

## Prospect of Nanotechnology for Sustainable Agriculture

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### Abstract

Nanotechnology has attracted a great deal of research interests in recent years due to its usefulness in several areas like electronics, energetics, optics, medical and bio sciences, catalysis etc. Small Sizes and large surface area of nanoparticles are attributed to their unique physico-chemical properties, which had opened up myriads of potential applications. During the 'Green Revolution' in 1970's, farmers had learnt the use of chemical fertilizers, pesticides, and herbicides and several scientific techniques for farming, which resulted a tremendous rise in the crop production and a positive impact in the economy. However, the crop production rate is about the saturate, hence a worry remains to feed huge global population. Nanotechnology has enpaved new avenue towards sustainability in agriculture to satisfy huge demand of grains and food products of the world. So far, nanomaterials are used in agriculture in the development nano-fertilizers, nano-pesticides or herbicides, nano-sensors, smart delivery systems for nano-genetics and nano-biotechnology, anti-microbial coating, also for water purification, plant disease diagnostics, seed germination, food packaging, crop protection etc. However, several challenges like environment toxicity, adverse effect in food chain, insufficient rules and regulation on nanomaterial usage are still remain, which are being taken care of scientific community.

**Keywords:** Sustainability, Agriculture, Nanomaterials *etc.*

### Introduction

Nanotechnology, an innovative and rapidly evolving field, holds significant promise for revolutionizing sustainable agriculture by enhancing productivity, efficiency, and environmental stewardship. Considering the growing urgency of global issues including soil degradation, water shortages, and the need for higher crop yields, nanotechnology presents innovative solutions by enabling the manipulation of materials at the atomic and molecular scales. Nanotechnology utilizes the principles and methods of the nanoscale to understand and manipulate biosystems through the use of biological principles and advanced nanoscale technologies (Mazumder *et al.*, 2023). The name 'nano' was derived from the Greek language, where it signifies "dwarf". Nano research and Nano Technology is the field of research and technology that focuses on things with spatial dimensions in the nano-meter range, namely from 10<sup>-9</sup> to 10<sup>-7</sup> meters. When bulk objects

shape their dimension in nano regime, remarkable changes occur in structural integrity and in optical, chemical, electronic, magnetic and mechanical properties. Due to unique physico-chemical properties, nano-materials been utilized in development of new devices/products with myriads of potential applications in different branches of science and technologies like agriculture, medical science, electronics, textiles and clothing, energetics, energy equipment etc.

The 'Green Revolution' in 1970's in India has targeted extensive production of semi-dwarf high yielding varieties of rice and wheat and outmost usage of irrigation, fertilizers and agrochemicals. Hence, there was a gigantic growth of production of crops; however, the growth has reached a plateau recently. Hence, there is again a demand of second 'Green Revolution' to attain the demand of food of world's largest population and also to improve the livelihood of farmers (Singh, 2012). Hence sustainability is an important driver at the agricultural sector to attain

global demand of crops at optimum production cost. At this juncture nano-science and nanotechnologies has enlightened a direction in agriculture to the progress of qualities and quantities of crops and foods and also food safety through innovative packaging material (Table 1) (Pokrajac *et al.*, 2021; Schroen *et al.*, 2020). The key application areas of nanotechnology in agriculture are versatile: (1) nanoparticles in the form of fertilizers, pesticides, fungicides to improve qualities of crops, (2) nano-sensors for the detection of diseases and residues of agrochemicals, (3) nano devices for the genetic engineering of plants. Here in, we briefly discuss the key advantages of nanotechnologies for their applications in agriculture. Then it discusses applications and prospects of nanotechnologies for sustainable agriculture. At the end it addresses it discusses several challenges associated with nanotechnologies to attain sustainability in agriculture.

#### **Key Advantages of nanomaterials in sustainable agriculture**

Nanomaterials exhibit excellent physical and chemical behavior due to their nanoscale dimensions. Many materials like fullerene, carbon nanorods, semiconductor quantum dots etc. can be synthesized using easy and relatively cost-effective methods like colloid sciences. There are some nanomaterials like carbon nanofiber, silicon nanowire etc., are also employed in nanoelectronics and nanoionics. Some nanoparticles like silica are biocompatible. Silica, fullerene, semiconductor quantum dots have the ability to be modified at the surface with many functional groups so that they can be dispersed in physiological medium. Due to luminescence properties semiconductor quantum dots and many other nanoparticles or conjugates has been progressively used for biomedical applications like bio imaging, bio sensing, antibacterial activity, drug delivery, and tissue engineering. Besides, nanotechnology requires minimum number of nanomaterials and energy, it has been projected as a technology to reduce work and to provide maintenance inputs to high productive and cheap outputs (Pokrajac *et al.*, 2021). In 2005, a careful investigation under the UN Millennium Project Report, task force on Science, Technology and Innovation had identified that nanotechnologies could enable developing countries to achieve millennium target goals and in turn in global development process.

#### **Different Prospects of nanotechnologies in sustainable agriculture: steps towards sustainable agriculture**

Nanotechnology paves developments of different nano-agrochemical agents to boost the crop production in cost effective methods while reducing the adverse ecological impacts of pesticides, insecticides, antifungal, antimicrobial fertilizers. The prospects or approaches of different nanomaterial to sustainable agriculture are discussed below.

##### **(A) Nano materials as nano-pesticides and nanoherbicides**

Each year about 20-40% crops are spoiled due to attack of different pests and pathogens worldwide (Flood, 2010). Biopesticides are always employed by the farmers to the control of pests and insects beside the conventional chemical pesticides. Chemical pesticides are costly for farmers and affect the environment adversely. Moreover, uncontrolled usage of chemical pesticides enhances the resistivity of pests and insects, diminishes nitrogen fixation in the soil, causes bioaccumulation, and destroys pollinator and other habitats like birds. Nanotechnology is newly adopted strategy in the group of biopesticides, which utilizes nontoxic and environment friendly nanoparticles. Nano-based conventional herbicides and pesticides assist in the slow and controlled supply of nutrients and agricultural chemicals to the plants (Duhan *et al.*, 2017). Pesticides after nano-formulation and nano-encapsulation have several desirable properties: greater solubility, crystallinity, permeability, thermal stability, biodegradability, and stiffness which are appropriate for sustainable farming practices (Dwivedi *et al.*, 2016). These nano pesticides reduce early active ingredient loss, improves plant foliar adherence, increases IPM effectiveness and reduces the adverse effects on non-target species (e.g., soil micro fauna). If properly applied, nano pesticides could increase crop production, food safety, and nutritive quality. It has been observed that metallic nanoparticles have antibacterial, antifungal and antipathogen activities (Saeed *et al.*, 2021). Fusarium Wilt is a soil borne fungal disease of tomato and lettuce, worldwide. *Fusarium oxysporum* is the fungus which reduces the production of tomato every year. Investigation shows when metallic Ag or copper oxide nanoparticle can control the disease in tomato plant. Different doses of MgO nanoparticle are observed to influence on the green peach aphid in a greenhouse habitat (Elmer *et al.*, 2021). Ag nanoparticles are observed to control of sclerotium forming phytopathogenic fungi, when fungal hyphae are exposed to Ag NPs the separation of layers of hyphal wall is damaged causing the destruction of hyphae

(Min *et al.*, 2009). Recently focus was given on nano-encapsulated pesticides to protect encapsulated active reagents from premature degradation and to increase their pest control efficacy for longer period. Nano-encapsulated pesticides are observed to exhibit slow releasing properties with enhanced solubility, permeability, and stability (Nuruzzaman *et al.*, 2016).

#### (B) Nano-fertilizers

The poor efficacy is the major issue with conventional fertilizers. China, is world's largest consumer of nitrogen fertilizers, they confront loss of nitrogen in fertilizers due to vaporization (~ 50%) and leaching (~5-10%). The leached and vaporized chemical fertilizers pose threats to environment too. The World is evolving toward smart and environmentally safe agricultural methods (Singh *et al.*, 2021). Advantages of nano-fertilizers are multifold: (1) Due to large surface area nanoparticle are able to absorb large number of metallic and metallic oxide nutrients and can steadily release those nutrients according to physiological demand of the plant. (ii) Nano-fertilizers have higher nutrition efficiency and environmental sustainability, as their leaching and evaporation is lower than chemical fertilizers. (iii) Nano-fertilizers are absorbed by plant through root or foliage and help plant to resist biotic and abiotic pressure. (iv) Use of nano-fertilizers reduces agricultural expenses. Several nano-particle like silica, Fe, TiO<sub>2</sub>, ZnO, Au *etc.* (Gupta *et al.*) are frequently used to develop various nano-fertilizers. The efficiency of nano-fertilizers is controlled by the nature of both nanoparticles (size, shape and composition) and plant (species, their susceptibility and their ability of uptake nano-fertilizers) (War *et al.*, 2020).

#### (C) Nanogenetic tool for agricultural modification or manipulation

Suitably modified nanotube, nanofibers, nanoshells can perform targeted delivery of genetic materials into the plant body which trigger gene expression and engineer genetic material inside the plants. The strategy of nanogenetic tool was adopted by the researcher to redesign the DNA of the seeds to incorporate desirable traits like changing yield, growth seasons and color of the plant into it. Gene sequencing of plant cells enables the identification of plants; the use of plant trait means and also modifies plant's response against environmental pressures and ailments. Recently, plasmid DNA was successfully injected into intact tobacco and maize cell by the bombardment with gold capped nanoparticles, as gold shell has an easy ability to absorb DNA materials. The plasmid DNA

transferred by gene gun method using gold capped nanoparticles could successfully expressed in intact tobacco and maize tissues. Scientists were also successful in the co-delivery of other molecules like protein along with DNA in tobacco, maize and onion plant tissues. The main advantage of protein delivery along with DNA into the plants is the convenient genome sequencing after the delivery. The genome of crop cultivating plants is massively investigated to rapidly enhance their cost-effective productivity (Branton *et al.*, 2010).

#### (D) Agricultural Diagnostics, Drug Delivery using Nanotechnology

Some nanomaterials like carbon, Ag, silica and aluminosilicates can themselves act as drug or can deliver precise quantities of required drugs, nutrients or agrochemicals to the targeted tissue or cell and hence can minimize the harmful effects of chemical pesticides or herbicides (Sharon *et al.*, 2010). Carbon nanofibers are used to strengthen several natural fibers like coconut and sisal. Carbon nanofibers are employed for making nanopesticides for control release of pesticides (Misra *et al.*, 2013). Ag nanoparticles have been found to have widespread antimicrobial activity. Hence, Agr nanoparticles are applied to plant tissues as drugs before the plant gets infected (Nair *et al.*, 2010). The fungal growth of *Botrytis cinerea* and *Penicillium expansum*, can be inhibited by ZnO nanoparticle, A Silica-Ag nanocomposite is observed to control of various plant diseases (Sharon *et al.*, 2010).

#### (E) Nano-sensors

Nano-sensors have been applied as a microscopic analysis of several targets *e.g.* pollutants and other molecules. There are three main components in a Nanobiosensor: immobilized bioreceptor probes (enzymes, antibodies, nucleic acids, lectins, tissue, microorganisms, organelles) specific to particular analytic molecules, a transducer, and a detector. Nano-sensors are highly target specific, convenient to handle, economical, and can detect at a level much lower as compared to their macroscale analogs. Available nanosensors can be categorized into four categories:

(1) Nano-sensors for pesticide detection: Electrochemical nano-sensors are amalgamation of nanotechnology with electrochemical techniques, which have been explored for the detection of pesticides. Recently, CuO, CuO-TiO<sub>2</sub>, and ZrO<sub>2</sub>, NiO nanoparticles, molybdenum nano-composite, peptide nanotubes and carbon nanotubes *etc.* are utilized for the electrochemical detection of pesticide particles in their microenvironment (Qu *et al.*, 2008; Wang *et al.*,

2014) and they exhibit higher sensitivity relative to optical sensors (Xie *et al.*, 2018). (2) Nano-sensors for detection of heavy metals: Optical nano-sensors (Fluorescence nano-sensor, surface plasmon resonance-based affinity sensor) and electrochemical nano-sensors (electrochemical-luminescence sensor, electrochemical sensor) are mainly utilized for the detection of several heavy metalize. Pb, Hg, Cd, Ag and Cu, which are hazardous for both human and environment. Optical nanosensor designed using nanohybrid quantum dots e.g, CdSe quantum dots for the detection of Cd metal (Wang *et al.*, 2016). Magnetic core (Fe<sub>2</sub>O<sub>3</sub>) encapsulated by thin silica nanoshell is an example of multimodal nanosensor with an immovable spacer arm, and a luminescent quantum dot for the recognition as well as the elimination of the spotted Hg. Such nanosensor can detect upto nanomolar level of Hg<sup>2+</sup>. The Ag nanoparticles stabilized with epicatechin can be used for sensitive detection of Pb<sup>2+</sup>. (3) Nano-sensors for detection of plant pathogens: Such nano-sensors mainly comprises of three different constituents: surface-functionalized nanoparticles, pro-smell fragments and enzymes that slice the pro-fragrances for generating the olfactory output. The detection of pathogens like bacteria is rapid (30 min) with 90.7 % precision and low level of detection at 10<sup>2</sup> CFU/ML (Duncan *et al.*, 2017). Several other nano-sensors of types of optical, electrochemical, and immunosensors were developed to detect plant pathogens and microorganisms. The surface plasmon resonance based optical nano-sensor (using gold nanorods) is able to detect picomolar concentration of Cymbidium mosaic virus or Odontoglossum ring spot virus. (4) Nano-sensors for detection of nanoparticles: There are several nanomaterials (such as humic acids and clay minerals) which occurs in environmentally naturally, some metallic or metallic oxide or composite nanomaterials are due to human deeds are discharged into the soil. These disposed nanomaterials are needed to be monitored as their entry to food chain is highly probable. There are some techniques like micro cavity sensing, which can detect nanoparticles.

#### **(F) Nanotechnology to mitigate abiotic stresses in plants**

In modern agriculture, abiotic stress tolerant plus transgenic plants are on high demand. There had been several research efforts to invent new methodologies to reduce the impacts of several abiotic stresses like drought, salinity, waterlog, temperature extremes, mineral nutrients, and heavy metals on the

natural growth and productivity of plants. Nanobiotechnology is one effort to mitigate abiotic stress in plants and is under investigation. Any natural habitat evolves by the modification of their biochemical, molecular and physiological pathways themselves to survive against harsh environmental conditions. Nanoparticles are applied to regulate or control the activities of antioxidant enzymes like chloramphenicol acetyltransferase (CAT), super oxide dismutase (SOD) and peroxidase which are very effective in overcoming the drought conditions (Beyene *et al.*, 2016). Studies revealed that application of silica nanoparticle induces protein accumulation and regulates antioxidant enzymes under saline conditions and hence results in the rise of chlorophyll II content dry weights. The use of Ag, Cu, ZnO and CeO nanoparticle enhances Physiological responses, osmotic regulation, increase the DW, reduces oxidative stress and the negative effects associated with salinity and hence increases plant development and yield (Noman *et al.*, 2020; Noohpishah *et al.*, 2021; Shi *et al.*, 2016; Torabian *et al.*, 2016. Applications of ZnO, Cu, Zn, silica, TiO<sub>2</sub> and Si nanoparticle efficiently relieves the impact of drought on plants by increasing antioxidant enzyme activity, improving phytohormone levels, and affecting physiological properties. Nanoparticles are the remedy for heavy metal contaminated environment. It has been observed that ZnO, silica, TiO<sub>2</sub>, Fe<sub>3</sub>O<sub>4</sub>, Si and Fe nanoparticles can improve the plant development and photosynthesis, and reduce oxidative stress-induced toxicity due to heavy metal (El-Saadony *et al.*, 2022).

#### **Bioplastic in Indian context**

The Ministry of Environment, Forest and Climate Change of The Government of India has revised the Plastic waste management rule, 2016 in August, 2021. The most striking features of the rule is complete ban on single use plastic (SUP) which cause the most hazard on environment including polystyrene and modified polystyrenes as well as direction to increase the thickness of carry bags (Banerjee *et al.*, 2024). India has an immense availability of massive amount of biomass for effective production of bio-degradable plastic. According to various studies, the bioplastic market in India is expanding at a steady rate. More research work is devoted in the field and hopefully in coming years bioplastics will overcome the present challenges to counter the toxic alternative fossil-fuel plastic (Rafey and Siddiqui, 2021).

#### **Different challenges of nanotechnologies in sustainable agriculture**

Nanotechnology based agriculture has driven farmers towards sustainability in agriculture. However, extensive research is required to remove all hurdles laid in the path. One big challenge is the large-scale synthesis of nanomaterials with narrow size distribution with controlled morphology, as it is expensive and laborious. The synthetic procedure should be green, by products should not lead environmental toxicity. Moreover, chemical synthesis is not always reproducible and infrastructures for the synthesis and characterization are limited, especially in agriculture based developing countries. Many nanomaterials contain metal which exhibit different level of bio-compatibility to different living species. Nanomaterial based agriculture leads to high probability of accumulation metal or metallic oxides in food products and also in the food chain. Hence, the dose level on nano-fertilizes, nano-pesticides, nano-herbicides, nano-gene delivery systems should be different for different plants. Second hurdle in nanomaterials-based agriculture is about incomplete data of nanomaterials with different crop-plants or living species in the food chain. The risks associated with prolonged exposure of farmers to nanomaterials or biotic/abiotic environment have not been assessed extensively, which should be exhaustively studied in laboratories before these nanomaterials are marketer and applied in the agricultural farms. Another common challenge related to commercializing nanotechnology, are: high processing costs, problems in the scalability of R & D for prototype and industrial production and concerns about public perception of environment, health and safety issues. The Governments across the world should form common and strict norms and monitoring, before commercialization and bulk use of these nanomaterials. The use of nanotechnology imposes threats to ecological stability by using toxic nanoparticles and acts as a risky element for human health. Thus, the applications of nanotechnology in agriculture should be monitored and controlled by

strict laws and regulations. However, there have been inconsistencies and differences of surveillance and regulation policies worldwide. Hence the nanomaterial-based agriculture always faces the concerns or threats of acute toxicity on the health of individuals and the environment during the manufacturing, trucking, and managing of nanomaterials. Therefore, there is an urge the area of research in nanotechnology-based farming with efficient regulation of policies for sustainable development of agriculture in the future.

**Conclusion and future perspective:**

Due to climate agricultural researchers have been exposed to several difficulties like alteration in pests, diseases, weed distribution, alteration in the metabolic rate and breeding cycles if insects which can expose the global population to a food crisis. After the first green revolution the rate of increase of production of crops is about to reach a plateau, while world's population curve is still growing upwards. At this juncture, nano-biotechnology and nanotechnology-based agriculture are bearing torch to attain the goal of sustainable literature. Efficient utilization of nanoparticle and their composites will lower production costs of crops and farming hazards and thus inspires world to invent sustainable green revolution. In spite of huge research efforts, there still remain many questions and problems which needed to be answered or resolved. These problems are related to toxicity, biocompatibility, acceptable threshold, and absorption capacity of various nanomaterials. The uptake and effect of nanomaterials on different plats at different stages of their life cycles are also required to be explored extensively. Thus, extensive research should be necessitated vitally to follow the behavior and outcome of changed crops. Simultaneously, thorough investigation has to be input about the interactions of nanomaterials and biological macromolecules found in food chain.

**Table 1:** Commonly used nanoparticles in agriculture (Gupta *et al.*, 2023; Kole *et al.*, 2013; Demirer *et al.*, 2018)

Types of nanoparticles	Applications in agriculture
Polymeric nanoparticles	Able to release delivery materials like agrochemicals
Metallic nanoparticles like Ag, Au and Cu nanoparticles	Applied as nano pesticides, fertilizers and as nano vehicle for the delivery of genetic material, protein and other biomaterials

Nano alumino-silicates, SiO <sub>2</sub> nanoparticle, ZnO nanoparticles, CuO nanoparticles	Applied for the delivery of nano pesticides or nano herbicides
Titanium-oxide nano particles	Applied as disinfectant for water bodies
Fullerene Nanoparticles	Applied for distribution of drugs
Carbon nanotubes	Applied to enhance seed germination, genomic alteration
Semiconductor quantum dots	Bioimaging interaction of nanoparticles with plant cell

## Reference

- Branton, D., Deamer, D.W., Marziali, A., Bayley, H., Benner, S.A., Butler, T., *et al.*, (2008). The potential and challenges of nanopores sequencing. *Nature Biotechnology*, 26(10): 1146-1153. DOI: 10.1038/nbt.1495
- Beyene, A.G., Demirer, G.S. and Landry, M.P. (2016). Nanoparticle-Templated Molecular Recognition Platforms for Detection of Biological Analytes, *Current Protocols in Chemical Biology*, 8(3):197-223. DOI:10.1002/epch.10
- Demirer, G.S., Zhang, H., Matos, J., Goh, N., Cunningham, F.J., Sung, Y., Chang, R., Aditham, A.J., Chio, L., Cho, M.-J., Staskawicz, B. and Landry, M.P. (2018). High aspect ratio nanomaterials enable delivery of functional genetic material without DNA integration in mature plants. *Nature Nanotechnology*, 14(5):456-464. DOI:10.1038/s41565-019-0382-5
- Duhan, J.S., Kumar, R., Kumar, N., Kaur, P., Nehra, K. and Duhan, S. (2017). Nanotechnology: the new perspective in precision agriculture. *Biotechnology Reports*, 15: 11–23. doi.org/10.1016/j.btre.2017.03.002
- Duncan, B., Le, N.D.B., Alexander, C., Gupta, A., Tonga, G.Y., Yazdani, M., Landis, R.F., Wang, L.-S.; Barmaoglu, S., Li, X. and Rottelo, V. M. (2017). Sensing by smell: nanoparticle- enzyme sensors for rapid and sensitive detection of bacteria with olfactory output. *ACS Nano*, 11(6): 5339–5343. doi/10.1021/acsnano.7b008
- Dwivedi, S., Saquib, Q., Al-Khedhairi, A.A. and Musarrat, J. (2016). Understanding the role of nanomaterials in agriculture. *Microbial inoculants in sustainable agricultural productivity*, 17: 271–88. DOI:10.1007/978-81-322-2644-4\_17.
- Elmer, W.H., Zuverza-Mena, N., Triplett, L.R., Roberts, E.L., Silady, R.A. and White, J.C. (2021). Foliar Application of Copper Oxide Nanoparticles Suppresses Fusarium Wilt Development on Chrysanthemum. *Environmental Science & Technology*, 55 (15): 10805–10810. doi.org/10.1021/acs.est.1c02323
- El-Saadony, M.T., Saad, A.M., Soliman, S.M., Salem, H.M., Desoky, E.-S.M., Babalghith, A.O., El-Tahan, A.M., Ibrahim, O.M., Ebrahim, A.A.M., El-Mageed, T.A.A., Elrys, A.S., Elbadawi, A.A., El-Tarabily, K.A. and AbuQamar, S.F. (2022). Role of Nanoparticles in Enhancing Crop Tolerance to Abiotic Stress: A Comprehensive Review. *Frontier in Plant Science*, 13: Article. 946717. doi.org/10.3389/fpls.2022.946717
- Flood, J. (2010). The importance of plant health to food security. *Food Security*, 2(3): 215–231. DOI:10.1007/s12571-010-0072-5
- Gupta, A., Rayeen, F., Mishra, R., Tripathi, M. and Pathak, N. (2023). Nanotechnology applications in sustainable agriculture: An emerging eco-friendly approach. *Plant Nano Biology*, 4: 100033 (1-12). doi.org/10.1016/j.plana.2023.100033
- Kole, C., Kole, P., Randunu, K.M., Choudhary, P., Podila, R., Ke, P.C., Rao, A.M. and Marcus, R.K. (2013). Nanobiotechnology can boost crop production and quality: first evidence from increased plant biomass, fruit yield and phytomedicine content in bitter melon (*Momordica charantia*). *BMC Biotechnology*, 1(37): 1-10. doi.org/10.1186/1472-6750-13-37
- Mazumder, M., Roy, S., Parvin, S., Das, B., Sarkar, A.K. (2023). Nanotechnological Approaches Against Fungal Pathogens of Economically Important Crop Plants. In: Malik, J.A., Sadiq

- Mohamed, M.J. (eds) Modern Nanotechnology. Springer, Cham. [https://doi.org/10.1007/978-3-031-31111-6\\_22](https://doi.org/10.1007/978-3-031-31111-6_22)
- Min, J.-S., Kim, K.-S., Kim, S.-W., Jung, J.-H., Lamsal, K., Kim, S.-B., Jung, M.-Y. and Lee, Y.-S. (2009). Effects of Colloidal Silver Nanoparticles on Sclerotium-Forming Phytopathogenic Fungi. *The Plant Pathology Journal*, 25(4): 376-380. DOI:10.5423/PPJ.2009.25.4.376
- Misra, A.N., Misra, M. and Singh, R. (2013) Nanotechnology in Agriculture and Food Industry. *International Journal of Pure and Applied Science&Technology*, 16(2): 1-9.
- Nair R, Varghese S.H., Nair B.G., Maekawa T, Yoshida Y. and Kumar D.S. (2010) Nanoparticulate material delivery to plants. *Plant Science*, 179(3): 154 163. doi.org/10.1016/j.plantsci.2010.04.012
- Noman, M., Shahid, M., Ahmed, T., Tahir, M., Naqqash, T., Muhammad, S., Sonf, F., Abid, H. M.A. and Aslam, Z. (2020). Green copper nanoparticles from a native *Klebsiella pneumoniae* strain alleviated oxidative stress impairment of wheat plants by reducing the chromium bioavailability and increasing the growth. *Ecotoxicology Environmental Safety*, 192:110303. doi: 10.1016/j.ecoenv.2020.110303
- Noohpisheh, Z., Amiri, H., Mohammadi, A. and Farhadi, S. (2021). Effect of the foliar application of zinc oxide nanoparticles on some biochemical and physiological parameters of *Trigonella foenum-graecum* under salinity stress. *Plant Biosystems*, 155(4): 1-19. doi.org/10.1080/11263504.2020.1739160
- Nuruzzaman, M., Rahman, M.M., Liu, Y. and Naidu, R. (2016). Nanoencapsulation, Nano-guard for Pesticides: A New Window for Safe Application. *Journal of Agricultural and Food Chemistry*, 64 (7): 1447–1483. doi/10.1021/acs.jafc.5b05214
- Pokrajac, L., Abbas, A., Chrzanowski, W. Dias, G.M., Eggleton, B.J., Maguire, S., Maine, E., Malloy, T., Nathwani, J., Nazar, L., Sips, A., Sone, J., Berg, A.v.d., Weiss, P.S. and Mitra, S. (2021). Nanotechnology for a Sustainable Future: Addressing Global Challenges with the *International Network4Sustainable Nanotechnology*. *ACS Nano*. 15(12):18608-18623. DOI:10.1021/acsnano.1c10919
- Qu, Y., Min, H., Wei, Y., Xiao, F., Shi, G., Li, X. and Lin, J. (2008). Au–TiO<sub>2</sub>/Chit modified sensor for electrochemical detection of trace organophosphates insecticides. *Talanta*, 76(4): 758–762. DOI:10.1016/j.talanta.2008.04.045
- Schroen, K., de Ruiter, J., Berton-Carabin, C. (2020) Micro technological Tools to Achieve Sustainable Food Processes, Products and Ingredients. *Food Eng. Rev.* Vol. 12, pp. 101-120.
- Singh, S. (2012) Achieving Second Green Revolution through Nanotechnology in India. *Agricultural Situation in India*, pp. 545 572.
- Saeed, A., Tahira, Qureshi, S. and Bhutta, W.M. (2021). Applications of Nano biotechnology in Plant Sciences. *Biomedical Journal of Scientific & Technical Research*, 35(11): 27236-27240. DOI: 10.26717/BJSTR.2021.35.005632
- Sharon, M., Choudhary, A.K., Kumar, R. (2010) Nanotechnology in Agricultural Diseases and food safety. *Journal of Phytological Research*, 2(4): 83 92.
- Shi, Y., Zhang, Y., Han, W., Feng, R., Hu, Y., Guo, J. and Gong, H. (2016). Silicon enhances water stress tolerance by improving root hydraulic conductance in *Solanum lycopersicum* L. *Frontier in Plant Science*, 7: p.196. doi.org/10.3389/fpls.2016.00196
- Singh, H., Sharma, A., Bhardwaj, S.K., Arya, S.K., Bhardwaj, N. and Khatri, M. (2021). Recent advances in the applications of nano-agrochemicals for sustainable agricultural development. *Environmental Science: Process& Impacts*, 23(2): 213–239. doi.org/10.1039/D0E M00404A
- Torabian, S., Zahedi, M. and Khoshgoftar, A.H. (2016). Effects of foliar spray of two kinds of zinc oxide on the growth and ion concentration of sunflower cultivars under salt stress. *Journal of Plant Nutrition*, 39: 172–180. doi.org/10.1080/01904167.2015.1009107
- Wang, J., Jiang, C., Wang, X., Wang, L., Chen, A.; Hu, J. and Luo, Z. (2016). Fabrication of an “ion-imprinting” dual-emission quantum dot nanohybrid for selective fluorescence turnon and ratiometric detection of cadmium ions. *Analyst*, 141(20): 5886–5892. doi.org/10.1039/C6AN00868B
- War, J.M., Fazili, M.A., Mushtaq, W., Wani, A.H. and Bhat, M.Y. (2020). Role of nanotechnology in crop improvement. *Nano biotechnology in*

- Agriculture. *Springer*, 63–97. DOI:10.1007/978-3-030-39978-8\_4
- Wang, M., Huang, J., Wang, M. *et al.*, (2014). Electrochemical nonenzymatic sensor based on CoO decorated reduced graphene oxide for the simultaneous determination of carbofuran and carbaryl in fruits and vegetables. *Food Chemistry*, Vol. 151:191–197.doi.org/10.1016/j.foodchem.2013.11.046
- Xie, Y., Yu, Y., Lu, L., Ma, X., Gong, L., Huang, X., Liu, G. and Yu, Y. (2018). CuO nanoparticles decorated 3D graphene nanocomposite as non-enzymatic electrochemical sensing platform for malathion detection. *Journal of Electroanalytical Chemistry*, 812: 82–89.doi.org/10.1016/j.jelechem.2018.01.043

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