Nanotechnology in Agriculture

Rinki Deka[a], Mukul Kalita[b*]

[a] *Department of Chemistry, Gauhati University, Guwahati. Assam, India, PIN-781014*

[b] *Department of Chemistry, Pandit Deendayal Upadhyaya Adarsha Mahavidyalaya, Amjonga, Assam, India, PIN-783124*

Abstract

Nanoparticles are not a recent occurrence in nature; they can be found in nature in the form of minerals, clays, bacterial byproducts etc. Apart from various perspectives of nanotechnology, it plays a crucial role in agriculture. Conventionally, chemical fertilizers, herbicides, pesticides etc. are heavily used in agriculture to sustain production, which have major adverse effects on the environment and human health. Again, as a result of pest infestation, microbial attacks, natural disasters, poor soil quality, and a lack of available nutrients, roughly one-third of crops grown conventionally suffer harmful effect. Abiotic stresses like drought stress, salinity stress, and flood stress are major concerned issues including critical issues like the increasing continuous food demands due to expanding global population. All of these issues cannot be mitigated by using the conventional procedures. Consequently, there is a pressing need to look for better options. Nanotechnology's use in this context has the potential to revolutionise agriculture's transition to sustainable practises. It has been extensively researched how to maintain plant health and soil using a variety of nanoparticle-based formulations, including nano-sized insecticides, herbicides, fungicides, fertilizers, and sensors etc. Although nanoparticles have been effectively applied to plants as fertilizers or to promote plant development, little is understood about the mechanism by which nanoparticles migrate across the cell walls. This chapter summarises current efforts to implement cutting-edge nanotechnology in agriculture in diverse directions including socio-economic issue, challenges, which may make it easier to meet the rising need for sustainable food production.

Keywords

Nanotechnology, Nanoparticles, Agriculture, Nano pesticide, Nano fertilizer, Nano herbicide

---

**Corresponding author. Tel: +91 9678613061*

Email Addresses - rinkideka22@gmail.com (R. Deka), mukulkalita88@gmail.com (M. Kalita)

1.1 Introduction

Nanotechnology has attracted a lot of attention due of its numerous uses in fields including medicine, pharmaceuticals, catalysis, agriculture, energy, and materials in recent years. Nanoparticles have the size in the range from 1 to 100 nm. Scientists have made substantial efforts to create nanoparticles using a variety of techniques, including physical, chemical, and biological ones. Also, plant extract-based green approaches for synthesising nanoparticles have the advantages of being quick, easy, and environmentally benign **[1].** The potential for improving fertilization, plant growth regulators, and insecticides in agriculture could be increased by using nanomaterials produced using sustainable ways. The development of a new generation of agrochemicals with the goal of lowering adverse environmental effects while preserving crop yields is made possible by the rapid transformation of agriculture and agricultural production brought about by nanotechnology **[2].** Nanomaterials in agriculture constitute one of the most cutting-edge methods for protecting crops due to their potential use as nanopesticides or as nanocarriers or as nonherbicides for active substances. In addition, the possibility of creating highly advanced nanometric materials out of agricultural and industrial wastes allows for the combination of nanotechnology and the circular economy idea **[3].** The issue of ensuring food security for the world population that is continually expanding is the biggest global concern facing by humanity. Chemical fertilizers and insecticides are widely used in agriculture to sustain production. However, it has been observed that a major negative influence on the environment and poses threat to human life exists **[4].** This necessitates the need to modernise agricultural methods with the safest and most efficient technology that concentrate on increased agricultural output with little negative impact on the environment or people. Nanoparticles act as efficient pesticide alternative as well as developing nano-formulations of agrochemicals for increased crop protection and yield **[5].**

In this chapter we discuss the various perspectives and significance of applying nanotechnology in agriculture and also discusses how various nanoparticles are applied in agricultural fields to increase production including socio-economic effects and various challenges faced by scientific community (**Figure: 1**).

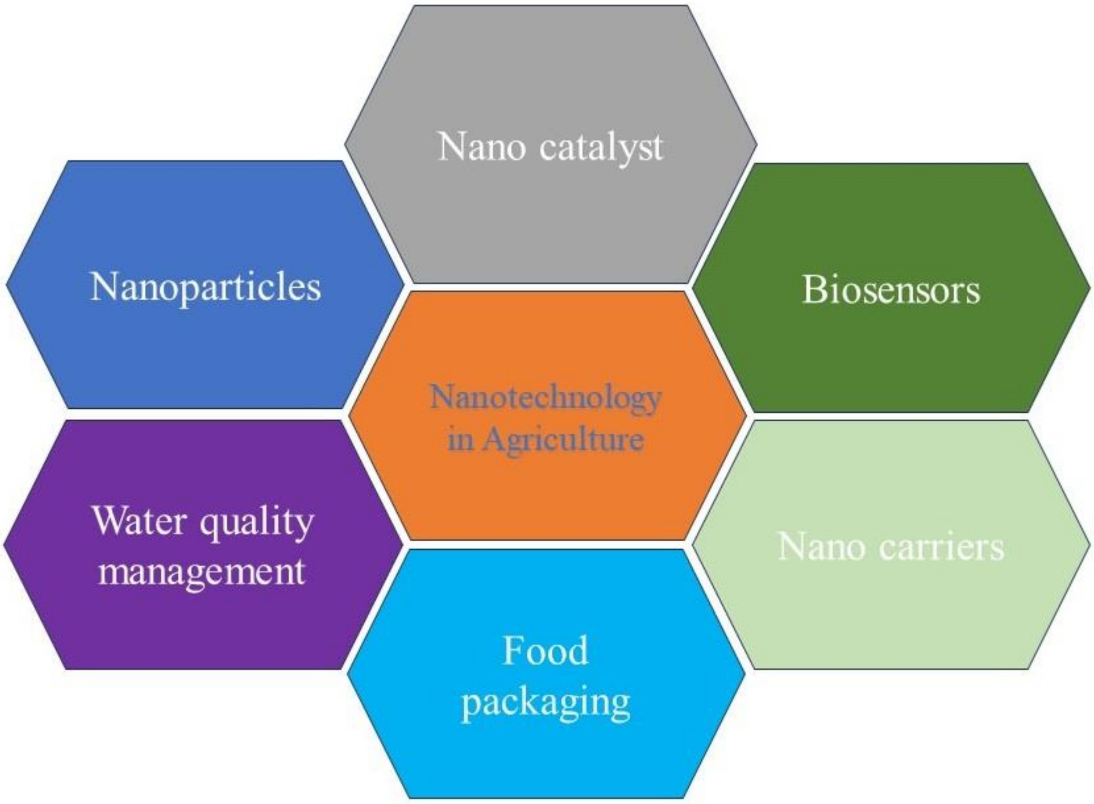

Figure: 1-Nanotechnology in Agriculture

1.2 Fundamentals of nanotechnology

Nanomaterials can be defined as natural or manufactured materials, typically ranging between 1 and 100 nm. Nanotechnology is an interdisciplinary branch of research that combines the fields of chemistry, engineering, physics, and materials science etc. It is a branch of science whose major goal is to create nanoscaled materials with precise shapes, sizes, morphological characteristics and various industrial methods of synthesis **[6].** At the nanoscale, materials can exhibit unusual physical, chemical, and biological characteristics. These characteristics could be fundamentally different from those of bulk materials and individual atoms or molecules. These materials have exceptional functional, magnetic, optical, electrical, and mechanical properties **[7].** Adding nano components frequently causes significant changes in the bulk characteristics of materials. Nano-sized ceramic or metal particles that are used to make composite materials can unexpectedly become significantly stronger than what is predicted by current materials science models **[8].** When compared to the same mass of material generated in a bigger form, nanoparticles have a substantially higher surface area. This may alter the strength or electrical characteristics of the material and increase its chemical reactivity (in certain situations, materials that are inert in their larger form become reactive when created in their nanoscale form) **[9].** At the nanoscale, particularly at the lower end, quantum effects may start to predominate the behaviour of matter, influencing how materials behave optically, electrically, and magnetically **[10].** Researchers from all over the world have been looking at various synthesis routes for nanomaterials, including physical, chemical, and biological techniques. There are significant worries over the release of dangerous toxic byproducts that typically accompany the synthesis process, despite the considerable control that can be exerted over the size and structure of nanomaterials through chemical and physical synthesis approaches **[11].** There are a large number of applications of nanoparticles such as nano capacitors-based filters, nano cables, nano transformer, nano insulators, nano based rectifiers, nano powders **[12]** used for welding rods and electrodes, nano engineering materials, nano sic arrestors **[13],** nano ZnO arrestors, nano capacitor-based microphones, nano technology used in receivers, nano alloys, nano electrets, nano thermo-electric materials nano nuclear engineering, nano medicines etc **[14].**

1.3 Application of nanotechnology in agriculture

There are a large number of applications of nanotechnology in different fields. Here, we will focus on agriculture. Applications of nanotechnology in agriculture are intended to boost output and safeguard crops while reducing any possible negative effects on the environment. In agriculture, "smart" delivery systems made of nanomaterials can precisely release nutrients or medications, improving plant health and yield **[15].** For instance, nano sensors are used to track soil quality and spot pests or illnesses, enabling prompt and targeted treatment. Polymeric nanoparticles are employed to deliver agrochemicals slowly and precisely in the agriculture sector **[16].** Polymeric nanoparticles have several benefits, including greater biocompatibility and less effect on creatures that aren't intended to be affected. Some of the polymeric nanoparticles are employed in agriculture, include polyethylene glycol, poly(epsilon-caprolactone) etc **[17].** On the other hand, the antibacterial properties of silver nanoparticles against a variety of phytopathogens are widely exploited. It is found that silver nanoparticles have been found to promote plant development **[18].** Again, for better seed germination, carbon nanoparticles like graphene, graphene oxide, carbon dots, and fullerenes are utilised **[19].** Other nanoparticles those are utilised in agriculture include magnetic copper oxide, and zinc oxide nanoparticles etc **[20].** In case of crop productivity, researchers able to greatly rise crop production by using nano pesticides and nano herbicides for weed and pest management including nano fertilizers. The formulations for nano herbicides use a variety of nanoparticles includes inorganic and polymeric nanoparticles. Additionally, nano-encapsulation of fertilizers and pesticides increases the effectiveness of managing nutrients and pests by lowering the overall amount of these chemicals required and limits their discharge into neighbouring ecosystems **[21].** For instance, the pesticide atrazine is enclosed in poly (epsiloncaprolactone) nanoparticles. This nano capsule demonstrated effective control of the targeted species, a low level of genotoxicity, and the ability to considerably limit atrazine mobility in soil **[22].** Each year, microbiological (virus, fungus, and bacteria) illnesses cause significant losses in the agriculture sector. Specific antibacterial nanomaterials are deployed in preventing microbial infestations. Colletotrichum gloeosporioides, Fusarium oxysporum, Fusarium solani, and Dematophora necatrix are a few of the typical pathogenic fungi that cause infections **[23, 24].** Many nanoparticles, including copper and nickel ferrite nanoparticles, have potent antifungal properties and are utilised to manage illness **[25].** Chitosan nanoparticles, zinc oxide nanoparticles, and silica nanoparticles are beneficial in the treatment of viral infections, including the mosaic virus for tobacco, potatoes, and lucerne **[26].** Hence, we could tell that nanotechnology has greatly influenced the agricultural field in diverse ways (**Figure: 2**).

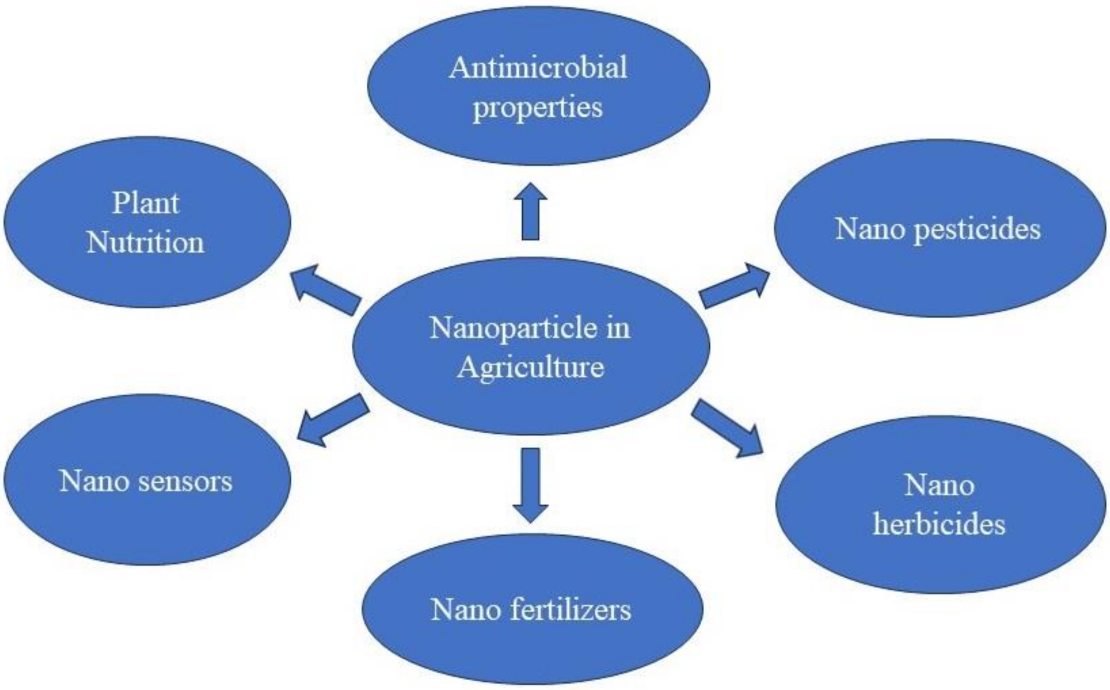

Figure: 2-Applications of Nanoparticles in agriculture

1.4 Interaction of nanoparticle with plant

Agriculture can get benefit from the development of more efficient and less contaminant agrochemicals (nanoformulations), devices that detect biotic or abiotic stresses before they affect production (nano sensors), or new genetic manipulation techniques that allow for greater efficiency during plant breeding programmes (nanotechnologies) **[27].** The plant uptake of nanoparticles is affected by several factors related to the nature of the nanoparticle itself, but also with the plant physiology and the interaction of the nanomaterials with the environment. The characteristics of a nanoparticle will have a significant impact on how it behaves and, consequently, whether a plant can absorb it **[28].** Nanoparticles can change in terms of their characteristics for being digested by plants as a result of interactions with other environmental elements. There are two methods for nanoparticles to migrate through tissues once they have entered the plant: *through the apoplast and the symplast* **[29]**. While symplastic transport involves movement of water and substances between the cytoplasm of adjacent cells through specialised structures called plasmodesmata and sieve plates, apoplastic transport occurs outside the plasma membrane through the extracellular spaces, cell walls of adjacent cells, and xylem vessels **[30].** The apoplastic channel is crucial for radial movement inside plant tissues and enables nanoparticles to enter the vascular tissues and root central cylinder for continued ascent of the aerial portion. After entering the central cylinder, nanoparticles can travel through the xylem and towards the aerial portion by tracing the transpiration stream. The movement of nanomaterials throughout plants is very significant since it can provide clues as to which areas of the plant they can access as well as potential final destinations and accumulation sites **[31].** In addition to the plant species, the properties and nature of the nanomaterials will have a significant impact on how they are transported and accumulated in plant tissues. Nanomaterials must be internalised by the plant cell and pass the plasma membrane in order to move via the symplastic pathway. Although these mechanisms are well understood in animal cells and less well understood in plant cells, nanoparticles can accomplish this in a number of different ways **[32, 33].**

Endocytosis: The nanoparticles enter the cell through invagination of the plasma membrane, resulting in the formation of a vesicle that can move to various cell compartments **[34].**

Pore formation: Some nanomaterials can disrupt the plasma membrane, causing pores to form that allow them to enter the cell and reach the cytoplasm without being encapsulated in any organelle **[35].**

Carrier proteins: Nanoparticles can bind to nearby proteins, including cell membrane proteins, which may serve as carriers for internalisation and uptake inside the cell **[32, 36].**
Plasmodesmata: Nanomaterials can also enter cells via plasmodesmata, which are specialised structures for transporting materials between cells. Of course, the nanoparticles must already be in the symplast, yet this method is critical in plants for translocation across the phloem **[37].**
Ion channels: These have been postulated as potential entry points for nanoparticles into cells. However, the size of such channels is roughly 1 nm, making it exceedingly unlikely that nanoparticles will be able to cross them successfully without significant alterations **[32, 33].**

1.5 Detection of plant diseases

Nanomaterials are useful in a variety of sectors, including life science, electronics, and chemical engineering, because to their distinctive and adaptable physicochemical features. Due to the necessity to create efficient miniaturised systems to enhance seed germination, growth, and plant protection from abiotic and biotic challenges, nanotechnology has recently attracted interest in plant research. In order to effectively control and manage illnesses and reduce crop loss, early and effective disease identification is essential **[38-40].** The most popular nanoparticles employed for molecular detection are gold nanoparticles, magnetic nanoparticles, and quantum dots. Due to their distinctive physiochemical characteristics, such as small size, surface effect, and catalytic effect, gold nanoparticles are frequently used in rapid immune diagnosis. They can also react with nucleic acids through an Au-S covalent bond and have a high application value in DNA identification and detection. In order to safeguard crops against epidemic illnesses, the cutting-edge discipline of nano-phytopathology employs nanotechnology for early detection, diagnosis, and management of plant disease and its pathogens **[41, 42].** The modern plant pathologist works to put his study of nano phytopathology to use in developing and/or evaluating eco-friendly diagnostic tools as well as understanding the governing variables of plant diseases. To monitor or comprehend pathogen population genetics, plant-microbe interactions, and gene transfer between pathogens and even the host, modern nano molecular techniques are applied. In addition, antibacterial and antifungal drugs have recently been developed using nanoparticles like nanosized silica-silver **[43].** Nanomaterials can also be employed for mycotoxin detection and detoxication, boosting plant resistance, predicting plant diseases, and nano-molecular diagnostics of plant pathogens. The bio-barcode assay is an incredibly sensitive way to find proteins or nucleic acids. DNA bio-bar coded tests use magnetic gold nanoparticles (AuMNPs) customised with oligo nucleotides for signal amplification and for the quick separation of a target protein from the sample. The high b-DNA-to-recognition agent ratio provides a way to amplify the signal significantly. It is especially promising since under ideal conditions, it enables the rapid detection of a wide range of protein targets at low concentrations and nucleic acids at high-zeptomolar levels **[44-46].** The bio-barcode assay is a novel idea that offers a potential substitution for the PCR (Polymerase chain reaction) method. Currently researchers focus on the use of nanotechnology for more rapid, affordable, and accurate plant disease diagnosis processes. In the coming years, this technology will have a significant impact on Indian agriculture. Utilising technology responsibly will create chances for the creation of novel materials and techniques that will improve our capacity to create analytical systems that are quicker, more dependable, and more sensitive **[47, 48].**

1.6 Food security and the use of nanotechnology

Around the world, people are very concerned about issues related to food security and safety. With the use of nanotechnology, there will be fantastic chances to increase agricultural output and improve food safety **[49].** To provide better food security, it is necessary that the nanotechnology must be applicable to all the component of food chain from fram to fork. The components include fram inputs, fram production system, postharvest management, processing, markets and finally consumers **[50].** Nanotechnology helps us to reduce framcosts, raise the value of production, increase rural incomes and enhance the quality of the natural resource base of agricultural production system **[51].**

Food production: Food availability is a necessary condition for food security. Food production can be enhanced by applying nanotechnology at fram level. Nanotechnology based biosensors deployed in crop fields and in the plants to monitor soil conditions, growth, and disease factors, can expand the concept of precision farming in which productivity can be optimized while providing inputs and conditions only in precise levels necessary **[52, 53].**

Food safety: Food safety means that all food products must be protected from chemical, biological, physical and radiation contamination during processing, handling and distribution.

Nanotechnology can fulfil the entire requirement to ensure the food safety. Nanotechnology is used to make nano-sensors which enable rapid testing of raw and processed food products in factory and during transport **[54, 55].**

Nanoparticles are employed in the food processing industry to improve food stability and preservation of food colour. Silicate nanoparticles can limit moisture loss and oxygen flow in packaging containers. This guarantees that the food stays fresh for a longer period of time. Numerous nanoparticles have the ability to selectively bind to infections, which can then be completely eliminated. The growth of biofilms can be prevented by using nanoparticles **[56].** An impenetrable barrier is created by biofilms, which are collections of closely spaced bacterial cells adhered to a variety of surfaces. These biofilms cause issues such buildup, biofouling, and biocorrosion in the food processing sectors. Against several Gram-positive bacteria, glycerol monolaurate has antibacterial properties. Three separate strains of MRSA (Methicillin-resistant Staphylococcus aureus) and S. aureus are prevented from forming biofilms using this technique. Organic substances (such as essential oil) have antibacterial qualities and are extremely sensitive to harsh physical conditions. But inorganic nanoparticles exhibit potent antibacterial activity at low concentrations and are more durable under harsh environments. As a result, manufacturers have recently expressed a strong interest in employing these nanoparticles in food packaging that is antibacterial **[57-59].** Extreme environmental conditions frequently lead to the degradation and eventual inactivation of bioactive substances found in food. Because these bioactive components can lengthen the shelf life of food goods by slowing down or halting the process of degradation until the product reaches the target site, nanoencapsulation of these bioactive ingredients is crucial. For instance, when curcumin, a medicinal component from Curcuma longa (turmeric), is enclosed, it becomes stable at various ionic strengths **[60, 61].**

1.7 Socio economic issues of agricultural nanotechnology

A chemical, industrial, and corporate agri-food system is becoming entrenched by the use of nanotechnology in high-tech farming methods. While embracing new technology is important, it is also our responsibility to monitor how these materials are being used in various fields. In a socioeconomic setting where various experiments are continually being conducted, food is a crucial component. Sustainable economic development would never be possible without having a strong scientific and technological basis **[63-66].** Because of its robust communication channels with other industries, the nanotechnology industry is playing a significant role in economic development. The nanotechnology sector is thought to be at the centre of the coming unstoppable technological revolution, and it significantly contributes to the expansion of the world economy **[67, 68].** Scientists, researchers, investors, and legislators worldwide are aware of nanotechnology's tremendous power because it has several applications in all industries. In the current global economy, highly developed nations are engaged in parallel and complementary nanotechnology competition with one another. As measured by economic growth, increased health and longevity, environmental protection, heightened security, social vitality, and improved human capabilities, nanotechnologies will support a new wave of industrial expansion that will magnify current resource and energy use **[69-72].** Our above discussion enables us to comprehend that whatever nanoparticles we use in the agriculture sector will originate from an agricultural field and travel from there to a main producer and customer. Thus, it will disrupt the ecological system as a whole, which could affect environmentally friendly practises. This information will help us to think not only for maintaining the food quality but also will help to maintain the eco-factors of the society in the future.

1.8 The challenges of nanotechnology in food and agriculture system

There are a lot of challenges of nanotechnology in food and agricultural systems. Achieving the necessary scale and quality for the production of nanomaterials is the one most challenging part in agricultural nanotechnology **[73, 74].** Providing nanomaterials in a way that would enable integration into the processes (such as the right particle size, surface chemistry, compatibility, etc.) depends upon various factors which is also a challenging part. Due of their varied characteristics and behaviours, the hazards carried out by nanomaterials to human health and the environment are difficult to evaluate **[75].** Because the size, shape, and charge of these materials affect their kinetic (absorption, distribution, metabolism, and excretion) and hazardous properties, even nanomaterials with the same chemical composition with different sizes or forms may exhibit remarkably varied toxicity **[76].** The usage and disposal of nano goods and materials in food and agriculture must take environmental health and safety considerations into consideration strictly. Another difficulty with nanotechnology, as with many other technologies, is the distance between fundamental research and implementation **[77].** In addition, nanotechnology in agriculture carries significant hazards. Either those nanotechnologies are completely safe for health or that they are hazardous cannot be said with certainty **[78].** Before making any decisions, it is important to take into account the risks connected with farmer's long-term exposure to nanomaterials, their unknown life cycles, interactions with the biotic or abiotic environment, and any potential increased bioaccumulation effects **[79, 80].**

1.9 Conclusion and future prospects

The application of nanotechnology could enable quick advancements in agricultural research that would produce enormous quantities of seeds and fruits without regard to the time of year. India will face significant challenges in the future, particularly as a result of climate change and the world's expanding population. The use of nanotechnology in agriculture enhances soil health and agricultural practises. In reality, the use of nanoscale transporters and compounds can improve the efficient use of fertilizers and pesticides, lowering the amount that must be sprayed while maintaining yield. Increased input efficiency, balanced crop nutrition, nano-herbicides for efficient weed control, nano-insecticide, smart delivery systems, nano-devices for identity preservation, the nano-food industry, environmental safety and sustainable farming, among others, are all possible under the influence of nanotechnology. The agricultural industry will be assisted in its fight against viruses, spores, and other crop pathogens by smart sensors and smart delivery systems. The efficiency of insecticides and herbicides will be improved by nanostructured catalysts, enabling the use of measured doses when needed. In the future, agricultural systems might be made intelligent using nanoscale technologies in tackling the risks and environmental impact on human health including plants.

References

1. Mohammadi, Masoud, et al. "Boehmite nanoparticles as versatile support for organic–inorganic hybrid materials: Synthesis, functionalization, and applications in eco-friendly catalysis." *Journal of Industrial and Engineering Chemistry* 97 (2021): 1-78.
2. Shelar, Amruta, et al. "Recent advances in nano-enabled seed treatment strategies for sustainable agriculture: Challenges, risk assessment, and future perspectives." *Nano-Micro Letters* 15.1 (2023): 54.

3. Kumari, Avnesh, et al. "Nanotechnology as a Powerful Tool in Plant Sciences: Recent Developments, Challenges and Perspectives." *Plant Nano Biology* (2023): 100046.
4. Sharma, Nayana, and Ritu Singhvi. "Effects of chemical fertilizers and pesticides on human health and environment: a review." *International journal of agriculture, environment and biotechnology* 10.6 (2017): 675-680.
5. Kumar, Sandeep, et al. "Nano-based smart pesticide formulations: Emerging opportunities for agriculture." *Journal of Controlled Release* 294 (2019): 131-153.
6. Abid, Namra, et al. "Synthesis of nanomaterials using various top-down and bottom-up approaches, influencing factors, advantages, and disadvantages: A review." *Advances in Colloid and Interface Science* 300 (2022): 102597.
7. Sajid, Muhammad. "Nanomaterials: types, properties, recent advances, and toxicity concerns." *Current Opinion in Environmental Science & Health* 25 (2022): 100319.
8. Yang, Yong, Jie Lan, and Xiaochun Li. "Study on bulk aluminum matrix nano-composite fabricated by ultrasonic dispersion of nano-sized SiC particles in molten aluminum alloy." *Materials Science and Engineering: A* 380.1-2 (2004): 378-383.
9. Sobolev, Konstantin, et al. "Nanomaterials and nanotechnology for high-performance cement composites." *Proceedings of ACI session on nanotechnology of concrete: recent developments and future perspectives* 7 (2006): 93-120.
10. Wautelet, Michel. "Introduction to the Nanoworld." *Key Engineering Materials* 444 (2010): 1-15.
11. Kurhade, Pranali, Shyam Kodape, and Rohit Choudhury. "Overview on green synthesis of metallic nanoparticles." *Chemical Papers* 75.10 (2021): 5187-5222.
12. Ganesan, Lieutenant J., and D. Edison Selvaraj. "Analysis of Thermal and Electrical Properties of Enamel Filled with Various Nanofillers such as ZrO_2, Al_2O_3 and CNT." *International journal of engineering research* 2.2 (2013): 178-182.
13. Pouraliakbar, Hesam, et al. "Predicting Charpy impact energy of Al6061/SiCp laminated nanocomposites in crack divider and crack arrester forms." *Ceramics International* 39.6 (2013): 6099-6106.
14. Sun, Yingman, et al. "Recent advances in Cu (II)/Cu (I)-MOFs based nano-platforms for developing new nano-medicines." *Journal of Inorganic Biochemistry* 225 (2021): 111599.
15. Panpatte, Deepak G., et al. "Nanoparticles: the next generation technology for sustainable agriculture." *Microbial Inoculants in Sustainable Agricultural Productivity: Vol. 2: Functional Applications* (2016): 289-300.
16. Vemula, Madhavi, and A. Reddy. "Polymeric nanoparticles as effective delivery systems in agriculture sustainability." *Nanotechnology for Environmental Engineering* (2023): 1-10.
17. Kumari, Avnesh, Sudesh Kumar Yadav, and Subhash C. Yadav. "Biodegradable polymeric nanoparticles-based drug delivery systems." *Colloids and surfaces B: biointerfaces* 75.1 (2010): 1-18.
18. Siddiqi, Khwaja Salahuddin, and Azamal Husen. "Plant response to silver nanoparticles: a critical review." *Critical Reviews in Biotechnology* 42.7 (2022): 973-990.

19. Chua, Chun Kiang, et al. "Synthesis of strongly fluorescent graphene quantum dots by cage-opening buckminsterfullerene." *Acs Nano* 9.3 (2015): 2548-2555.
20. Priyanka, N., et al. "Role of engineered zinc and copper oxide nanoparticles in promoting plant growth and yield: present status and future prospects." *Advances in Phytonanotechnology* (2019): 183-201.
21. Ghosh, Sougata, Sirikanjana Thongmee, and Ajay Kumar, eds. *Agricultural nanobiotechnology: Biogenic nanoparticles, nanofertilizers and nanoscale biocontrol agents*. Woodhead Publishing, 2022.
22. Chen, Xiao-ting, and Tongxin Wang. "Preparation and characterization of atrazine-loaded biodegradable PLGA nanospheres." *Journal of Integrative Agriculture* 18.5 (2019): 1035-1041.
23. Rodrigues, Sónia M., et al. "Nanotechnology for sustainable food production: promising opportunities and scientific challenges." *Environmental Science: Nano* 4.4 (2017): 767-781.
24. Wang, Su-Yan, et al. "Biocontrol ability of phenazine-producing strains for the management of fungal plant pathogens: A review." *Biological Control* 155 (2021): 104548.
25. Rabbani, Atiya, et al. "Development of bactericidal spinel ferrite nanoparticles with effective biocompatibility for potential wound healing applications." *RSC advances* 11.3 (2021): 1773-1782.
26. Sofy, Ahmed R., et al. "Molecular characterization of the Alfalfa mosaic virus infecting Solanum melongena in Egypt and the control of its deleterious effects with melatonin and salicylic acid." *Plants* 10.3 (2021): 459.
27. Pérez-de-Luque, A., and M. C. Hermosín. "Nanotechnology and its use in agriculture Bio-nanotechnology: A Revolution in Food, Bomedical and Health Sciences; eds. D. Bagchi, M. Bagchi, H. Moriyama, F. Shahidi." (2013): 299-405.
28. Kah, Melanie. "Nanopesticides and nanofertilizers: emerging contaminants or opportunities for risk mitigation?." *Frontiers in chemistry* 3 (2015): 64.
29. Roberts, Alison. "Plasmodesmata and the control of symplastic transport. Plant Cell Environ." *Plant, Cell and Environment* 26 (2003): 103-124.
30. Servin, Alia D., et al. "Synchrotron verification of TiO2 accumulation in cucumber fruit: a possible pathway of TiO2 nanoparticle transfer from soil into the food chain." *Environmental Science & Technology* 47.20 (2013): 11592-11598.
31. Lv, Jitao, et al. "Accumulation, speciation and uptake pathway of ZnO nanoparticles in maize." *Environmental Science: Nano* 2.1 (2015): 68-77.
32. Schwab, Fabienne, et al. "Barriers, pathways and processes for uptake, translocation and accumulation of nanomaterials in plants–Critical review." *Nanotoxicology* 10.3 (2016): 257-278.
33. Rico, Cyren M., et al. "Interaction of nanoparticles with edible plants and their possible implications in the food chain." *Journal of agricultural and food chemistry* 59.8 (2011): 3485-3498.

34. Feng, Youzhi, et al. "The role of metal nanoparticles in influencing arbuscular mycorrhizal fungi effects on plant growth." *Environmental science & technology* 47.16 (2013): 9496-9504.
35. Wong, Min Hao, et al. "Lipid exchange envelope penetration (LEEP) of nanoparticles for plant engineering: a universal localization mechanism." *Nano letters* 16.2 (2016): 1161-1172.
36. Rispail, Nicolas, et al. "Quantum dot and superparamagnetic nanoparticle interaction with pathogenic fungi: internalization and toxicity profile." *ACS Applied Materials & Interfaces* 6.12 (2014): 9100-9110.
37. Zhai, Guangshu, et al. "Transport of gold nanoparticles through plasmodesmata and precipitation of gold ions in woody poplar." *Environmental science & technology letters* 1.2 (2014): 146-151.
38. Yadav, A.; Yadav, K. 2018. Nanoparticle-based plant disease management: Tools for sustainable agriculture. *Nanobiotechnology Applications in Plant Protection*, ed. by K.A. Abd-Elsalam & R. Prasad, 29-61.
39. Tomer, A.*; et al.* 2021. Nanotechnology for detection and diagnosis of plant diseases. *Biobased Nanotechnology for Green Applications*, 221-37.
40. Rafique, Muhammad, et al. "A review on green synthesis of silver nanoparticles and their applications." *Artificial cells, nanomedicine, and biotechnology* 45.7 (2017): 1272-1291.
41. Malerba, Massimo, and Raffaella Cerana. "Chitosan effects on plant systems." *International journal of molecular sciences* 17.7 (2016): 996.
42. Flood, Julie. "The importance of plant health to food security." *Food security* 2.3 (2010): 215-231.
43. Liu, Yan, et al. "Use of nanoparticles for controlled release of biocides in solid wood." *Journal of Applied Polymer Science* 79.3 (2001): 458-465.
44. Song, Mei-Rong, et al. "Dispersible silica nanoparticles as carrier for enhanced bioactivity of chlorfenapyr." *Journal of Pesticide Science* 37.3 (2012): 258-260.
45. Walter, Achim, Frank Liebisch, and Andreas Hund. "Plant phenotyping: from bean weighing to image analysis." *Plant methods* 11.1 (2015): 1-11.
46. Manjunatha, R. L., Dhananjay Naik, and K. V. Usharani. "Nanotechnology application in agriculture: A review." *Journal of Pharmacognosy and Phytochemistry* 8.3 (2019): 1073-1083.
47. Ismail, Massalimov, et al. "Modern prospects of nanotechnology in plant pathology." *Nanotechnology: An Agricultural Paradigm* (2017): 305-317.
48. Mishra, Gaurav, et al. "Nanotechnology Applications for Sustainable Crop Production." *Applying Nanotechnology for Environmental Sustainability*. IGI Global, 2017. 164-184.
49. Ghouri, Muhammad Zubair, et al. "Nanotechnology: Transformation of agriculture and food security." *Bioscience* 3 (2020): 19.
50. Chhipa, Hemraj. "Applications of nanotechnology in agriculture." *Methods in microbiology*. Vol. 46. Academic Press, 2019. 115-142.
51. Gothandam, K. M., et al., eds. *Nanotechnology, food security and water treatment*. Cham: Springer International Publishing, 2018.

52. Sekhon, Bhupinder Singh. "Nanotechnology in agri-food production: an overview." *Nanotechnology, science and applications* (2014): 31-53.
53. Haris, Mohammad, et al. "Nanotechnology–A new frontier of nano-farming in agricultural and food production and its development." *Science of The Total Environment* 857 (2023): 159639.
54. Sharon, Madhuri, Ajoy Kr Choudhary, and Rohit Kumar. "Nanotechnology in agricultural diseases and food safety." *Journal of Phytology* 2.4 (2010).
55. Berekaa, Mahmoud M. "Nanotechnology in food industry; advances in food processing, packaging and food safety." *Int. J. Curr. Microbiol. App. Sci* 4.5 (2015): 345-357.
56. Misra, Amarendra N., Meena Misra, and Ranjeet Singh. "Nanotechnology in agriculture and food industry." *International Journal of Pure and Applied Sciences and Technology* 16.2 (2013): 1.
57. Lee, Jaesang, Shaily Mahendra, and Pedro JJ Alvarez. "Nanomaterials in the construction industry: a review of their applications and environmental health and safety considerations." *ACS nano* 4.7 (2010): 3580-3590.
58. Jha, Zenu, et al. "Nanotechnology: prospects of agricultural advancement." *Nano Vision* 1.2 (2011): 88-100.
59. Jena, Barsarani, et al. "Nanotechnology and its potential application in postharvest technology." *Bio-Nano Interface: Applications in Food, Healthcare and Sustainability* (2022): 93-107.
60. Ramkumar, C., Angadi Vishwanatha, and Rahul Saini. "Regulatory aspects of nanotechnology for food industry." *Nanotechnology Applications in Dairy Science*. Apple Academic Press, 2019. 169-184.
61. Peters, Ruud, et al. "Inventory of Nanotechnology applications in the agricultural, feed and food sector." *EFSA Supporting Publications* 11.7 (2014): 621E.
62. Parisi, Claudia, Mauro Vigani, and Emilio Rodríguez-Cerezo. "Agricultural nanotechnologies: what are the current possibilities?." *Nano Today* 10.2 (2015): 124-127.
63. Lyons, Kristen, Gyorgy Scrinis, and James Whelan. "Nanotechnology, agriculture, and food." *Nanotechnology and global sustainability*. CRC Press, 2018. 146-169.
64. Lyons, Kristen, Gyorgy Scrinis, and James Whelan. "Nanotechnology, agriculture, and food." *Nanotechnology and global sustainability*. CRC Press, 2018. 146-169.
65. Pandey, Garima. "Challenges and future prospects of agri-nanotechnology for sustainable agriculture in India." *Environmental Technology & Innovation* 11 (2018): 299-307.
66. David, Kenneth, and Paul B. Thompson, eds. *What can nanotechnology learn from biotechnology?: social and ethical lessons for nanoscience from the debate over agrifood biotechnology and GMOs*. Academic Press, 2011.
67. Vijayalakshmi, C., C. Chellaram, and S. Logesh Kumar. "Modern approaches of nanotechnology in agriculture-a review." *Biosci Biotechnol Res Asia* 12 (2015): 327-331.
68. Mukherjee, Anirban, et al. "Public perception about use of nanotechnology in agriculture." *Advances in phytonanotechnology*. Academic Press, 2019. 405-418.

69. Ditta, Allah. "How helpful is nanotechnology in agriculture?." *Advances in Natural Sciences: Nanoscience and Nanotechnology* 3.3 (2012): 033002.
70. Miller, Georgia. "Contemplating the implications of a nanotechnology “revolution”." *Presenting Futures*. Dordrecht: Springer Netherlands, 2008. 215-225.
71. Chen, Hongda, and Rickey Yada. "Nanotechnologies in agriculture: new tools for sustainable development." *Trends in Food Science & Technology* 22.11 (2011): 585-594.
72. Kumar, Amit. *Nanotechnology development in India: an overview*. New Delhi: Research and Information System for Developing Countries, 2014.
73. Lowry, Gregory V., Astrid Avellan, and Leanne M. Gilbertson. "Opportunities and challenges for nanotechnology in the agri-tech revolution." *Nature nanotechnology* 14.6 (2019): 517-522.
74. He, Xiaojia, Hua Deng, and Huey-min Hwang. "The current application of nanotechnology in food and agriculture." *Journal of food and drug analysis* 27.1 (2019): 1-21.
75. Stone, Vicki, et al. "Nanomaterials for environmental studies: classification, reference material issues, and strategies for physico-chemical characterisation." *Science of the total environment* 408.7 (2010): 1745-1754.
76. Petersen, Elijah J., et al. "Strategies for robust and accurate experimental approaches to quantify nanomaterial bioaccumulation across a broad range of organisms." *Environmental Science: Nano* 6.6 (2019): 1619-1656.
77. Wen, Liping, Ye Tian, and Lei Jiang. "Bioinspired super-wettability from fundamental research to practical applications." *Angewandte Chemie International Edition* 54.11 (2015): 3387-3399.
78. Yaktine, Ann, and Leslie Pray, eds. *Nanotechnology in food products: workshop summary*. National Academies Press, 2009.
79. Younis, Sherif A., et al. "Advancements of nanotechnologies in crop promotion and soil fertility: Benefits, life cycle assessment, and legislation policies." *Renewable and Sustainable Energy Reviews* 152 (2021): 111686.
80. Malakar, Arindam, et al. "Nanomaterials in the environment, human exposure pathway, and health effects: A review." *Science of the Total Environment* 759 (2021): 143470.