great loss of fertilizers. Nanotechnology can help significantly to get rid of these issues with the help of nanoencapsulated fertilizers, as they have been effectively absorbed by the plants, and prevent wastage. The technique of nanoencapsulation has strong control on releasing of nutrients and surface protection (Mani and Mondal 2016). To fulfill the need of potassium, phosphorus, and nitrogen in soil, inorganic supplements like urea and diammonium phosphates are used, which causes squander in economy and environment (Martinho 2018; Milewska-Hendel et al. 2016). The perspective of using nanoencapsulated chemical nutrients is to give the sustainable release and efficient absorption of nutrients by the roots of plants. This is actually effective in reducing the environmental pollution and wastage. These nanoencapsulated supplements seem to be a better substitute for conventional fertilizers.

Various scientific approaches are being applied and studies undertaken to fulfill the requirements of all 22 crucial elements by using nanocomposite materials and nanoclays (Monreal et al. 2016). The fertilizers that are coated with sulphur nanoparticles are used to compensate the amount of sulphur in soil. In this perspective some nanoparticles like kaolin and chitosan have already performed well and give very good results in controlled release of N, P, and K fertilizers. The improved absorption of essential elements from the soil with the help of nanoencapsulation really helped. Protection of plants from various contamination and environmental hazards with upgradation in growth of seeds and roots can be done by using nanosilica or silicon oxide film. To enhance the production of the crop, nonvenomous TiO_2 nanoparticles are being used. Other problems like discharge of water or high rate of dissolving water, denitrification of fertilizers, and sustainable release of fertilizers are being wisely handled by applications of nanomaterials like nanoclays, montmorillonites, zeolites, and bentonites (Morales-Díaz et al. 2017; Mufamadi and Sekhejane 2017; Nasrollahzadeh et al. 2019).

3.3 Nanobiosensors

When nanosensors are arranged with bioreceptors, they collectively form biosensors. These nanobiosensors are very efficient and effective in diagnosis and analysis of atomic-level data of the crop, like detection of pathogens/infections in crop, presence of various chemicals, or moisture content of the soil. Nanobiosensors, made up of antibodies that are encapsulated on fiber optic, can be a good example to sense pathogenic bacteria *Escherichia coli* (Nima et al. 2014). Nanobiosensors are mainly made up of silicon nanoparticles that are fluorescent in nature, and antibodies that are helpful in the detection of various Gram bacteria, for example, *Xanthomonas axonopodis*, which causes severe harm to Solanaceae plants. The specific optical characteristics of Au nanoparticles make them very efficient biosensor for detecting infection, for example the karnal-bunt infection in wheat. Although this is a primary phase of detecting diseases through biosensors, there are many gold biosensors made up of carbon nanotubes (CNTs), nanowires, and silicon nanoparticles that are reported for the diagnosis of plant diseases and pathogens (Nuruzzaman et al. 2016).

3.4 Nanopesticides and Nanoherbicides

Crop production and growth of the plant can be enhanced by developing specific immunity in the plants and by destroying undesirable seeds, grasses, insects, or microorganisms (Ozdemir and Kemerli 2016). However, the excessive use of pesticides could also decrease the process of nitrogen fixation in leguminous plants, and bioaccumulation of pest control chemicals can also deteriorate quality of soil. The application of nanopesticides is really effective and has shown remarkable advantages to overcome these major issues. But the demerit of this process is the frequent runoff and leaching of the soil, which causes major wastage (Pandey 2018a). To resolve this issue, it is essential to encapsulate these pesticides and their sustainable release with increased solubility. Several novel nanoparticles are

Table 1 Outcomes of nanopesticides

S. no.	Nanopesticides	Impacts
1	Ag nanoparticles	Guards oak trees against powdery mildew
2	Hydrophobic nano silica	Controls the spread of *Spodoptera littoralis*
3	Glycol-coated essential-oil-filled polyethylene nanoparticles	Protection of harvest from *Tribolium castaneum*
4	Hydrophobic aluminum silicate nanoparticles as phenolic suspension	Protects *silk worm* from grasserie disease

reported, which are made from silver and titanium oxide, and indicated excellent outcomes to control infection and pest specifically in rice and silkworms (Pandey 2018b). CNTs coated with pesticides, Mancozeb, Zineb, and citric acid have shown remarkable results in controlling the fungal infection. The nanoformulation technique is an efficient method to upgrade the forte and amount of natural constituents. This is obtained because of the anti-pathogenic feature of the nanoparticles and internal immunity of plants (Parisi et al. 2015; Patra and Baek 2017) (Table 1).

Another severe problem that arises in agricultural practice is the growth of weeds along with the crop. Use of herbicides is badly affecting the standing crop and causing deterioration in crop quality and production amount, which is considerably a big loss. Agri-nanotechnology for sustainable agriculture and controlled delivery of herbicides through nanoparticles basically help in proper mixing of herbicides and soil particles, which is very effective in removing the unwanted vegetation without harming the standing crop. Coated nanoparticles are actually very helpful in controlled release and delivery of herbicides in plants. As an example, CNTs containing silver and zinc oxide nanoparticles releasing herbicides containing triazine and ametryn have shown excellent results in controlled release of these herbicides (Prasad et al. 2016, 2017).

3.5 Nanofiltration in Agriculture

Water scarcity is the major problem of agricultural practice at global level. To manage this, development of pocket-friendly equipment and innovative means of irrigation is required, and to cure the water wastage, changing conventional irrigation techniques is needed, although these changes cannot be made in those areas where continual water scarcity is found. Nanotechnology can be helpful in giving rise to solution of this problem; nanosensors give the details about the availability of water in the soil. The use nanofilters is also an effective way to conserve waste water of irrigation with the help of water treatment process (Quist-Jensen et al. 2015). The nanofilters are very useful for removal of hardness and waste water treatment, having dimensions of 0.5–1 nm. It is also suggested that the water used for irrigation should not contain larger particles (>50 μm), heavy metals, or poisonous substances, and must have stumpy salt concentration (Rai et al. 2018). So, it is essential to remove all unwanted substances from the water that is to be used for the purpose of irrigation. The lower quality of water used for irrigation may cause decrease in quality and quantity of the crop. In some countries, where the climate is hot and dry, solar-powered nanofilters have given amazing results. They are found very effective to manage removal of salts from water that is used for irrigation. Application of nanofilters has also shown remarkable enhancement in crop production with the reduction in the demand of fertilizers and irrigation (about 25%) (Raliya and Tarafdar 2014).

3.6 Micronutrient Supply

Although the micronutrients are required in a very small quantity, that is, 100 ppm, they play very significant role in plant physiology. These micronutrients act as activators with so many enzymes. The measured release of important growth hormones of plants has also been observed in chitosan nanoparticles, for example, release of 1-naphthylacetic acid (Rienzie et al. 2019). Nanoparticles of iron oxide when directly applied have shown progressive impact on plant growth. These plants are rich in calcium and their pH value is also high. Nanoparticles containing iron enhanced crop production, protein level, and their weight (Rossi et al. 2014). The dearth of iron in soyabean can also be compensated by an application of nanoemulsion of iron. The presence of micronutrients like Mn, Fe, Cu, B, Zn, and Mo is an essential component of plant growth (Saharan et al. 2013). During the Green Revolution, the drastic increase in the production of crops resulted in a big variation in the concentration of micronutrients in the soil. To compensate the concentration of these micronutrients, nanoformulations of these micronutrients are provided, either through infusion or through spraying on the plants. Nanotechnology actually helps in developing smart seeds by the action of nanoemulsion; these smart seeds are programmed seeds that will germinate only in favorable conditions (Schmid and Stoeger 2016; Sekhon 2014). Smart seeds have very unique properties, like they are capable enough to detect water availability and favorable conditions for their germination and growth. The use of nanosilicon dioxide when applied with SiO_2 in tomato plants has also shown excellent results in germination (Sertova 2015).

3.7 Nanogenetic Changes in Agricultural Crops

Nanotechnology proposes groundbreaking ideas of genetic changes in plants with the help of nanofibers/nanocapsules or nanoparticles. These nano-tools act as a supplier and grasp plant gene and materials regulating the movement of genes. The application of nanofibers in crop modulation, drug supply, and environment

Table 2 Merits of nanoformulation over traditional formulation

Preferable characteristics	Specimens of nanofertilizers
Formulations with the characteristics of sustained release	Nanoformulations are able to manage smartly the dispersion rate of nutrients as per need of the crop
Regulation on distribution and solubility of micronutrients	Micronutrients on nanoformulations increase their solubility and help in disseminating insoluble micronutrients in the soil
Novel methodology for sustained release	Encapsulation of fertilizers through polymer coating specifically monitors the release of nutrients and time intervals
Effective release of nutrients	Nanoformulation potentially increases the time period and efficiency of fertilizers
Percolation of nutrients	Nanoformulation effectively controls and minimizes the loss of nutrients from the soil

impact analysis is widely appreciated. Silicon nanoparticles (mesoporous) have been known for an effective method to transport distant DNA into plant cell (Shweta et al. 2016; Corsi et al. 2018). It has also been reported that nanoparticles that are made up of starch are very efficient in holding and transferring of genetic stuff through cell wall of the plant cell. Nanobiosensors are also playing an important role by noticing the dispersion of pollen grain impurities that arise from modified crops. The merger of nanotechnology and biotechnology has given an amazing way of developing three-dimensional (3D) molecular structure of synthetic DNA sequence as a crystal. The above method can be used to upgrade the crop production by linking and categorizing desired necessary organic compounds like carbohydrates, lipids, and protein fragments to these DNA crystals (Corsi et al. 2018). The agrochemicals encapsulated in nanoparticles are helpful in target-specific sustained delivery of these compounds. They are actually working as a gene gun and giving effective results (Siddiqui et al. 2015; Singh et al. 2018a, b). For example, mesoporous nanosilica and gold-capped NPs have shown excellent result in introducing particular DNA-strands to tobacco and corn plants (Table 2).

3.8 Nanotechnology in Seed Treatment

Seed treatment through nanotechnology gives upgradation in the number and weight of seeds along with weather resistance. This treatment gives about 75% enhancement in dry mass, greater than 15% enhancement in shelf-life, and around 85% enhancement in drought resistance. It has also been observed that there is a threefold increase in vitamin level when they are treated with nanosolutions. This amazingly improves productivity and hence increases revenue (Sozer and Kokini 2009; Subramanyam and Siva 2016; Sun-Waterhouse and Waterhouse 2016).

3.9 Diagnosis of Disease and Pest

Introduction of pest, contaminants, microorganisms, and diseases has led to great harm to agricultural business. The biosensors are extremely useful in the exact and specific detection of such hazards. These biosensors are an efficient tool to make agricultural practice healthier, by averting the occurrence of pests, contagions, and diseases, along with better surveillance of soil health, which automatically results in enhanced productivity and nutrients of food grains (Wakeil et al. 2017; Wang et al. 2017).

3.10 Reinforced Supply of Nutrients and Phytosanitary Products

The novel delivery system in accordance with nanotechnology helps in attaining nutrients and sustained protection of goods, resulting into the upgradation in the quality, magnitude, and the resilience of agricultural products (Wang et al. 2019; Yan et al. 2019) (Fig. 2).

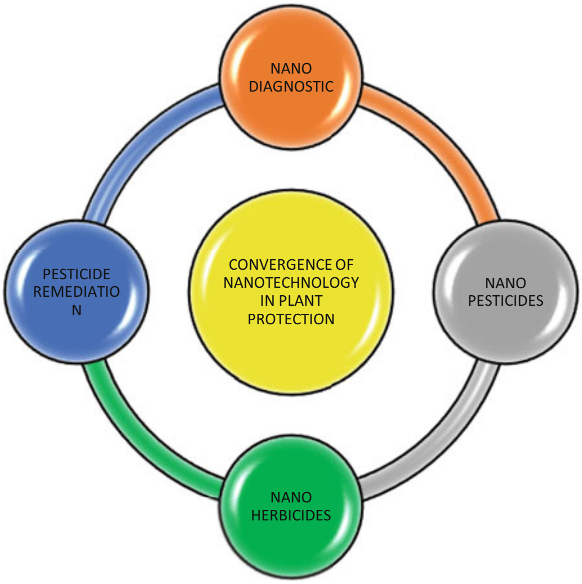

Fig. 2 Nanotechnology in crop protection

3.11 Ecological Aspects of Nanotechnology and Agro-Industry

3.11.1 Viable Use of Water

One of the biggest merits of nanotechnology is seen in desiccated and dry areas, as lesser water availability leads to great damage to the crop production and economy in these areas. The application of nanohydrogels might check the water consumption and enhance the sustainability of crops by controlled absorption of essential nutrients and water (Sozer and Kokini 2009). It has been reported that soil loaded with nanosilver-coated hydrogels is capable to hold 7.5% more water as compared to the normal soil, and hydrogels have shown capacity to store 150 times more water than their weight.

3.11.2 Reduced Pollution and Runoff

Applications of nanotechnology in agricultural practices are extremely helpful in decreasing pollution caused due to chemical fertilizers and treatment practices, and play a significant role in remediation of heavy metals that pollute the soil. This makes possible the use of soil again. Nanosolutions compensate the amount of agrochemicals that have been lost by leaching and runoff and thus effectively conserve the economic loss as well (Yang et al. 2017; Zhang et al. 2016).

4 Agriculture Scenario in India

Indian agriculture is facing an extensive challenge in terms of climatic change, nutrient deficiency, dwindling of cultivable land, stagnancy in crop yield, declining water availability and organic matter in soil, and paucity of manual labor (Pandey 2020).

- The Indian agriculture is still under distress of the fatigue caused by the practices of the Green Revolution. The fertilizer consumption has observed an exponential rise of around four times in the last 50 years of Indian agriculture.
- The existing proportion of 10:2.7:1 for nitrogen, phosphorus, and potassium in India is far off the ideal quotient of 4:2:1. This excessive and unwarranted fertilization is worsening the soil vigor and is an issue of serious concern (Pandey and Jain 2020).
- The extent of nutrient loss is constantly increasing the percentage crop deficit of about 25–30% with every year. In order to sustain the vigor and health of the soil, it is vital to maintain a balanced use of inorganic and organic nutrients; however, the decline in the accessibility of organic nutrients and the subsidy given to the inorganic ones are making it hard to accomplish. Drastic disparities in

meteorological conditions—for instance, the unexpected surge in temperature leading to intermittent droughts, unpredictable rainfalls, thinning of polar icecaps due to global warming, etc.—are additional causes to introduce and adapt alternative approaches in the agri-sector (Pandey 2018c; Prasanna 2007).

5 Challenges

The challenges connected to the sustainable use of nanoparticles for agri-practices are mainly because of the associated health and environmental risks, their co-contamination, and toxicity issues (Yashveer et al. 2014; Singh et al. 2018a, b). The general characteristics and the hazards linked with the usage of nanoparticles are evaluated from the data available in various published articles. The human beings, animals, plants, and the environmental components get the exposure to nanomaterials at some stage during their production, handling, disposal, and managing of the products containing nanoparticles (Sahoo et al. 2021; https://www.azonano.com/article.aspx?ArticleID=5647). The remarkable characteristics of nanoparticles are generally related to their synthesis routes. The chemical composition, tiny dimensions, and shape-effects of nanoparticles are the key reasons to their toxicity that lead to the aggregation and translocation of nanoparticles inside the body causing organ dysfunctions, organ damage, asthmatic attacks, carcinogenic effects, organ enlargements, irreversible oxidative stress, etc. (Singh et al. 2021; Sivarethinamohan and Sujatha 2021; Aamir Iqbal 2020).

6 Future Perspectives

Sustainable agriculture is a coordinated balance between the biotic and abiotic components of agricultural ecosystem for attaining energy balance with the stability of food chains. Nanotechnology has an optimistic prospect for implementing positive changes in the agri-sector to achieve this balance. The applications of nanotechnology certainly can offer inventive and economical solutions and alternatives for enhancing the soil fertility, crop production, pest management, irrigation, and processing and packaging of agricultural products (Seleiman et al. 2021; Chhipa 2016). New skills, specializations, and procedural transformations based on the principles of nanotechnology and increased use of nanochemicals, along with the support, guidance, and regulations from the government, will lead to sustainable growth of agricultural sector. The trailblazing advances in the field of nanotechnology are creating new developments for the reformation of the agricultural sector. Nanosensors have the capability of sensing the pathogens at very low percentage levels (Usman et al. 2020). Nanotechnology provides solutions for converting hazardous and tenacious chemical substances into their harmless or negligibly harmful forms and at times into some advantageous components to be useful to agriculture. Further exploration is needed to reconnoiter in what ways the nanotechnology could aid the nutritional value and the production rate of the crop along with augmenting the nutrient-absorption capacity of soil by using nanofertilizers (He et al. 2019). Further research is necessary in the areas of energy requirement and energy production, crop production, disease diagnosis, detection and control of pollutants from water and soil, protection and packing of food, nutrient supply, and environment management to achieve high and quality yield by effectively using the available resources without altering the environmental sustainability.

7 Conclusion

Agriculture sector being the lone provider of food for all the living beings should necessarily make use of nanotechnology to meet the surging demand of growing population. Nanotechnology has been established as an adept technique to sustainably manage agricultural resources, for the precise delivery of nutrients and drugs to the plants, and for sustaining the fertility of soil. Despite a lot of information in the published articles and patents, still the accurate toxicity information of numerous nanoparticles is unknown and imperceptible. This lacuna in the knowledge, statistics, risk assessment, and management is restraining their wide acceptance and applications. Therefore, it is very much necessary to develop an all-inclusive database, legislations, regulatory policies, and alarm system, along with global cooperation, for successful exploitation of this technology to achieve sustainability in agriculture sector. Nanotechnology in the field of agriculture may still take years to advance from the laboratory to the land, and to achieve this, funds, plans, and support should be provided for this buoyant field to flourish.

References

Aamir Iqbal M (2020) Nano-fertilizers for sustainable crop production under changing climate: a global perspective. In: Sustainable crop production. IntechOpen, London. https://doi.org/10.5772/intechopen.89089

Ajitha B, Ashok Kumar Reddy Y, Sreedhara Reddy P (2015) Green synthesis and characterization of silver nanoparticles using Lantana camara leaf extract. Mater Sci Eng C Mater Biol Appl 49: 373–381. https://doi.org/10.1016/j.msec.2015.01.035

Ali MA, Rehman I, Iqbal A et al (2014) Nanotechnology: a new frontier in agriculture. Nanotechnology, a new frontier in Agriculture. Adv Life Sci 1(3):129–138

Amin M (2018) Nanofiltration systems and applications in waste water treatment: review article. Ain Shams Eng J 9(4):1. https://doi.org/10.1016/j.asej.2018.08.001

Awwad AK, Salem NM, Aqarbeh MM et al (2020) Green synthesis, characterization of silver sulfide nanoparticles and antibacterial activity evaluation. Chem Int 6(1):42–48. https://doi.org/10.5281/zenodo.3243157

Baker S, Volova T, Prudnikova SV et al (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

Bhainsa KC, D'Souza SF (2006) Extracellular biosynthesis of silver nanoparticle using the fungus Aspergillus fumigates. Colloids Surf B Biointerfaces 47:160–164. https://doi.org/10.1016/j.colsurfb.2005.11.026

Castro L, Blázquez ML, Muñoz JA et al (2013) Biological synthesis of metallic nanoparticles using algae. IET Nanobiotechnol 7:109–116. https://doi.org/10.1049/iet-nbt.2012.0041

Chaudhary R, Nawaz K, Khan AK et al (2020) An overview of the algae-mediated biosynthesis of nanoparticles and their biomedical applications. Biomol Ther 10(11):1498. https://doi.org/10.3390/biom10111498

Chhipa H (2016) Nanofertilizers and nanopesticides for agriculture. Environ Chem Lett 15(1): 15–22. https://doi.org/10.1007/s10311-016-0600-4

Contado C (2015) Nanomaterials in consumer products: a challenging analytical problem. Front Chem 3:48. https://doi.org/10.3389/fchem.2015.00048

Corradini E, De Moura MR, Mattoso LHC (2010) A preliminary study of the incorporation of NPK. Express Polym Lett 4:509–515

Corsi I, Winther-Nielsen M, Sethi R et al (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

Cui HX, Sun CJ, Liu Q, Jiang J, Gu W (2010) Applications of nanotechnology in agrochemical formulation, perspectives, challenges and strategies. In: International conference on Nanoagri, Sao Pedro, Brazil, pp 28–33

Cushen M, Kerry J, Morris M et al (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

Darroudi M, Ahmad MB, Abdullah AH et al (2011) Green synthesis and characterization of gelatin-based and sugar-reduced silver nanoparticles. Int J Nanomedicine 2011(6):569–574. https://doi.org/10.2147/IJN.S16867]

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

Dhawan A, Shanker R, Das M et al (2011) Guidance for safe handling of nanomaterials. J Biomed Nanotechnol 7(1):218–224

Du J, Singh H, Yi TH (2017) Biosynthesis of silver nanoparticles by Novosphingobium sp. THG-C3 and their antimicrobial potential. Artif Cells Nanomed Biotechnol 45(2):211–217. https://doi.org/10.1080/21691401.2016.1178135

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

Eychmuller A (2000) Structure and photophysics of semiconductor nanocrystals. J Phys Chem B 104:6514–6528

Fayaz AM, Girilal M, Rahman M et al (2011) Biosynthesis of silver and gold nanoparticles using thermophilic bacterium Geobacillus stearothermophilus. Process Biochem 46:1958–1962. https://doi.org/10.1016/j.procbio.2011.07.003

Feregrino-Perez AA, Magaña-López E, Guzmán C et al (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 et al (2016) Nanotechnology in agriculture: which innovation potential does it have? Front Environ Sci 4:20. https://doi.org/10.3389/fenvs.2016.00020

Garg D, Sarkar A, Chand P et al (2020) Synthesis of silver nanoparticles utilizing various biological systems: mechanisms and applications-a review. Prog Biomater 9(3):81–95. https://doi.org/10.1007/s40204-020-00135-2

Gehrke I, Geiser A, Somborn-Schulz A (2015) Innovations in nanotechnology for water treatment. Nanotechnol Sci Appl 8:1–17

Gour A, Jain NK (2019) Advances in green synthesis of nanoparticles. Artif Cells Nanomed Biotechnol 47:844–851. https://doi.org/10.1080/21691401.2019.1577878

Handy RD, Owen R, Valsami-Jones E (2008) The ecotoxicology of nanoparticles and nanomaterials: current status, knowledge gaps, challenges, and future needs. Ecotoxicology 17(5):315–325

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

He X, Deng H, Hwang HM (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

Hegde K, Brar SK, Verma M et al (2016) Current understandings of toxicity, risks and regulations of engineered nanoparticles with respect to environmental microorganisms. Nanotechnol Environ Eng 1:5. https://doi.org/10.1007/s41204-016-0005-4

Hochella MF Jr, Mogk DW, Ranville J et al (2019) Natural, incidental, and engineered nanomaterials and their impacts on the earth system. Science 363:6434. https://doi.org/10.1126/science.aau8299

Huang L, Weng X, Chen Z et al (2014) Green synthesis of iron nanoparticles by various tea extracts: comparative study of the reactivity. Spectrochim Acta A Mol Biomol Spectrosc 130:295–301. https://doi.org/10.1016/j.saa.2014.04.037

Joseph T, Morrison M (2006) Nanotechnology in agriculture and food, a nanoforum report. www.nanoforum.org

Kalpana-Sastry R, Rashmi HB, Rao NH, Ilyas SM (2009) Nanotechnology and agriculture in India: the second green revolution? Presented at the OECD conference on "Potential environmental benefits of nanotechnology: fostering safe innovation-led growth" session 7. Agricultural nanotechnology, Paris, France

Khanna P, Kaur P, Goyal D (2020) Algae-based metallic nanoparticles: Synthesis, characterization and applications. J Microbiol Methods 163:105656. https://doi.org/10.1016/j.mimet.2019.105656

Kouhkan M, Ahangar P, Babaganjeh LA et al (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

Kuang Y, Wang Q, Chen Z et al (2013) Heterogeneous Fenton-like oxidation of monochlorobenzene using green synthesis of iron nanoparticles. J Colloid Interface Sci 410:67–73. https://doi.org/10.1016/j.jcis.2013.08.020

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

Kumar S, Nehra M, Dilbaghi N et al (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 et al (2019) Recent developments in biosensors to combat agricultural challenges and their future prospects. Trends Food Sci Technol 88:157–178

Lirdprapamongkol K, Warisnoicharoen W, Soisuwan S et al (2014) Eco-Friendly synthesis of fucoidan-stabilized gold nanoparticles. Am J Appl Sci 7:1038–1104

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

Luo F, Yang D, Chen Z et al (2016) One-step green synthesis of bimetallic Fe/Pd nanoparticles used to degrade Orange II. J Hazard Mater 303:145–153. https://doi.org/10.1016/j.jhazmat.2015.10.034

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

Machado S, Pinto SL, Grosso JP et al (2013) Green production of zero-valent iron nanoparticles using tree leaf extracts. Sci Total Environ 445:1–8. https://doi.org/10.1016/j.scitotenv.2012.12.033

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 VJ (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

Menon S, Rajeshkumar S, Venkat Itumar S (2017) A review on biogenic synthesis of gold nanoparticles, characterization, and its applications. Resour Efficient Technol 3:516–527. https://doi.org/10.1016/j.reffit.2017.08.002

Milewska-Hendel A, Gawecki R, Zubko M et al (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

Mohan Kumar K, Mandal BK, Siva Kumar K et al (2013) Biobased green method to synthesise palladium and iron nanoparticles using Terminalia chebula aqueous extract. Spectrochim Acta A Mol Biomol Spectrosc 102:128–133. https://doi.org/10.1016/j.saa.2012.10.015

Monreal CM, DeRosa M, Mallubhotla SC et al (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 et al (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

Mukherjee P, Ahmad A, Mandal D et al (2001) Fungus mediated synthesis of silver nanoparticles and their immobilization in the mycelial matrix: a novel biological approach to nanoparticle synthesis. Nano Lett 1:515–519. https://doi.org/10.1021/nl0155274

Mukhopadhyay SS (2014) Nanotechnology in agriculture prospects and constraints. Nanotechnol Sci Appl 7:63–71

Narayanan R, El-Sayed MA (2005) Catalysis with transition metal nanoparticles in colloidal solution: nanoparticle shape dependence and stability. J Phys Chem B 109:12663–12676

Nasrollahzadeh M, Sajadi SM, Sajjadi M et al (2019) Applications of nanotechnology in daily life. Interf Sci Technol 28:113–143

Nima AZ, Lahiani MH, Watanabe FXY et al (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

Njagi EC, Huang H, Stafford L et al (2010) Biosynthesis of iron and silver nanoparticles at room temperature using aqueous sorghum bran extracts. Langmuir 27(1):264–271. https://doi.org/10.1021/la103190n

Nuruzzaman M, Rahman MM, Liu Y et al (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

Pandey G (2020) Agri-nanotechnology for sustainable agriculture. In: Bauddh K, Kumar S, Singh R, Korstad J (eds) Ecological and practical applications for sustainable agriculture. Springer, Singapore. https://doi.org/10.1007/978-981-15-3372-3_11

Pandey G, Jain P (2020) Assessing the nanotechnology on the grounds of costs, benefits, and risks. Beni-Suef Univ J Basic Appl Sci 9:63. https://doi.org/10.1186/s43088-020-00085-5

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

Prasanna BM (2007) Nanotechnology in agriculture. In: Parsad R, Gupta VK, Bhar LM, Bhatia VK (eds) Advances in data analytical techniques: module- VI. Indian Agricultural Statistics Research Institute, New Delhi

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

Rai PK, Kumar V, Lee SS et al (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. Elsevier, London, pp 279–296

Rossi M, Cubadda F, Dini L et al (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 et al (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

Sahoo M, Vishwakarma S, Panigrahi C et al (2021) Nanotechnology: current applications and future scope in food. Food Front 2:3–22. https://doi.org/10.1002/fft2.58

Salata OV (2004) Applications of nanoparticles in biology and medicine. J Nanobiotechnol 2:3–9

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

Seleiman MF, Almutairi KF, Alotaibi M et al (2021) Nano-fertilization as an emerging fertilization technique: why can modern agriculture benefit from its use? Plan Theory 10:2

Senthil M, Ramesh C, Velur P (2012) Biogenic synthesis of Fe3O34 nanoparticles using Tridax procumbens leaf extract and its antibacterial activity on pseudomonas aeruginosa. Dig J Nanomater Biostruct 7(4):1655–1660

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
Shivaji S, Madhu S, Singh S (2011) Extracellular synthesis of antibacterial silver nanoparticles using psychrophilic bacteria. Process Biochem 46:1800–1807. https://doi.org/10.1016/j.procbio.2011.06.008
Shweta TDK, Singh S, Singh S et al (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 et al (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
Singaravelu G, Arockiamary JS, Kumar VG et al (2007) A novel extracellular synthesis of monodisperse gold nanoparticles using marine alga, Sargassum wightii Greville. Colloids Surf B Biointerfaces 57(1):97–101. https://doi.org/10.1016/j.colsurfb.2007.01.010
Singh H, Du J, Yi TH (2016a) Kinneretia THG-SQI4 mediated biosynthesis of silver nanoparticles and its antimicrobial efficacy. Artif Cells Nanomed Biotechnol. https://doi.org/10.3109/21691401.2016.1163718
Singh H, Du J, Yi TH (2016b) Biosynthesis of silver nanoparticles using Aeromonas sp. THG-FG1.2 and its antibacterial activity against pathogenic microbes. Artif Cells Nanomed Biotechnol. https://doi.org/10.3109/21691401.2016.1163715
Singh J, Dutta T, Kim KH et al (2018a) 'Green' synthesis of metals and their oxide nanoparticles: applications for environmental remediation. J Nanobiotechnol 16:84. https://doi.org/10.1186/s12951-018-0408-4
Singh R, Glick BR, Rathore D (2018b) Biosurfactants as a biological tool to increase micronutrient availability in soil: a review. Pedosphere 28(2):170–189
Singh H, Sharma A, Bhardwaj SK et al (2021) Recent advances in the applications of nano-agrochemicals for sustainable agricultural development. Environ Sci Processes Impacts 23:213–239. https://doi.org/10.1039/D0EM00404A
Sivarethinamohan R, Sujatha S (2021) Unlocking the potentials of using nanotechnology to stabilize agriculture and food production. AIP Conf Proc 2327:020022. https://doi.org/10.1063/5.0039418
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
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
Suganya KS, Govindaraju K, Kumar VG et al (2015) Blue green alga mediated synthesis of gold nanoparticles and its antibacterial efficacy against Gram positive organisms. Mater Sci Eng C Mater Biol Appl 47:351–356. https://doi.org/10.1016/j.msec.2014.11.043
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
Thakkar KN, Mhatre SS, Parikh RY (2010) Biological synthesis of metallic nanoparticles. Nanomedicine 6(2):257–262. https://doi.org/10.1016/j.nano.2009.07.002
Thakur S, Karak N (2014) One-step approach to prepare magnetic iron oxide/reduced graphene oxide nanohybrid for efficient organic and inorganic pollutants removal. Mater Chem Phys 144(3):425–432. https://doi.org/10.1016/j.matchemphys.2014.01.015
Usman M, Farooq M, Wakeel A et al (2020) Nanotechnology in agriculture: current status, challenges and future opportunities. Sci Total Environ 721:137778. https://doi.org/10.1016/j.scitotenv.2020.137778
Venkatesan J, Manivasagan P, Kim SK et al (2014) Marine algae-mediated synthesis of gold nanoparticles using a novel Ecklonia cava. Bioprocess Biosyst Eng. https://doi.org/10.1007/s00449-014-1131-7

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 T, Lin J, Chen Z et al (2014) Green synthesized iron nanoparticles by green tea and eucalyptus leaves extracts used for removal of nitrate in aqueous solution. J Clean Prod 83: 413–419. https://doi.org/10.1016/j.jclepro.2014.07.006

Wang C, Kim YJ, Singh P et al (2016) Green synthesis of silver nanoparticles by Bacillus methylotrophicus, and their antimicrobial activity. Artif Cells Nanomed Biotechnol 44(4): 1127–1132. https://doi.org/10.3109/21691401.2015.1011805

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

Wang P, 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 et al (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 et al (2017) Toxicity assessment of nanoparticles in various systems and organs. Nanotechnol Rev 6(3):279–228

Yashveer S, Singh V, Kaswan V et al (2014) Green biotechnology, nanotechnology and bio-fortification: perspectives on novel environment-friendly crop improvement strategies. Biotechnol Genet Eng Rev 30:113–126

Zhang Q, Han L, Jing H et al (2016) Facet control of gold nanorods. ACS Nano 10:2960–2974. https://doi.org/10.1021/acsnano.6b00258