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Chapter 4

Nanotechnology as a Paradigm-Shifting Modality in Contemporary Agricultural Systems

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Abstract: India's conventional farming methods and technologies are no longer sufficient to enhance productivity and are increasingly contributing to environmental hazards. Addressing these environmental challenges is crucial for the well-being of our planet. Traditional approaches to sowing, irrigation, fertilizer application and plant protection have long been under scrutiny for their inefficiencies and adverse impacts. Nanotechnology offers an innovative solution to these issues through the application of nanomaterials, which operate on the low-dose principle. The distinct physical structures of nanomaterials grant them unique properties, setting them apart from conventional materials. This chapter highlights the extensive applications of nanotechnology in agriculture and explores its future potential. Nanofertilizers, for instance, can break yield barriers without causing environmental harm. Similarly, the use of nanomaterials in plant protection can prevent the development of resistance in pests. By integrating nanotechnology into areas such as precision water management, soil and water reclamation, biotechnology, pest surveillance, pest control, next-generation pesticides and food processing, India can achieve unprecedented and sustainable agricultural productivity.

Keywords: Modern agriculture, Nanotechnology, Efficiency, Nanofertilizers, Environment.

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1 Introduction

Agriculture serves as the backbone of most developing countries, contributing significantly to national income and providing livelihood for more than half the population. Currently, the global population stands at approximately 6 billion, with 50 % residing in Asia. In developing countries, food shortages caused by environmental challenges and political instability are common, whereas developed nations often experience food surpluses (Singh *et al.*, 2019; Singh *et al.*, 2021). To address these issues, developing nations are focusing on creating drought- and pest-resistant crops to maximize yields, while developed countries are driven by consumer demand for fresher and healthier foods (Anonymous, 2009). Nanotechnology offers transformative solutions to agricultural challenges. By leveraging nanoparticles and nanocapsules, nanotechnology enhances pesticide and fertilizer delivery systems, enabling controlled and delayed release, increased absorption efficiency and reduced environmental impact. For instance, nano-crystals improve the effectiveness of pesticides, allowing lower doses to achieve desired results.

This multidisciplinary science, combining insights from biology, chemistry and physics, manipulates atoms and molecules to create materials with novel properties. In developing nations like India, with a population of 1.27 billion (2014-2015 census), food security is a pressing concern. Agriculture faces challenges such as nutrient deficiencies, population pressure, industrialization, water scarcity, soil degradation and erosion. Fertilizers play a pivotal role in crop productivity, contributing 35-40% to yields.

However, traditional fertilizers often come with drawbacks, including negative impacts on plant health. Nano-fertilizers improve nutrient use efficiency by up to threefold and enhance stress tolerance in crops. They are eco-friendly, promote carbon uptake, improve soil aggregation and ensure the slow, targeted release of nutrients encapsulated in nano-scale polymers. These fertilizers supply essential nutrients like NPK in balanced proportions, reducing the quantity and cost compared to conventional fertilizers. However, excessive use could expose soil microbes and plants to potentially harmful levels of chemical reactivity (Sadik *et al.*, 2009).

The integration of nanotechnology with sensing devices further reforms agriculture. Sensors monitor soil conditions, pH, moisture and toxicity levels, while providing real-time updates on crop health. Wireless technology and cloud-based systems enhance field monitoring, offering centralized control over multiple nodes. Hence, nanotechnology, with innovations in fertilizers and sensors, positions itself as a game-changer in modern agriculture.

2. Properties of Nanoparticles

Nano-bio interfaces are inherently complex, with their activities influenced by various factors, including the characteristics of nanoparticles, the biological components they interact with (such as proteins, cell membranes, endocytic vesicles, or organelles), the surrounding medium and any mutual changes that occur during interaction (Tarafdar *et al.*, 2015). The surface behaviour of nanoparticles is governed by properties like chemical composition, solubility, surface charge, semi-conductivity, size, shape, surface curvature, crystallinity, porosity, surface heterogeneity, roughness and functionalization with charged groups, peptides, or polymers (Mani & Mondal, 2016). Additional factors include the size-to-ratio aspect, hydrophobicity, surface area, solubility, surface contamination, ability to generate reactive oxygen species (ROS), competitive binding at receptor sites and dispersion or aggregation tendencies. The enhanced activity of nanoparticles is primarily attributed to two principal properties.

2.1 Increased surface area

The contact angle refers to the angle formed at the intersection of the liquid-vapor interface and the solid surface interface. Wetting is inversely proportional to the contact angle. Liquids containing nanoparticles exhibit unique spreading behaviours on solid surfaces. Smaller nanoparticles have lower contact angles compared to larger ones due to their higher surface-to-volume ratio. This reduction in contact angle enhances wetting (Guo *et al.*, 2013).

2.2 Quantum effect

The quantum effect arises primarily from quantum confinement, which leads to an increase in the band gap as particle size decreases. This phenomenon, accompanied by increased surface energy, can alter various properties of nanoparticles, such as melting point, reactivity and magnetic characteristics (Somasundaran *et al.*, 2010).

2.3 Behavioural patterns of nano fertilizers

In nano fertilizers, nutrients are encapsulated within nanomaterials and coated with a thin protective layer. This encapsulation and coating regulate the controlled release of nutrients from the fertilizer capsule. Nanomaterials such as nanotubes and nanopores are commonly used for encapsulating fertilizers (Twardowski, 2007).

2.4 Flow of nanoparticles and nanomaterials in ecosystems

The movement of nanoparticles and nanomaterials in ecosystems is dynamic and multifaceted. These materials, originating from industries, agriculture and natural sources, disperse into water bodies, soil particles and the atmosphere. From these environments, nanomaterials integrate into living systems, including plants and microorganisms present in soil and water. They subsequently propagate through the food chain, transferring to higher trophic levels (Monticone *et al.*, 2000).

3. Need of Nanotechnology in Indian Agriculture

Indian agriculture is currently facing a range of challenges, including stagnation in crop productivity, declining soil fertility, nutrient deficiencies, erratic climate patterns, shrinking arable land and water shortages (Maitra & Pine, 2020). After the Green Revolution, Indian agriculture has shown signs of fatigue, with reduced nutrient use efficiency. Crops are no longer responding to the application of nutrients, whether routine or as per recommended fertilizer doses (Maitra *et al.*, 2018). The unbalanced and improper use of fertilizers is widespread in Indian agriculture, causing significant damage to both crop land and natural water bodies. Nitrogen fertilizers, particularly urea, are heavily subsidized by the government, leading to their overuse compared to other nutrients. This excessive reliance on nitrogen fertilizers disrupts groundwater quality and contributes to eutrophication in aquatic ecosystems. Such unregulated fertilization practices are a major concern for the rapid decline of soil health. There has been a consistent decline in nutrient use efficiency across various crops and cropping systems in different agroclimatic zones of India (Pattanayak *et al.*, 2022). Ensuring food and nutritional security for India's growing population, especially amidst the challenges posed by climate change, is a formidable task. At the same time, the emergence of multi-nutrient deficiencies in Indian soils adds a new layer of complexity (Praharaj *et al.*, 2021). This situation highlights the urgent need for a more efficient system for input delivery and management.

Considering the aforementioned issues, there is a need for the intervention of novel technologies with transformative potential. In this context, nanotechnology emerges as a promising solution, offering a range of nanomaterials in various types and forms.

4. Role of Nanotechnology in Agriculture

Nanotechnology integrates multiple scientific disciplines, including engineering, medicine, biology, physics and chemistry (Fig. 2). Its precise application in agriculture and plant breeding has the potential to significantly boost food production, productivity and economic development, thereby addressing global food security challenges (Ndlovu *et al.,* 2020). In recent years, nanotechnology has become a critical tool in modern agriculture. As science and technology continue to evolve, nanotechnology has made its mark across various fields, including agriculture, telecommunications, the food industry and cosmetics. In agriculture, nano biotechnology offers insights into crop biology, aiding in the improvement of yield and nutritional quality through breeding. The adoption of nanotechnology in agriculture is essential for enhancing crops, diagnosing plant diseases and monitoring plant health and soil quality. These advancements ultimately improve plant performance, which remains the core objective of breeding programs (Sertova, 2015).

4.1 Hormonal effects in plants

Various plant growth regulators, such as Nano-5 and Nano-Gro, are being widely produced and utilized globally to enhance hormonal effects. Syngenta, a prominent agricultural company, has been manufacturing Primo MAXX, a plant growth regulator, for several years (Ndlovu *et al.,* 2020).

4.2 Genetic manipulation and crop improvement

Nanotechnology offers transformative potential in plant science, enabling genetic modification and acting as a protective shield against pathogens, thereby aiding crop improvement (Elizabath *et al.,* 2019). This technology empowers breeders to develop plants with enhanced resistance to environmental stresses such as drought, cold, diseases and salinity. For instance, zinc nanoparticles are commonly used to boost the productivity of *Pennisetum americanum*, while TiO_2 nanomaterials have been shown to increase mung bean yields (Manjunatha *et al.,* 2019).

Advancements in nanotechnology, coupled with gene sequencing, enable the precise identification and utilization of plant genetic resources. Nano-genomics technology facilitates the use of nanomaterials as carriers of DNA or RNA, delivering genetic material to specific cellular targets for gene expression (Ndlovu *et al.,* 2020). Nanofertilizers have shown significant promise in improving crop yield and quality by enhancing nutrient efficiency, reducing environmental waste and lowering production costs, contributing to sustainable agriculture. For example, phosphatic nano-fertilizers have been reported to increase the growth rate by 32% and seed yield by 20% in soybean (*Glycine max*) compared to conventional fertilizers.

Additionally, carbon nanoparticle nanotubes made of Au, SiO_2, ZnO and TiO_2 enhance plant development by improving nutrient uptake and utilization (Fraceto *et al.,* 2016). Studies have demonstrated that nanotechnology can boost germination, seedling growth, photosynthetic activity, nitrogen metabolism, mRNA expression and gene expression, making it a powerful tool for crop improvement. Nutrient deficiencies can also be addressed using nanocarriers that optimize nutrient delivery to plants. Furthermore, nanotechnology aids in identifying superior genes to enhance disease resistance and productivity in crops. Just as genetically modified agriculture has revolutionized the food chain, nanotechnology, applied from seeds to stomach and genome to gluten, is poised to enhance agribusiness control over global food systems at every stage (Bhau *et al.,* 2016).

4.3 Resistance against abiotic stress

Nano-barcode particles are typically produced through the semi-automated lamination of inert metals like gold, silver or platinum. These nano-barcodes are utilized in gene expression analysis to enhance resistance against environmental stresses and to protect chloroplasts from damage caused by corrosiveness and ultraviolet radiation (Ndlovu *et al.,* 2020). Additionally, farm managers employ various nanoparticles, GPS (Global Positioning System) and remote sensing technologies to effectively identify crop pests and detect environmental stresses such as drought, pollution, or nutrient deficiencies. This enables strategic planning to safeguard crops accordingly (Joshi *et al.,* 2019).

4.4 Seed science

To enhance germination in rainfed crops, researchers are exploring the use of metal oxide nanoparticles and carbon nanotubes. Studies reveal that carbon nanotubes (CNTs) improve tomato seed germination by facilitating moisture transport. CNTs penetrate the seed coat, creating new pores that channel water from the substrate into the seeds, thereby promoting germination in rainfed agricultural systems. Additionally, titanium nanoparticles (Ti NPs) at a concentration of 20 g/L have been shown to significantly increase wheat ear mass, seed number, biomass, stem elongation, flowering, yield, starch content.

Similarly, CNTs enhance tomato seed germination by penetrating their tough outer coat. Multi-walled carbon nanotubes have also been reported to improve germination rates in crops like soybean, barley and corn when applied via spraying or encapsulation (Acharya and Pal, 2020). Nanoparticles such as manganese, molybdenum and MWCNTs have increased germination percentages in crops like *Brassica juncea* and *Phaseolus mungo*. Silver nanoparticles are commonly used for seed dressing and surface sterilization. Cowpea, cabbage and cucumber seeds treated with Nano-863 for 2, 4, or 12 hours showed higher germination rates, bud length, diameter and fresh bud weight compared to seeds soaked in water. Garlic treated with Nano-863-treated water exhibited bolt heights approximately 5 cm taller after 20 days compared to untreated controls (Huang *et al.,* 2015).

4.5 Seed storage

Stored seeds release various volatile aldehydes that indicate the extent of aging. These emitted compounds can also influence nearby seeds. Biosensors can be employed to detect these aldehydes and identify seeds showing signs of deterioration, allowing their separation from healthy ones before use (Reddy *et al.,* 2017). Similarly, nanosensors can accurately detect the presence of insects or fungi within stored grains in storage facilities.

4.6 Disease and pest control

In 2011, Pimentel and Burgess highlighted that approximately 545 million kilograms of pesticides are used annually on crops in the United States, yet less than 0.15% effectively reaches the intended target to control pests (Vega-Vásquez *et al.,* 2020). This underscores the excessive and uncontrolled application of pesticides, alongside ineffective pest control strategies. Plant diseases, typically caused by pathogenic microorganisms such as bacteria, fungi, nematodes and viruses, significantly compromise crop quality and yield. Various methods, including cultural, physical, chemical, legislative, genetic, breeding and integrated pest and disease management approaches, are employed to mitigate these issues. However, these strategies often fall short; potentially due to challenges in identifying economic threshold levels necessary for effective control (Elizabath *et al.,* 2019). Nano-based diagnostics offer promising solutions by detecting diseases and agrochemical residues through differential protein measurement in healthy and diseased crops, enabling precise identification of pathogen species and optimal therapeutic intervention stages (Chung *et al.,* 2017; Elizabath *et al.,* 2019) (Tables 1 & 2).

Table 1. List of nano-based products used in agricultural sector

Products	Application	References
Super combined fertilizer and pesticides	Release active ingredients slowly	Bhan et al. (2018)
PRIMO MAXX	Control of insect pests of rice peanuts and cotton	

Subdue MAXX	Control *Pythium* and *Phytopthera* blight	
Nano green	Induce rice yields by 25%	
Nanopesticide	For crop protection 10-150 nm	
Nanoemulsion	Insect pest control 10-400 nm	
Herbicide	Prevent weed growth	
Teprosyn-Zn	Corrects Zn deficiencies in wheat, maize, sunflower, groundnut and soybean	Jatav & Nirmal (2013)
Sulfur coated fertilizer	Slow release of sulfur contents	
Chitosan-coated NPK	Controlled release of nutrients and water-retention abilities	Cicek & Nadaroglu (2015)

Table 2. List of encapsulated & non-encapsulated nanopesticides used against pests

Ingredients	**Target organisms**	**References**
Avermectin	*Martianus dermestoides*	Bhan et al. (2018)
Nanopermethrin	*Aedes aegypti*	
Artemisia arborescens	*Bemisia tabaci*	
Azadirachta indica	*Bemisia tabaci*	
Nanoalumina	*Sitophilus oryzae*	
Nanosilica	*Anopheles stephensi*, *Culex quinquefasciatus*, *Aedes aegypti*	
Aloe vera	*Anopheles stephensi*	
Emblica officinalis	*Culex quinquefasciatus*	
Rhizopus	*Anopheles stephensi*	
Nelumbo nucifera	*Culex quinquefasciatus*	
Nano-silica	*Sitophilus oryzae*	Jatav & Nirmal (2013)
Imidacloprid	*Melanagromyza sojae*, *Bemisia tabaci*	Sekhon (2014)
Carbofuran + Imidacloprid	*Aphis gossypii*, *Amrasca biguttula*	
Aqueous leaf extract of *Tinospora cordifolia*	*Anopheles subpictus*, *Culex quinquefasciatus*	
Garlic essential oil	*Tribolium castaneum*	
DNA-tagged gold nanoparticles	*Spodoptera litura*	

Nanotechnology facilitates nanoparticle-mediated gene transfer to develop pest-resistant and stress-tolerant crop varieties (Chung *et al.,* 2017). Biomarkers play a critical role in indicating disease stages (Sertova, 2015), while nano silica-silver composites and silicon enhance plant's disease resistance and stress tolerance. Their use in smaller doses also promotes environmental sustainability (Bhan *et al.,* 2018). Furthermore, nano-sensors and carbon nanotubes improve plant disease monitoring and defense by enhancing disease resistance mechanisms (Cicek & Nadaroglu, 2015).

4.7 Monitoring of plant growth stages

Nano-sensors are bio-receptor probes immobilized to provide an early response to environmental changes. They can be integrated with GIS systems, enabling large-scale monitoring of crop cultivation areas. These sensors allow precise tracking of all plant growth stages, including critical phases like photosynthesis and seed germination, to achieve optimal yields (Ghasemnezhad *et al.,* 2019). Additionally, nano-sensors can analyze the composition of plants and soil, detecting substances such as urea, pesticides, metabolites, glucose and pathogens. Their application enhances the ability to assess crop health, detect microbial contamination and determine the appropriate harvest time (Singh *et al.,* 2016). Functioning as external monitoring devices, these sensors facilitate on-site observation of environmental conditions, plant growth and protection (Jatav & Nirmal, 2013). TiO_2 nanoparticles shown to boost spinach growth by enhancing nitrogen metabolism and improving light absorption capacity (Ali *et al.*, 2014).

4.8 Secondary metabolites exploitation

Secondary metabolites, such as alkaloids, phenolics and terpenoids, act as natural self-defense mechanisms in plants, providing protection against insects (Cicek & Nadaroglu, 2015). Nanostructures offer valuable tools for identifying these crucial metabolites; for example, nano-convectors can detect terpenoids, anthocyanins and other beneficial secondary metabolites in medicinal herbs and shrubs. Additionally, nano-polymers can enhance the catalytic activity of plant cells, leading to increased protein production (Ghasemnezhad *et al.,* 2019). On the other hand, mycotoxins are toxic secondary metabolites produced by fungi that pose significant risks to living organisms. Nanostructured polymer layers, with their porous properties, could serve as receptors to detect similar harmful metabolites (Sertova, 2015).

4.9 Smart delivery of agrochemicals

Nanobiosensors utilizing carbon nanotubes or nano-cantilevers are exceptionally small, capable of trapping and delivering even the tiniest molecules and individual proteins (Abd-Elrahman & Mostafa, 2015). Smart sensors and delivery systems play a crucial role in the horticultural industry by combating infections and crop pathogens. Nano-based catalysts enhance the efficiency of pesticides and herbicides, enabling the use of lower doses (Sertova, 2015). For instance, nano-encapsulated pesticides improve the solubility of poorly soluble active ingredients and ensure their slow release. This targeted and controlled release minimizes toxicity to non-target organisms. Such nanoparticulate delivery systems require a tailored approach based on the life cycle and behaviour of the target pest or pathogen (Jatav & Nirmal, 2013). Research indicates that nanoparticles of various metals are cost-effective and reliable alternatives for managing insects and pests. This innovative technology has revolutionized the smart delivery of agrochemicals, contributing to its growing popularity (Kumar, 2020).

4.10 Nano fertilizers

One of the key contributions of nanotechnology in agriculture is the development of nano-based fertilizers, also known as nano fertilizers (Ali *et al.*, 2018). These nutrients can be encapsulated within nanomaterials such as nanotubes or nanoporous substances coated with thin protective polymer films or formulated as nanoscale particles or emulsions. Nano fertilizers possess unique features, including exceptionally high absorption efficiency, large surface area, high pore volume and well-ordered pore structures. These attributes enable the slow release of nutrients and improve their uptake by crops, making them more efficient compared to conventional polymer-coated fertilizers developed over recent decades (Ali *et al.*, 2018). Key examples include nitrogen-based fertilizers, potash fertilizers, nanoporous zeolites, zinc nano fertilizers, zeolites and nano clays, all of which release nutrients gradually throughout the crop growth cycle. This slow release reduces the risks of leaching, adsorption, surface runoff and nutrient degradation (Ndlovu *et al.*, 2020). Unlike traditional fertilizers, nano fertilizers can be designed to deliver nutrients in a controlled and gradual manner, minimizing nutrient losses and environmental contamination. Additionally, foliar applications of nano fertilizers have been shown to significantly enhance crop yields (Singh *et al.*, 2016).

4.11 Precision farming

Precision farming is defined as a system in which the goal is to maximize the production with minimum inputs like fertilizers, pesticides, herbicides etc. (Bhattacharyay *et al.*, 2020). Computers, global satellite positioning systems and remote sensing devices are used to measure the different parameters in the localized niche and accordingly localized applications with variable rate are done. Thus, precision farming helps to reduce the agricultural wastes and lowers the environmental pollution. This leads to sustainability in the production system. Nano sensors linked into a GPS system for real-time monitoring can be used to carry out precision farming; the nano sensors can be spread throughout the field where they can measure and monitor the soil parameters. Nano sensors containing carbon nano-tubes are very small and these tubes can trap small molecules and measure their amount. This type of nano materials can be engineered, so that they create an electrical or chemo signal when they come in contact with such proteins or bacteria or water. The dendrimers are the actual molecules which are branched and bind with the target proteins or any chemical (Dashora & Sharma, 2018). Thus, precision farming will lead to enhanced and sustainable productivity due the accurate information provided through nano sensors.

Furthermore, nanosensors designed for agricultural applications offer numerous advantages, including monitoring and analysing crop growth, rhizosphere parameters, nutrient composition, toxic effects and microbial infections. Additionally, they play a crucial role in assessing the release of fertilizers and pesticides into the environment, which impacts soil health, crop vitality, productivity and overall safety. These functions contribute significantly to promoting sustainable agriculture and maintaining a healthy environmental system. (Yadav *et al.*, 2023).

5 Challenges

The agricultural sector, despite its potential advantages, remains relatively marginal compared to other fields of nanotechnology application (Kumar, 2020). While nanotechnology has found success in genetics and plant breeding, its adoption in agriculture is limited due to challenges such as poor cargo loading capacity (VegaVásquez *et al.*, 2020). Additionally, concerns over the potential negative effects of nanoparticles on human health pose significant barriers. Studies suggest that even low concentrations of nanosized titanium dioxide can cause microvascular dysfunction in rats and nanoparticles smaller than 1 µm can penetrate healthy human skin, potentially affecting vital organs such as the brain and blood vessels (Wani & Kothari, 2018). Various governmental and non-governmental organizations, along with scientific and safety councils, are actively providing recommendations to mitigate risks to human health, the environment, animals and plants (Huang *et al.*, 2014). The primary challenge for large-scale adoption of this technology lies in addressing these safety concerns. As the adage goes, "technology-yes, but safety-must." Therefore, a thorough assessment of the risks and consequences associated with nanoparticles is crucial before implementing this technology on a broader scale (Acharya and Pal, 2020).

6 Positive Aspects

Nanotechnology represents an innovative approach in plant breeding, aiming to meet the growing global food demand with precision (Elemike *et al.*, 2019). The nanomaterials developed through this technology enhance the efficiency of microorganisms in breaking down harmful and unwanted substances (Paneru & Kumar, 2023). This degradation process contributes to agricultural safety by reducing toxic residues in soil and water (Prasad *et al.,* 2017). Environmentally friendly green nanomaterials are now being integrated into agriculture to boost yield, improve input use efficiency and lower fertilization costs. Additionally, these materials significantly mitigate greenhouse gas emissions by curbing the production of nitrous oxide, methane and carbon dioxide in the agricultural sector (Omanovic-Miklicanin & Science, 2017).

The application of nanotechnology in plant breeding also minimizes chemical hazards, nutrient losses, pest outbreaks and crop yield reductions. It stabilizes fluctuating climatic conditions and enhances food security (Elemike *et al.,* 2019). This technology effectively reduces crop losses by addressing stress caused by biotic and abiotic factors, diseases and pest infestations, often at an early stage. Operating at the nanoscale, comparable to that of viruses or pathogens, nanotechnology enables the early detection and eradication of these threats (Sah *et al.,* 2014). Moreover, plants treated with low doses of antimicrobial micronutrients coated with nanoparticles demonstrate increased resilience to biotic stresses like fungal root infections (Lowry *et al.,* 2019). Biopolymer-based nanomaterials, synthesized from cellulose and starch, are non-toxic and safe for humans, gaining worldwide acceptance due to their environmental and health safety. Through these advancements, nanotechnology equips plants with enhanced functions, enabling them to withstand biotic and abiotic stresses in a rapidly changing climate.

7 Negative Aspects

Nanotechnology offers numerous benefits but also presents significant negative impacts. Like other chemical processes, it can have unintended and undesirable effects on non-target plants and plant-associated organisms. To enable large-scale adoption, a thorough understanding of its agro-ecological implications, potential benefits and nanotoxicity is essential (Bindraban *et al.,* 2015). As with any technology, its advantages come with limitations. For instance, the accumulation of nanomaterials in food products raises human health and environmental concerns. The growing use of nanotechnology in agriculture, especially in plant breeding, has sparked concerns among breeders, agriculturists, environmentalists, researchers and the public regarding its short- and long-term safety for living beings and ecosystems. Research has documented the adverse effects of metal oxide nanoparticles on plant growth and seed germination, leading to phytotoxicity, cytotoxicity and genotoxicity. Improper application of this technology could pose significant risks to living organisms. Studies have identified the harmful impact of nanomaterials on plants and soil microbes. For example, phytotoxicity effects have been reported for five types of nanomaterials, including multiwalled carbon nanotubes, aluminum, alumina, zinc and zinc oxide, as well as the negative impact of nano-TiO_2 on chloroplast photochemical reactions. Engineered nanoparticles pose risks to humans, animals and ecosystems, with some evidence indicating impacts on growth, enzyme activity, chlorophyll and protein content in algae, which vary depending on algae type and nanomaterial properties (Huang *et al.*, 2015). In Canada, the use of nanotechnology in organic food production is banned, as it is classified as a "Prohibited Substance or Method" (Pramanik & Pramanik, 2016). Similarly, the International Federation of Organic Agriculture Movements opposes nanotechnology in organic farming due to its unpredictable and potentially harmful effects. A key concern is that nanoparticles can penetrate cells and nuclei, potentially causing cell death or DNA mutations (Pramanik & Pramanik, 2016). While carbon nanotubes enhanced root elongation in onions and cucumbers, they significantly reduced root length in tomatoes (Mishra *et al.*, 2017). In recent years, global policy debates have emerged regarding the regulation and governance of nanotechnology. Nanoparticles used in agriculture, such as nanopesticides, nano-herbicides and nano-fertilizers, may obstruct plant vascular bundles, disrupting the transfer of nutrients, water and photosynthesis products. They may also hinder pollination by physically blocking pollen-stigma interactions (Ndlovu *et al.*, 2020). Additionally, airborne nanoparticles pose severe health risks to humans and animals, potentially causing respiratory and circulatory system issues, emphysema, asthma, genotoxicity and chronic pulmonary diseases (Elizabath *et al.*, 2019). Given these risks, nanotechnology in agriculture requires cautious and well-regulated application. Research on its toxicological aspects remains limited, but ongoing studies aim to broaden its safe and effective use. Comprehensive efforts are necessary to understand nanoparticle interactions in the environment, ensuring their safe integration into agricultural practices for a sustainable future (Mishra *et al.*, 2017).

Conclusions

Nanotechnology plays a vital role in sustaining agricultural activities by minimizing negative impacts on crops, plants, animals and human health. Significant advancements in nanotechnology have been made in various agricultural domains, such as crop improvement, disease diagnosis, pest management and soil health monitoring. Nano-derived tools, including nano-sensors and nanoparticles, are extensively utilized in plant breeding and genetic transformation programs to develop superior crop varieties. This innovative technology holds immense potential to transform agriculture and the food system due to its diverse and impactful applications. However, despite its substantial benefits, the adoption of nanotechnology has raised concerns about safety and practical implementation. Nanotechnology offers extensive research opportunities in areas such as plant breeding, medicine, healthcare, energy, materials and manufacturing. Its applications extend across the entire food chain, enhancing food safety, quality control and the development of novel food ingredients or additives.

References

Abd-Elrahman, S. H., & Mostafa, M. A. M. (2015). Applications of nanotechnology in agriculture: An overview. Egyptian Journal of Soil Science, 55(2), 197–214.

Acharya, A., & Pal, P. K. (2020). Agriculture nanotechnology: Translating research outcomes to field applications by influencing environmental sustainability. NanoImpact, 19, 100232.

Ali, M. A., Rehman, I., Iqbal, A., Din, S., Rao, A. Q., Latif, A., Samiullah, T. R., Azam, S., & Husnain, T. (2014). Nanotechnology, a new frontier in agriculture. Advancement in Life Science, 1, 129–138.

Ali, S., Shafique, O., Mahmood, T., Hanif, M. A., Ahmed, I., & Khan, B. A. (2018). A review about perspectives of nanotechnology in agriculture. Pakistan Journal of Agricultural Research, 31.

Anonymous. (2009). Nanotechnology and nanoscience applications: Revolution in India and beyond. Strategic Applications Integrating Nano Science.

Bhan, S., Mohan, L., & Srivastava, C. N. (2018). Nanopesticides: A recent novel eco-friendly approach in insect pest management. Journal of Entomological Research, 42(2), 263–270.

Bhattacharyay, D., Maitra, S., Pine, S., Shankar, T., & Pedda Ghouse Peera, S. K. (2020). Future of precision agriculture in India. Protected Cultivation and Smart Agriculture, 1, 289–299.

Bhau, B. S., Phukon, P., Ahmed, R., Gogoi, B., Borah, B., Baruah, J., Sharma, D. K., & Wann, S. B. (2016). A novel tool of nanotechnology: Nanoparticle-mediated control of nematode infection in plants. In Microbial Inoculants in Sustainable Agricultural Productivity: Vol. 2: Functional Applications (pp. 253–269).

Bindraban, P. S., Dimkpa, C., Nagarajan, L., Roy, A., & Rabbinge, R. (2015). Revisiting fertilizers and fertilization strategies for improved nutrient uptake by plants. Biology and Fertility of Soils, 51, 897–911.

Chung, I. M., Rajakumar, G., Gomathi, T., Park, S. K., Kim, S. H., & Thiruvengadam, M. (2017). Nanotechnology for human food: Advances and perspective. Frontiers in Life Science, 10(1), 63–72.

Cicek, S., & Nadaroglu, H. (2015). The use of nanotechnology in agriculture. Advances in Nano Research, 3(4), 207.

Dashora, A., & Sharma, K. (2018). Green synthesis of nanoparticles and their applications. Advanced Science, Engineering and Medicine, 10, 523–541.

Dhewa, T. (2015). Nanotechnology applications in agriculture: An update. Octa Journal of Environmental Research, 3(2).

Elemike, E. E., Uzoh, I. M., Onwudiwe, D. C., & Babalola, O. O. (2019). The role of nanotechnology in the fortification of plant nutrients and improvement of crop production. Applied Sciences, 9(3), 499.

Elizabath, A., Babychan, M., Mathew, A. M., & Syriac, G. M. (2019). Application of nanotechnology in agriculture. International Journal of Pure and Applied Biosciences, 7(2), 131–139.

Fraceto, L. F., Grillo, R., de Medeiros, G. A., Scognamiglio, V., Rea, G., & Bartolucci, C. (2016). Nanotechnology in agriculture: Which innovation potential does it have? Frontiers in Environmental Science, 4, 186737.

Ghasemnezhad, A., Ghorbanpour, M., Sohrabi, O., & Ashnavar, M. (2019). A general overview on the application of nanoparticles in agriculture and plant science. Comprehensive Analytical Chemistry, 87, 85–110.

Guo, D., Xie, G., & Luo, J. (2013). Mechanical properties of nanoparticles: Basics and applications. Journal of Physics D: Applied Physics, 47, 013001.

Huang, S., Wang, L., Liu, L., Hou, Y., & Li, L. (2015). Nanotechnology in agriculture, livestock and aquaculture in China: A review. Agronomy for Sustainable Development, 35, 369–400.

Jatav, G. K., & Nirmal, D. E. (2013). Application of nanotechnology in the soil-plant system. Asian Journal of Soil Science, 8(1), 176–184.

Joshi, H., Choudhary, P., & Mundra, S. L. (2019). Future prospects of nanotechnology in agriculture. International Journal of Chemical Studies, 7(2), 957–963.

Kumar, R. (2020). Application of nanotechnology in crop disease management. Universe International Journal of Interdisciplinary Research, 1(2).

Lowry, G. V., Avellan, A., & Gilbertson, L. M. (2019). Opportunities and challenges for nanotechnology in the agri-tech revolution. Nature Nanotechnology, 14, 517–522.

Maitra, S., & Pine, S. (2020). Smart irrigation for food security and agricultural sustainability. Indian Journal of Natural Sciences, 10(60), 20435–20439.

Maitra, S., Zaman, A., Mandal, T. K., & Palai, J. B. (2018). Green manures in agriculture: A review. Journal of Pharmacognosy and Phytochemistry, 7(5), 1319–1327.

Mishra, S., Singh, H. B., & Mishra, A. K. (2017). Application of nanotechnology in agriculture. International Journal of Agricultural and Environmental Biotechnology, 10(5), 543–553.

Mukhopadhyay, S. S. (2014). Nanotechnology in agriculture: Prospects and constraints. Nanotechnology, Science and Applications, 7, 63–71.

Nair, R., Varghese, S. H., Nair, B. G., Maekawa, T., Yoshida, Y., & Kumar, D. S. (2010). Nanoparticulate material delivery to plants. Plant Science, 179(3), 154–163.

Nath, S., Bhattacharjee, R., & Sinha, S. (2016). Role of nanotechnology in agriculture. Journal of Biotechnology and Crop Science, 5(8), 79–88.

Paneru, P., & Kumar, M. (2023). Development of size and shape dependent model for bandgap of semiconductor nanomaterials. Modern Physics Letters B, 37(29), 2350111.

Prasad, R., Bhattacharyya, A., & Nguyen, Q. D. (2017). Nanotechnology in sustainable agriculture: Recent developments, challenges and perspectives. Frontiers in Microbiology, 8, 1014.

Rajput, V. D., Minkina, T., Suskova, S., Mandzhieva, S., Tsitsuashvili, V., Fedorenko, A., & Purvis, W. O. (2018). Nanotechnology in soil-plant system: A sustainable way for improving plant growth. Environmental Geochemistry and Health, 40, 2679–2693.

Raliya, R., Tarafdar, J. C., Biswas, P., & Datta, A. (2016). Engineered nanoparticles for precision agriculture and sustainable crop production. Trends in Biotechnology, 34(6), 588–590.

Ramesh, K., & Sharma, S. K. (2020). Application of nanotechnology in precision farming. Indian Journal of Agricultural Sciences, 90(5), 833–840.

Rao, P. H., & Bharathi, R. (2018). Role of nano fertilizers in agriculture. International Journal of Current Microbiology and Applied Sciences, 7(4), 2319–7706.

Ravindran, R., & Rajasankar, J. (2019). Applications of nanotechnology in agriculture. Asian Journal of Agricultural Research, 13(1), 1–9.

Sastry, R. K., Rashmi, H. B., Rao, N. H., & Ilyas, S. M. (2011). Integrating nanotechnology into agri-food systems research in India: A conceptual framework. Technological Forecasting and Social Change, 78(9), 1629–1637.

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.

Sharma, A., Kumar, V., & Kumar, P. (2019). Nanotechnology: A tool to enhance crop production. Journal of Plant Nutrition, 42(10), 1190–1201.

Singh, D., & Singh, S. (2019). Nanotechnology in crop improvement: Recent advances and future prospects. Indian Journal of Biotechnology, 18(2), 123–134.

Singh, K. K., Singh, S. P., Kumari, B., Paliwal, A. K., Chauhan, J. S., & Rawat, J. M. S. (2019). Income generation of farmers via medicinal plants cultivation: A review. Int. J. Pure Appl. Biosci, 7, 174-177.

Singh, K. K., Meena, R. K., Singh, S.P. and Chauhan, J.S. (2021). Approaches to Relieve a Worldwide Global Warming through Agriculture, In: Akshat Uniyal & Isha Sharma, (eds) Trends in Agriculture: Traditional and Modern Approaches. pp. 279-289.

Singh, S.P. Singh, K.K. and Kumari, B. (2021), Assessment of Biodiversity Loss and Sustainability Due to Urbanization, In: Akshat Uniyal & Isha Sharma, (eds) Trends in Agriculture: Traditional and Modern Approaches. pp. 325-334.

Srivastava, G., Das, C. K., Das, A., Singh, S. K., Roy, M., Kim, H., & Singh, P. K. (2021). Role of nanomaterials in sustainable agriculture: Recent developments, challenges and future prospects. Environmental Science and Pollution Research, 28(5), 5282–5300.

Subramanian, K. S., & Sharmila Rahale, C. (2020). Nanofertilizers for balanced crop nutrition. Research Journal of Agricultural Sciences, 11(5), 1017–1024.

Tarafdar, J. C., Raliya, R., & Mahawar, H. (2017). Development of zinc nanofertilizer to enhance crop production in pearl millet (Pennisetum americanum). Agricultural Research, 6(4), 372–379.

Tiwari, D. K., Dasgupta-Schubert, N., Villaseñor Cendejas, L. M., Villegas, J., Carreto Montoya, L., & Borjas García, S. E. (2013). Interfacing carbon-based nanomaterials with living plants: A mesoscopic photosynthetic analysis. Nanoscale Research Letters, 8, 218.

Usman, M., Farooq, M., Wakeel, A., Nawaz, A., Cheema, S. A., ur Rehman, H., & Ashraf, I. (2020). Nanotechnology in agriculture: Current status, challenges and future opportunities. Science of the Total Environment, 721, 137778.

Wang, P., Lombi, E., Zhao, F. J., & Kopittke, P. M. (2016). Nanotechnology: A new opportunity in plant sciences. Trends in Plant Science, 21(8), 699–712.

Yadav, R. S., & Handa, S. (2019). Nanotechnology applications in agriculture. Current Agriculture Research Journal, 7(1), 60–68.

Zhang, H., Wang, H., Chen, Q., Liu, X., & Wang, H. (2018). Potential risks of nanoparticles in agriculture. Environmental Science & Technology, 52(22), 13199–13210.