World Journal of Pharmaceutical Science and Research
www.wjpsronline.com
Review Article
ISSN: 2583-6579
SJIF Impact Factor: 3.454
Year - 2023
Volume: 2; Issue: 6
Page: 79-90

SYSTEMATIC REVIEW ON APPLICATION OF NANOPARTICLES IN AGRICULTURE

Anmar A. Al-Shimary*[1], Marwah A. Al-Azzawi[2], Safa M. Abdulateef[3]

[1]Department of Chemistry, College of Science, Mustansiriyah University, Baghdad-Iraq.
[2]Department of Physics, College of Science, Mustansiriyah University, Baghdad-Iraq.
[3]College of Sciences, Al-Nahrain University, jadriya, Baghdad, Iraq.

Article Received: 09 August 2023 || Article Revised: 30 September 2023 || Article Accepted: 23 November 2023

Corresponding Author: Anmar A. Al-Shimary
Department of Chemistry, College of Science, Mustansiriyah University, Baghdad-Iraq.

ABSTRACT

Agriculture is the world's largest industry along with this agriculture is the economic foundation of most emerging nations. One of the most crucial conservation challenges of the twenty-first century is how and where we produce food. Agriculture must produce more food and other agricultural products in the 21st century to feed a growing population with a reduced rural labor force, as well as more feedstocks for a potentially enormous bioenergy market, contribute to the overall development of the many developing nations that depend heavily on agriculture, adopt more efficient and sustainable production techniques, and adapt to climate change. Farmers must adjust to a changing environment in addition to serving the interests of regulators, consumers, food processors, and merchants. Pressures in the agriculture sector are growing as a result of factors like climate change, soil erosion, biodiversity loss, shifting consumer food preferences, and worries about how food is produced. Additionally, the yield of crops can be increased by adding various chemicals, antibiotics, fungicides, and herbicides to agricultural soil. However, extensive use of those chemicals creates resistance to those chemicals, raising environmental concerns such as the contamination of crops and soil with antibiotic residues and antibiotic resistance genes (ARGs), among other issues. Due to its numerous uses in fields including medicine, pharmaceuticals, catalysis, energy, and materials, nanotechnology has attracted a lot of attention in recent years. Nowadays, a wide range of industries use nanomaterials. To solve the different issues that arise in agricultural practices, a sustainable agricultural system is required. Studies show that the use of nanomaterials in agriculture benefits the farmer by boosting crop yields, lowering water use, and generally enhancing the quality of the soil, minimizing any potential adverse consequences from an overdose. Regarding its uses, we are attempting to discuss several applications of nanotechnology in the agricultural domains in this review. This review paper provides a comprehensive overlook of the developing application of nanotechnology in the agriculture sector, covering new developments, challenges, and opportunities.

INTRODUCTION

Agriculture has always been the backbone of most of the developing countries. The population of the world is increasing rapidly. It is expected to reach nearly six billion by the end of 2050. Nanotechnology is the science of manipulating materials at the nanoscale. [Baig et al., 2021] Nanotechnology, as a scientific discipline, involves manipulating materials at the nanoscale. This field explores working with particles at the smallest possible size, which holds promise for enhancing agricultural productivity by addressing challenges that have remained unresolved through conventional means. Regarding management strategies, endeavors are being made to enhance the efficacy of applied fertilizers by utilizing nano clays and zeolites. Additionally, efforts are focused on restoring soil fertility by facilitating the controlled release of fixed nutrients [Sun et al., 2021].

In order to increase earnings, the farming community frequently concentrates on reducing the cost of agricultural inputs. Farmers use fertilizers, herbicides, and fungicides to maximize crop productivity in order to accomplish this goal. Extended use of chemical-based products leads to the Due to overuse of agrochemicals, the current situation has resulted in a considerable conflict between increased crop output and the health of the soil and groundwater. Due to population expansion over the past few decades, there has been an enormous increase in agricultural areas throughout the world. [Vijaykumar et al., 2022]

In controlled environment agriculture and precision farming, the determination of crop input requirements is predicated upon their specific needs, after which the requisite quantities are timely and accurately supplied to the appropriate location. This process is facilitated through the utilization of nano biosensors and satellite systems. To address the challenges pertaining to perennial weed management and the depletion of weed seed banks, researchers have developed nano herbicides [Yadav et al., 2023]. Nano-structured formulations, with their ability to employ mechanisms such as targeted delivery or slow/controlled release, offer the potential for the precise release of active ingredients in response to environmental stimuli and biological demands. Empirical studies indicate that using nano fertilizers leads to enhanced nutrient utilization efficiency, diminished soil toxicity, mitigated risks associated with excessive dosages, and reduced application frequency. [Muller et al., 2017] Hence, nanotechnology has a high potential for achieving sustainable agriculture, especially in developing countries. Furthermore, the inherent challenges posed by plants, pests, and diseases in the agricultural ecosystem persist, necessitating the continual exploration of remedies. Although modern agricultural practices propose various solutions, the outcomes are only sometimes replicated across farms due to the individual characteristics of each farm, including its distinct topography, soil composition, available technological resources, and anticipated crop yields. [Majumdar et al., 2021].

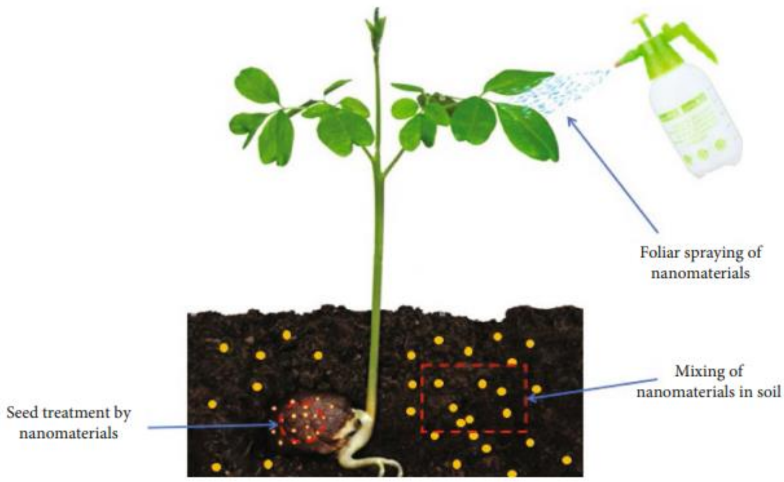

Image: Methods for applying nanomaterials in the agricultural field

Source Vijaykumar et al., 2022

By using efficient monitoring techniques and tools, precision agriculture techniques reduce the need for pesticides, fertilizers, and herbicides. This method includes the targeted application of agricultural chemicals for efficient nutrient uptake and disease resistance. Nanoscale transporters, nanosensors, nano fertilizers (NFs), nano herbicides, and nano pesticides are examples of such items. The farming community may eliminate agrochemicals while maintaining good crop output, safeguarding the health of the soil and water, and making a positive contribution to a cleaner environment by implementing precision agriculture practices based on nanotechnology. In order to increase crop productivity Nanoscale materials and devices can help in crucial fields like fertilizer delivery, pest management, monitoring the environment, variable rate technology, automated machinery, and data analytics by combining current technologies and data-driven decision-making tools with them. Improved nutrient implementation, efficient and targeted application of pesticides, continual evaluation of soil and plant parameters, and precise input delivery are all possible outcomes of integration. (Yadav et al., 2023)

Consideration must be given to the major economic, legal, social, and risk consequences of nanotechnology. From a financial standpoint, nanotechnology has the potential to completely transform a number of sectors, including healthcare, energy, and agriculture. It can increase productivity, cut production costs, and create novel materials with special qualities. However, it is also important to consider the significant expenditures of research and development as well as potential liability issues.

Agricultural Applications of Nanomaterials

In recent times, the utilization of nanomaterials has become prevalent across numerous domains. Within agriculture, the application of nanomaterials has proven advantageous to farmers in several ways. These include the promotion of soil health, augmentation of crop productivity, reduction in water requirements, and more. These benefits address the primary concerns surrounding crop production.

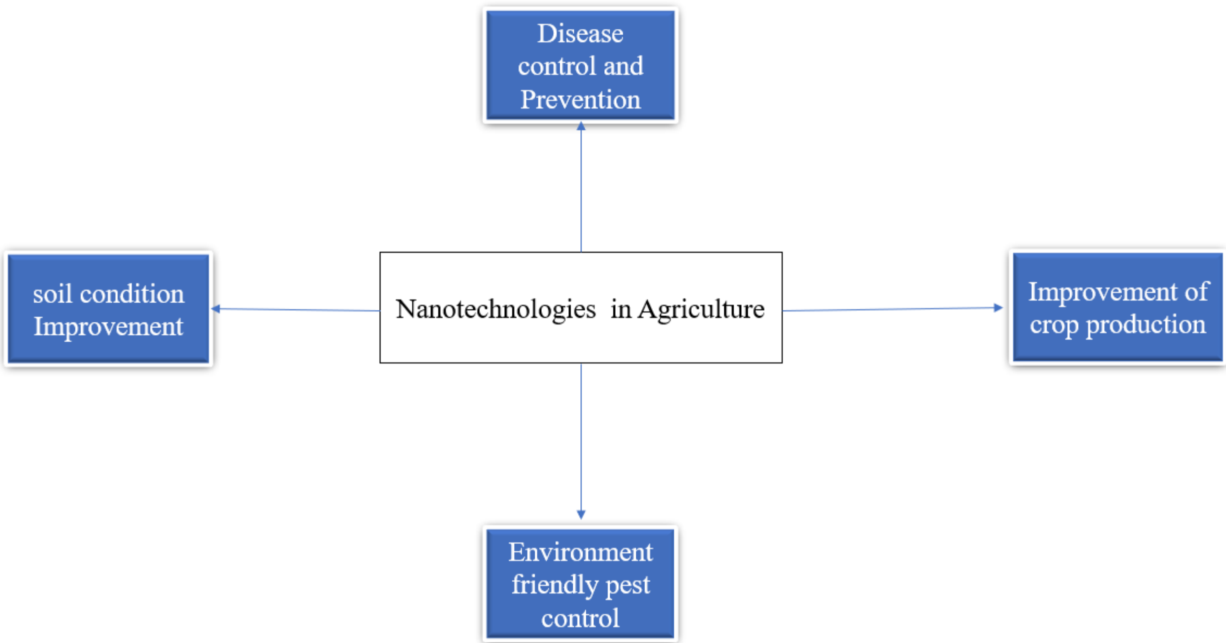

Figure 1: Some applications of nanotechnologies in agriculture.

Table: List of different nanomaterial types used in agriculture with respect to examples and mode of application.

Sr. No	Type of Nanomaterial	Examples	Application Method
1	Nano fertilizers [modified urea nanoparticles]	modified urea nanoparticle chitosan, zeolite, polyacrylic acid, clay minerals, and hydroxyapatite	Root applications foliar application [Shah et al., 2016, Yadav et al., 2023, Mali et al., 2020]
2	Nano pesticide	Inorganic nanoparticles like Ni, Cu, SiO2, Ag, ZrO2, and TiO2	Root applications foliar application Spraying [Hong et al., 2021]
3	Nano biosensors	Polystyrene (PS) nanoparticles	Inflow application to check the pH of soil [Malik et al., 2013, Omara et al 2019]
4	Nanocomposites	Copper-based and chitosan-based Nanoparticles or nanocomposites	Soil Application [Vemula, A. 2022. Rajkuberan et al., 2022]
5	Encapsulated nanoparticles	Zno, Iron, Copper nanoparticles	Seed encapsulation [Zhao et al., 2021]

1. Nanoparticles Use in Plant Growth

According to a study, nanomaterials possess the potential to enhance plant growth and production, and their application in agriculture is receiving more and more attention. Nanomaterials like nanocellulose, nanocarbon, and nano lignocellulose are three distinct types of nanomaterials that may have an effect on plant growth have been identified. Graphene nanomaterial, fullerenes, and carbon nanotubes (CNTs) nanocomposites are just a few examples of nanocarbons that have shown significant promise for enhancing plant growth. Using CNTs on tomato plants, for instance, greatly improved growth [Khodakovskaya et al., 2013] It has also been noted that nano lignocellulose, a compound made of lignin and cellulose nanoparticles, promotes plant development. It is well known that nano lignocellulose helps plants absorb more amount water and nutrients which improves the growth of roots. According to research activities, the application of cellulose based nanofibers can alter the hydrophobicity of soybean leaf surfaces, providing resistance to the obligate biotrophic fungus *Phakopsora pachyrhizi*.[Saito et al., 2021]

2. Nanoparticles Use in Improved Micronutrient Supply

The growth and development of crops depend on the availability of 17 essential nutrients. The three primary elements - carbon, hydrogen, and oxygen - obtained from the atmosphere constitute over 90 percent of the fresh plant tissue. Macronutrients, required in substantial quantities and sourced from the soil, encompass nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), and magnesium (Mg) [White et al., 2010]. Legumes, however, exhibit an exception as they can fix nitrogen from the air. Regarding Saskatchewan's soils, calcium and magnesium are generally not limiting factors due to the soil characteristics. The soil's nitrogen, phosphorus, potassium, and sulfur supply are often supplemented through fertilizers and manure [Kebede, E. (2021)].

The remaining essential nutrients derived from the soil are referred to as micronutrients because they are needed in small amounts. They are boron (B), chloride (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni) and zinc (Zn). Micronutrients are important for plant growth, as plants require a proper balance of all the essential nutrients for normal growth and optimum yield. [Na, S. 2007]

The plant is effectively supported by the NP microcapsules' quick uptake and translocation of the micronutrients inside. NFs have structures that are extremely water-soluble, stable for extended periods of time, hold greater efficacy after field application, can have a release that is timed, is specifically targeted, is less eco-toxic, and features simple delivery and removal procedures. Targeted nutrient locations in plant root systems are reached by NPs. Adsorption of nutrients results in the accumulation of nutrients on nanoparticles (NPs), which are then further attached via ligands, enclosed in a nanoparticulate polymeric shell, and trapped in the polymer. [Yadav et al., 2023, Dutta et al., 2022]

The prevention of contamination of water and soil on agricultural property is made possible by recent advancements in agricultural technology. Additionally, the answers are available in the shape of impermeable materials that can hold onto water and release it gradually as needed. [Patra et al., 2022] This method could reduce water consumption and help mitigate drought when used in conjunction with wireless nanosensors that are Nanotechnology may also help to reduce a variety of stresses in order to boost plant productivity and advance sustainable agriculture. [Shang et al., 2019] In order to clarify the effects on soil bacteria, more research is required on the delivery of nano nutrients in plant systems. In order to achieve the best dose concentrations for PA, it is also necessary to investigate the destiny of administered NPs. Because of its small particle size and high surface area, NF is highly reactive with other substances. Such NPs also easily dissolve with water and other chemicals. [Ameen 2021] Plant-applied surfaces, such as foliage, can be perfectly penetrated by NPs with particle sizes of less than 100 nm. NP-encapsulated fertilizers facilitate nutrient uptake for crop plants. As an illustration, NF composed of zeolite gradually releases nutrients, minimizing the loss of nutrients mostly nitrate and ammonia due to nitrification volatilization and leaching in soil.

3. Nanoparticles Use in the Delivery of Biofertilizers

Nowadays biofertilizer and PGPRs is used to improve the production of various crop varieties Basically, biofertilizers are the live microorganism’s mixture or sporulated formulation of that particular microorganism. *Mycorrhizal fungi, Rhizobium* and *Azotobacter*, *Azospirillum*, *Pseudomonas*, and algae that are blue-green in color are examples of common biofertilizers used in agricultural practices. (Thomas et al., 2019)

These bacteria break down complicated organic substrates into utilizable substances that plants may easily use. Crop productivity is increased by these substances. Yet, because of problems regarding storage, heat sensitivity, and shorter shelf life, biofertilizers sometimes fall short of objectives in the field. (Thomas et al., 2019 & Kumar et al.., 2021). To reverse the effects of desiccation, biofertilizers in liquid form water-in-oil emulsions and additives are used to mitigate the effects of desiccation. (The viability and effectiveness of living things nevertheless declines when they are kept in liquid biofertilizers for an extended period of time. The desiccation resistance of the biofertilizer inoculum is increased by coating the biofertilizer with polymeric NPs. Additionally, by thickening the oil phase during storage, the addition of hydrophobic silica NPs to liquid formulations enhances cellular viability. (Krishnaprabu, S 2020, Shukla et al., 2015) In vitro evidence of plant growth promotion has been shown when certain NPs such *Pseudomonas fluorescens*, *Bacillus subtilis*, and *Paenibacillus elgii* are used with PGPRs. In addition, NPs are much less necessary than chemical fertilizers. Numerous hectares of crops can be fertilized with one liter of nano biofertilizer. Among NPs, gold and silver have been in-depth research. It has been demonstrated that using gold nanoparticles combination with plant growth-promoting microorganisms like P. *fluorescens, P. elgii,* and *B. subtilis*. (Rai et al.,2012, de Moraes et al., 2021)

4. Nanoparticles Use in the Delivery of Chemical Fertilizers

In to make up for the soil's deficiencies for N, P, and K, chemical fertilizers that are applied on agricultural land. Crop productivity has significantly increased because of the use of fertilizers including ammonia, urea, nitrate, phosphate, etc. However, using them can have negative consequences. Chemical fertilizers are regularly applied to the soil in overabundance. The estimate states that the forty to seventy percent N, between eighty and nine percent P, and fifty to seventy percent K–based fertilizers in the environment also contribute to environmental pollution. (Duhan et al., 2017) basically, unused or excess fertilizer runoff into nearby water bodies and streams can result in algal blooms and water pollution, which can be reduced by the use of nanomaterials. Due to their higher surface tension than conventional materials, nanomaterials are better able to resist the release of fertilizers. For instance, compared to standard phosphate fertilizers, nano-hydroxyapatite, a phosphate fertilizer, has dramatically improved phosphorus utilization efficiency. (Elsayed et al., 2022) In order to reduce the environmental emission of fertilizers, NMs can also be employed as a covering material (Milani et al., 2012). For instance, it has been noted that urea particles coated with zinc oxide nanoparticles have a slower rate of nutrient release, hence reducing nutrient leaching into the environment. By employing this strategy, plants can utilize the applied fertilizers more effectively, lowering their environmental impact. The excessive flow of fertilizers into water bodies and rivers can be reduced by covering NM in fertilizer crystals, which lowers pollution and lowers the risk of algal blooms. (Beig et al., 2023 & Amin et al., 2023)

5. Nanoparticles Use in Use as Nano insecticides

Insecticide is defined as any chemical substance that is used to kill insects. Such substances are used primarily to control pests that infest cultivated plants or to eliminate disease-carrying insects in specific areas. Due to the toxic nature of insecticides, it causes adverse effects on humans and other ecological factors. A new branch of study called nano pesticides for plant protection offers fresh approaches to designing active chemicals at the nanoscale. Future development of more potent and secure pesticides/biopesticides may be enabled by nano pesticide-based formulations. [Nie et al., 2023]

Several nanoparticles or nanoformulations, especially Most plant insects are sensitive to Ag's insecticidal properties. [Rouhani et al.] To combat phytopathogens and insect pests, various nanoparticle compositions were developed. For instance, ZnO-TiO2-Ag NPs were helpful against *Frankliniella occidentalis* Pergande, whereas Ag-Zn NPs were helpful against *Aphis nerii*. (2012) Rouhani et al. The unique insecticidal properties of nanosilica. Nanosilica kills insects by absorbing their cuticular lipids. The surface-charged nano silica is efficient against a number of important agricultural insect pests. [Ulrichs et al., 2005]

6. Nanoparticles as fungicidal agent

Some literature review states that some of the most prevalent soil-borne fungus that cause several plant diseases include *Fusarium oxysporum* spp, *Macrophomina phaseolina* spp, *Sclerotium rolfsii* spp, and *Rhizoctonia solani* spp. [Tippannanavar et al., 2020] such as wilt, downy mildew, etc. That causes extensive loss in crop productivity. To control such diseases farmers are familiar with and frequently employ synthetic fungicides, which are not very successful at protecting plants from diseases and are harmful to the environment. Nanotechnology provides a clever answer to environmental problems in the present day at the nanoscale. It is a developing area, and numerous techniques can be used to create nanoparticles. Because of their solubility, permeability, low dose-dependent toxicity, low dose, increased bioavailability, targeted delivery, bioavailability, and controlled release, nano fungicides are effective. [Khot et al., 2012] In order to eliminate fungal phytopathogens that stick to the cytosolic membrane, nanoparticles alter the permeability of cells, damage DNA, interfere with the oxidation of proteins and the fungi's electron transport chain, produce reactive oxygen species, prevent the absorption of nutrients, and change protein synthesis. To counteract phytopathogens, which may also help in plant development, they are used as foliar sprays. [Paul et al., 2021]

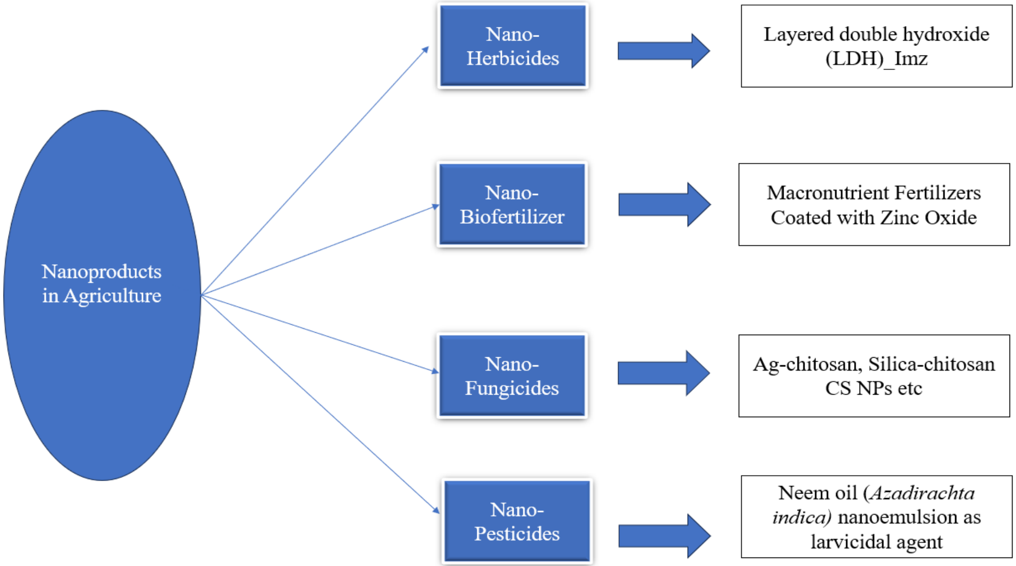

Fig 3: Different nanoparticles in the agriculture sector.

Advantages of nanoparticles

The benefits of nanotechnology in agriculture were discussed in this section, including better germination of seeds and plant growth enhancement, increased macro and micronutrient availability, reduction of abiotic as well as biotic plant stress, and the capacity to utilise less fertilizer and pesticide by using effective delivery systems. Nanotechnology can be utilized to create nano insecticides, nano fungicides, and nano herbicides as well as to help transport both chemical and biological fertilizers. Particular nanoparticles have also been found to support plant development. Some important advantages are summarized in table number. In the medical area, nanotechnology is widely used as nanomedicine. Certain nanoparticles may find use in tissue engineering, pharmaceuticals, targeted medications, biomedical implants, new diagnostic tools, imaging, and techniques (Haleemet al., 2023). Furthermore, by altering the secondary structures during amyloid peptide aggregation, nanoparticles have been employed to prevent amyloid fibrillation (Mohammed et al., 2023).

Table No 2: Different advantages of nanoparticles in agriculture.

Sr. No	Nanoparticle	Effect on plant	Plant Name	Reference
1.	Zinc Oxide	Growth enhancement	Tomato	Raliya, R., Nair et al
2.	Silicon Dioxide and Hydrogels	Improved seed germination process by increasing soil water retention capacity	Tomato and Wheat	Siddiqui, M. H Yasmeen, F., Raja
3.	Copper oxide nanoparticle-embedded hydrogels	Improved micronutrient supply through slow-release	Tomato	Shang, H.; Ma,
4.	Silicon dioxide	Abiotic and biotic stress alleviation	Sugarcane	Namjoyan, S.,
5.	Copper oxide and silver oxide	Reduces pests	Tobacco and Rice	Chen and Wu Namburi, K. R., Kora

Disadvantage of nanoparticles

Nanotechnology has been praised as an innovative breakthrough with the potential to dramatically change a number of economic sectors, including agriculture. Although nanotechnology has significant uses in agriculture, there are also a number of possible hazards and downsides that must be taken into consideration. Using nanotechnology in agriculture raises ethical issues concerning the security and safety of our food supply. There is concern that the presence of nanoparticles in food could endanger human health and safety, and there is little information on the long-term implications of NPs exposure. NPs can be difficult to confine because they are small and quickly moved by air or water currents. NPs have the ability to accumulate in the soil, water, and air after being discharged into the environment, which could pose ecological problems. (Tiede, K., Hassellöv) For instance, NPs might alter the equilibrium of macro- and microbes in the soil, which will reduce its fertility. (Pietroiusti, A., Stockmann-Juvala) Concerning human health, the use of nanotechnology in agriculture is problematic. Negative health impacts from exposure to NPs include respiratory issues, cardiovascular disease, and brain impairment. (Rajput, V. D., Minkina et al)

Agriculture workers are more likely to be exposed to nanoparticles, it can have detrimental effects on health over time. A significant amount of money has to be devoted to research and development until nanotechnology may be used in agriculture. Since small-scale farmers who cannot afford the high costs of nanomaterials and related technologies may not have access to them, the advantages of nanotechnology in agriculture may potentially be imbalanced.

CONCLUSION

The agricultural sector is facing several difficulties in the twenty-first century as it tries to produce more food to feed a growing population because of a dwindling rural labor force, a changing climate, and urbanization. To address this issue, countries that depend on agriculture must implement more efficient procedures, cut back on employment, and employ sustainable production methods. Nanotechnology has the ability to increase agricultural productivity and yields while maintaining environmental safety, even in harsh areas. Predictions about the potential use of nanotechnology in agriculture have been made by many countries. In order to feed the expanding population while preserving the planet's finite resources, nanotechnology will be essential. Before the widespread use of nanomaterials for sustainable development, the negative effects of these materials, if any, must be evaluated and taken into consideration. If we can get through these obstacles, the future will be prosperous and bright.

A new and promising technology that has the potential to greatly enhance food and agricultural systems is nanotechnology. However, it is essential to look into the dangers connected to using nanoparticles in agricultural practices; a risk assessment of their use is required. Precision farming based on nanotechnology has the potential to boost agricultural yield by improving input management and resource conservation. Precision farming has the potential to accelerate the green revolution while also revolutionizing agriculture. By minimizing agricultural waste, smart agriculture can help to lessen environmental contamination. Nanotechnology may also shield the environment from pollution.

REFERENCES

1. Ameen, F., Alsamhary, K., Alabdullatif, J. A., & ALNadhari, S. (2021). A review on metal-based nanoparticles and their toxicity to beneficial soil bacteria and fungi. Ecotoxicology and Environmental Safety, 213; 112027.
2. Amin, S., Aziz, T., Zia-ur-Rehman, M., Saleem, I., Rizwan, M., Ashar, A., ... & Maqsood, M. A. (2023). Zinc oxide nanoparticles coated urea enhances nitrogen efficiency and zinc bioavailability in wheat in alkaline calcareous soils. Environmental Science and Pollution Research, 1-10.
3. Anjali, C. H., Sharma, Y., Mukherjee, A., & Chandrasekaran, N. (2012). Neem oil (Azadirachta indica) nanoemulsion—a potent larvicidal agent against Culex quinquefasciatus. Pest management science, 68(2): 158-163.
4. Baig, N., Kammakakam, I., & Falath, W. (2021). Nanomaterials: A review of synthesis methods, properties, recent progress, and challenges. Materials Advances, 2(6): 1821-1871.
5. Batty, A. L., Dixon, K. W., Brundrett, M., & Sivasithamparam, K. (2001). Constraints to symbiotic germination of terrestrial orchid seed in a mediterranean bushland. New phytologist, 152(3): 511-520.
6. Beig, B., Niazi, M. B. K., Jahan, Z., Haider, G., Zia, M., Shah, G. A., ... & Hayat, A. (2023). Development and testing of zinc sulfate and zinc oxide nanoparticle-coated urea fertilizer to improve N and Zn use efficiency. Frontiers in Plant Science, 13: 1058219.
7. Chen, J. N., Wu, L. T., Kun, S. O. N. G., Zhu, Y. S., & Wei, D. I. N. G. (2022). Nonphytotoxic copper oxide nanoparticles are powerful “nanoweapons” that trigger resistance in tobacco against the soil-borne fungal pathogen Phytophthora nicotianae. Journal of Integrative Agriculture, 21(11): 3245-3262.
8. De Moraes, A. C. P., Ribeiro, L. D. S., de Camargo, E. R., & Lacava, P. T. (2021). The potential of nanomaterials associated with plant growth-promoting bacteria in agriculture. 3 Biotech, 11(7): 318.
9. Duhan, J. S., Kumar, R., Kumar, N., Kaur, P., Nehra, K., & Duhan, S. (2017). Nanotechnology: The new perspective in precision agriculture. Biotechnology Reports, 15: 11-23.
10. Dutta, S., Pal, S., Panwar, P., Sharma, R. K., & Bhutia, P. L. (2022). Biopolymeric nanocarriers for nutrient delivery and crop biofortification. ACS omega, 7(30): 25909-25920.
11. Elsayed, A. A., Ahmed, E. G., Taha, Z. K., Farag, H. M., Hussein, M. S., & AbouAitah, K. (2022). Hydroxyapatite nanoparticles as novel nano-fertilizer for production of rosemary plants. Scientia Horticulturae, 295: 110851.
12. Haleem, A., Javaid, M., Singh, R. P., Rab, S., & Suman, R. (2023). Applications of Nanotechnology in Medical field. *Global Health Journal*.
13. Hong, J., Wang, C., Wagner, D. C., Gardea-Torresdey, J. L., He, F., & Rico, C. M. (2021). Foliar application of nanoparticles: mechanisms of absorption, transfer, and multiple impacts. Environmental Science: Nano, 8(5): 1196-1210.
14. Kebede, E. (2021). Contribution, utilization, and improvement of legumes-driven biological nitrogen fixation in agricultural systems. Frontiers in Sustainable Food Systems, 5: 767998.
15. Khodakovskaya, M. V., Kim, B. S., Kim, J. N., Alimohammadi, M., Dervishi, E., Mustafa, T., & Cernigla, C. E. (2013). Carbon nanotubes as plant growth regulators: effects on tomato growth, reproductive system, and soil microbial community. Small, 9(1): 115-123.
16. Khot, L. R., Sankaran, S., Maja, J. M., Ehsani, R., & Schuster, E. W. (2012). Applications of nanomaterials in agricultural production and crop protection: a review. Crop protection, 35: 64-70.

17. Krishnaprabu, S. (2020). Liquid microbial consortium: A potential tool for sustainable soil health. Journal of Pharmacognosy and Phytochemistry, 9(2): 2191-2199.
18. Kumar, S., Sindhu, S. S., & Kumar, R. (2022). Biofertilizers: An ecofriendly technology for nutrient recycling and environmental sustainability. Current Research in Microbial Sciences, 3: 100094.
19. Majumdar, S., & Keller, A. A. (2021). Omics to address the opportunities and challenges of nanotechnology in agriculture. Critical Reviews in Environmental Science and Technology, 51(22): 2595-2636.
20. Mali, S. C., Raj, S., & Trivedi, R. (2020). Nanotechnology a novel approach to enhance crop productivity. Biochemistry and Biophysics Reports, 24: 100821.
21. Malik, P., Katyal, V., Malik, V., Asatkar, A., Inwati, G., & Mukherjee, T. K. (2013). Nanobiosensors: concepts and variations. International Scholarly Research Notices, 2013.
22. Milani, N., McLaughlin, M. J., Stacey, S. P., Kirby, J. K., Hettiarachchi, G. M., Beak, D. G., & Cornelis, G. (2012). Dissolution kinetics of macronutrient fertilizers coated with manufactured zinc oxide nanoparticles. Journal of Agricultural and Food Chemistry, 60(16): 3991-3998.
23. Mohammed, A. A., Barale, S. S., Kamble, S. A., Paymal, S. B., & Sonawane, K. D. (2023). Molecular insights into the inhibition of early stages of Aβ peptide aggregation and destabilization of Alzheimer's Aβ protofibril by dipeptide D-Trp-Aib: A molecular modelling approach. *International Journal of Biological Macromolecules*, *242*: 124880.
24. Muller, A., Schader, C., El-Hage Scialabba, N., Brüggemann, J., Isensee, A., Erb, K. H., ... & Niggli, U. (2017). Strategies for feeding the world more sustainably with organic agriculture. Nature communications, 8(1): 1-13.
25. Na, S. (2007). Micronutrients: functions, sources and application methods. Carbon NY, 100: 45.
26. Namburi, K. R., Kora, A. J., Chetukuri, A., & Kota, V. S. M. K. (2021). Biogenic silver nanoparticles as an antibacterial agent against bacterial leaf blight causing rice phytopathogen Xanthomonas oryzae pv. oryzae. Bioprocess and Biosystems Engineering, 44(9): 1975-1988.
27. Namjoyan, S., Sorooshzadeh, A., Rajabi, A., & Aghaalikhani, M. (2020). Nano-silicon protects sugar beet plants against water deficit stress by improving the antioxidant systems and compatible solutes. Acta Physiologiae Plantarum, 42, 1-16.
28. Nie, D., Li, J., Xie, Q., Ai, L., Zhu, C., Wu, Y., ... & Tan, W. (2023). Nanoparticles: A Potential and Effective Method to Control Insect-Borne Diseases. Bioinorganic Chemistry and Applications, 2023.
29. Omara, A. E. D., Elsakhawy, T., Alshaal, T., El-Ramady, H., Kovács, Z., & Fári, M. (2019). Nanoparticles: A novel approach for sustainable agro-productivity. Environment, Biodiversity and Soil Security, 3(2019): 29-62.
30. Patra, S. K., Poddar, R., Brestic, M., Acharjee, P. U., Bhattacharya, P., Sengupta, S., ... & Hossain, A. (2022). Prospects of hydrogels in agriculture for enhancing crop and water productivity under water deficit condition. International Journal of Polymer Science, 2022.
31. Paul, A., & Roychoudhury, A. (2021). Go green to protect plants: repurposing the antimicrobial activity of biosynthesized silver nanoparticles to combat phytopathogens. Nanotechnology for Environmental Engineering, 6(1): 10.
32. Pawar, V. A., & Laware, S. L. (2018). Seed priming a critical review. Int. J. Sci. Res. Biol. Sci, 5(5): 94-101.
33. Pietroiusti, A., Stockmann-Juvala, H., Lucaroni, F., & Savolainen, K. (2018). Nanomaterial exposure, toxicity, and impact on human health. Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology, 10(5): e1513.

34. Rai, M., & Ingle, A. (2012). Role of nanotechnology in agriculture with special reference to management of insect pests. Applied microbiology and biotechnology, 94: 287-293.
35. Rajkuberan, C., Rajiv, P., Mostafa, M., & Abd-Elsalam, K. A. (2022). Multifunctional copper-based nanocomposites in agroecosystem applications. In Copper Nanostructures: Next-Generation of Agrochemicals for Sustainable Agroecosystems (pp. 595-613). Elsevier.
36. Rajput, V. D., Minkina, T., Sushkova, S., Tsitsuashvili, V., Mandzhieva, S., Gorovtsov, A., ... & Gromakova, N. (2018). Effect of nanoparticles on crops and soil microbial communities. Journal of Soils and Sediments, 18: 2179-2187.
37. Raliya, R., Nair, R., Chavalmane, S., Wang, W. N., & Biswas, P. (2015). Mechanistic evaluation of translocation and physiological impact of titanium dioxide and zinc oxide nanoparticles on the tomato (Solanum lycopersicum L.) plant. Metallomics, 7(12): 1584-1594.
38. Rouhani, M., Samih, M. A., & Kalantari, S. (2012). Insecticide effect of silver and zinc nanoparticles against Aphis nerii Boyer De Fonscolombe (Hemiptera: Aphididae). Chilean journal of agricultural research, 72(4): 590.
39. Rouhani, M., Samih, M. A., & Kalantari, S. (2013). Insecticidal effect of silica and silver nanoparticles on the cowpea seed beetle, Callosobruchus maculatus F.(Col.: Bruchidae).
40. Saito, H., Yamashita, Y., Sakata, N., Ishiga, T., Shiraishi, N., Usuki, G., ... & Ishiga, Y. (2021). Covering soybean leaves with cellulose nanofiber changes leaf surface hydrophobicity and confers resistance against Phakopsora pachyrhizi. Frontiers in Plant Science, 1827.
41. Shah, M. A., Wani, S. H., & Khan, A. A. (2016). Nanotechnology and insecticidal formulations. Journal of Food Bioengineering and Nanoprocessing, 1(3): 285-310.
42. Shang, H., Ma, C., Li, C., Zhao, J., Elmer, W., White, J. C., & Xing, B. (2021). Copper oxide nanoparticle-embedded hydrogels enhance nutrient supply and growth of lettuce (Lactuca sativa) infected with Fusarium oxysporum f. sp. lactucae. Environmental science & technology, 55(20): 13432-13442.
43. Shang, Y., Hasan, M. K., Ahammed, G. J., Li, M., Yin, H., & Zhou, J. (2019). Applications of nanotechnology in plant growth and crop protection: a review. Molecules, 24(14): 2558.
44. Shukla, S. K., Kumar, R., Mishra, R. K., Pandey, A., Pathak, A., Zaidi, M. G. H., ... & Dikshit, A. (2015). Prediction and validation of gold nanoparticles (GNPs) on plant growth promoting rhizobacteria (PGPR): a step toward development of nano-biofertilizers. Nanotechnology Reviews, 4(5): 439-448.
45. Siddiqui, M. H., & Al-Whaibi, M. H. (2014). Role of nano-SiO2 in germination of tomato (Lycopersicum esculentum seeds Mill.). Saudi journal of biological sciences, 21(1): 13-17.
46. Sun, N., Yu, H., Wu, H., Shen, X., & Deng, C. (2021). Advanced nanomaterials as sample technique for bio-analysis. TrAC Trends in Analytical Chemistry, 135: 116168.
47. Thomas, L., & Singh, I. (2019). Microbial biofertilizers: types and applications. Biofertilizers for sustainable agriculture and environment, 1-19.
48. Tiede, K., Hassellöv, M., Breitbarth, E., Chaudhry, Q., & Boxall, A. B. (2009). Considerations for environmental fate and ecotoxicity testing to support environmental risk assessments for engineered nanoparticles. Journal of chromatography A, 1216(3): 503-509.
49. Tippannanavar, M., Verma, A., Kumar, R., Gogoi, R., Kundu, A., & Patanjali, N. (2020). Preparation of nano fungicides based on imidazole drugs and their antifungal evaluation. Journal of agricultural and food chemistry, 68(16): 4566-4578.

50. Ulrichs, C., Mewis, I., & Goswami, A. (2005). Crop diversification aiming nutritional security in West Bengal: biotechnology of stinging capsules in nature's water-blooms. Ann Tech Issue of State Agri Technologists Service Assoc, 1-18.
51. Vemula, A. (2022). Chitosan Bionanocomposite: A Potential Approach for Sustainable Agriculture. Med. Agric. Environ. Sci, 2: 41-46.
52. Vijayakumar, M. D., Surendhar, G. J., Natrayan, L., Patil, P. P., Ram, P. M., & Paramasivam, P. (2022). Evolution and recent scenario of nanotechnology in agriculture and food industries. Journal of Nanomaterials, 2022.
53. White, P. J., & Brown, P. (2010). Plant nutrition for sustainable development and global health. Annals of botany, 105(7): 1073-1080.
54. Yadav, A., Yadav, K., Ahmad, R., & Abd-Elsalam, K. A. (2023). Emerging Frontiers in Nanotechnology for Precision Agriculture: Advancements, Hurdles and Prospects. Agrochemicals, 2(2): 220-256.
55. Yasmeen, F., Raja, N. I., Razzaq, A., & Komatsu, S. (2016). Gel-free/label-free proteomic analysis of wheat shoot in stress tolerant varieties under iron nanoparticles exposure. Biochimica et Biophysica Acta (BBA)-Proteins and Proteomics, 1864(11): 1586-1598.
56. Zhao, X., Chen, Y., Li, H., & Lu, J. (2021). Influence of seed coating with copper, iron and zinc nanoparticles on growth and yield of tomato. IET nanobiotechnology, 15(8): 674-679.
57. Zheng, L., Hong, F., Lu, S., & Liu, C. (2005). Effect of nano-TiO 2 on strength of naturally aged seeds and growth of spinach. Biological trace element research, 104: 83-91.