Nanotechnology in Agriculture: Enhancing Crop Yield and Sustainability

Muhammad Shahid Khan[1,*], Arooj Ali[2], Muhammad Uzair Zafar[3], Sana Alam[4], Saba Bibi[5], Adeeba Naseer[4,6], Nadeem Ali[7], Muhammad Imtiaz Rashid[7] and Khurram Shahzad[7]

[1]Department of Physics, University of Okara, Pakistan
[2]Institute of Physics, Faculty of Physical and Mathematical Sciences, The Islamia University, Bahawalpur 63100, Pakistan
[3]Department of Botany, The Islamia University of Bahawalpur, Pakistan
[4]Department of Zoology, The Islamia University of Bahawalpur-63100, Pakistan
[5]Department of Zoology, Hazara University, Mansehra, Pakistan
[6]College of Fisheries, Southwest University, Chongqing 400715, China
[7]Centre of Excellence in Environmental Studies, King Abdulaziz University, Jeddah, Saudi Arabia
*Corresponding author: mshahid.khan@uo.edu.pk

Abstract

Nanotechnology is a major advance in agriculture that helps solve big problems in food production and sustainability around the world. Using nanotechnology, agriculture can improve its accuracy, efficiency and commitment to the environment. Nano-fertilizers, nano-pesticides and nano-sensors are used to improve the use of resources, decrease waste of chemicals and help preserve soil and water. Nanotechnology improves plant resistance to environmental problems by altering their genes and cells which increases their ability to take in light and withstand stresses. They help farmers to get better harvests and follow sustainable methods by lessening harm to nature and protecting different species. Even so, using nanotechnology in real life requires dealing with problems such as risks to the environment, people's health, the ability to be used on a large scale, cost and regulation. If handled properly, nanotechnology can help feed the world, protect the environment and reduce the negative effects of climate change on agriculture.

Keywords: Nanotechnology, Sustainable Agriculture, Nano-fertilizers, Crop Resilience

Cite this Article as: Khan MS, Ali A, Zafar MU, Alam S, Bibi S, Naseer A, Ali N, Rashid MI and Shahzad K, 2025. Nanotechnology in agriculture: enhancing crop yield and sustainability. In: Nisa ZU, Altaf S, Zahra A and Saeed K (eds), Nanobiotech in Holistic Health: Innovations for Integrated Well-being. Unique Scientific Publishers, Faisalabad, Pakistan, pp: 51-57. https://doi.org/10.47278/book.HH/2025.414

A Publication of Unique Scientific Publishers

Chapter No: 25-008

Received: 18-Feb-2025
Revised: 19-Apr-2025
Accepted: 01-May-2025

Introduction

People have depended on agriculture for a long period to obtain what they need for food, clothing and bioenergy. As the world's population increases and the climate changes, farmers have to find new ways to make farming both more productive and sustainable. Nanotechnology, by working with small materials at the nanoscale, provides new answers to these issues. Because of it, farmers can make things that are very precise, so interventions can be used to enhance various parts of farming (Shang et al., 2019).

Nanotechnology can change farming methods to make them more efficient, better for the environment and sustainable. The use of nanomaterials lets farmers handle nutrients and pesticides more efficiently, use less and keep a close eye on the soil. Furthermore, nanotechnology can be applied to create smart ways to transport drugs, biosensors and materials that help crops withstand different environmental problems (Gupta et al., 2023). The increase in world population and the need for more food bring problems to agriculture such as lower yields, issues from pests and diseases, climate change and a lack of water. With nanotechnology, nanoparticles contribute to nutrient delivery, pest control and stress management because of their unique shape, size, form and electrochemical features. The large surface area and strong structure of nanomaterials make them better for agricultural use than regular materials. Metal-based engineered nanoparticles have attracted notice for their adjustable properties (Zulfiqar et al., 2024).

Nanotechnology assists in saving the environment by helping to produce clean air and environmentally safe products. But there are worries that nanoparticles can be toxic because they may change how cells interact with their environment, absorb nutrients and carry out their metabolic processes. Because of these risks, companies must take steps to evaluate and control them (Klaine et al., 2008). Using nanotechnology in farming makes resources more efficient cuts down on contaminating the environment and helps crops grow better by applying just the right number of pesticides and fertilizers. Precision farming and monitoring crop health in real time help build a food supply that will last for years to come (Lead et al., 2018).

This chapter examines the transformative role of nanotechnology in agriculture, exploring its applications, benefits, and challenges in building a sustainable agricultural framework.

2. Nanotechnology in an Agricultural Context

Nanometer is equal to one-billionth of a meter; it is too small for most humans to imagine. At this level, the properties of materials are quite different from those you see in larger pieces. At this size, quantum effects are noticeable; the ratio of surface to volume increases and materials may have unusual reactivity and interaction abilities. Nanotechnology in agriculture uses nanomaterials, nano-sensors and nano-devices to boost productivity make farming more efficient and help it be more sustainable. Due to their special physical, chemical and biological traits, nanoparticles are suitable for many uses, including farming and conserving the environment. Nanoparticles key features such as a great deal of surface area, increased responsiveness and ways to interact with biological substances that are not seen in larger particles (Nasrollahzadeh et al., 2019).

In agricultural applications, nanotechnology in farming helps farmers focus their actions more accurately. Unlike before, nanoscale technologies make it possible to manage certain biological activities with great accuracy. Because of this, farming is more efficient, sustainable and friendlier to the environment (Shang et al., 2019).

Agriculture has consistently been the most important industry since it sends raw materials to both the feed and food industries (Velasco-Muñoz et al., 2021). Because there are more people on our planet and fewer natural resources, growing food must be productive, successful and protect the environment. Much of objectives for future will depend on our transformation taking place (Mukhopadhyay, 2014).

2.1 Current Agricultural Challenges

With the world's population increasing, global agriculture must discover how to produce more food without harming the environment (Duro et al., 2020). The amount of farmable land is shrinking, there is less water and climate change is making it much harder for traditional farming to meet food needs (Ingrao et al., 2023). Environmental pollution can happen because of the many chemicals, water pollution and greenhouse gas emissions from traditional farming (Chataut et al., 2023). Conventional approaches for fertilizing and handling pests can damage the environment and lead to extra resources being wasted (Shanmugavel et al., 2023).

2.2 Nanoscale Materials: A Comprehensive Solution

Nanotechnology is helping farmers manage nutrition, water supply, pests, diseases, the environment and crop strength. They can address global agricultural issues and sustainably help people get food (Shang et al., 2019).

2.3 Improved Nutrient and Water Delivery

A good way to deliver nutrients and water is essential for healthy crop growth. The usual way of adding fertilizers and watering plants often allows nutrients to escape which both reduces the size of harvests and harms the environment. By using nanoscale fertilizers, farmers get better results from using less fertilizer, as their plants better absorb essential nutrients. The approach helps to cut down waste and pollutants and protects the environment (Yadav et al., 2023). Nano-hydrogels and nano-clays are being added to soils to help them keep water. Their ability to hold water, nano-hydrogels help soil soak up about 40% more water and are valuable in places with less water. Also, when irrigation uses nano-based technology, less water evaporates and less runs out. These innovations improve the way we use water and protect agriculture in places where droughts could occur (Zaib et al., 2023).

2.4 Nano-fertilizers: Precision Nutrient Delivery and Improved Absorption

Nano-fertilizers are revolutionizing plant nutrition by providing nutrients with remarkable precision. Plant nutrition is being improved by the accurate supply of nutrients with nano-fertilizers. Using typical fertilization techniques often means adding too much fertilizer and a lot of it is wasted. Unlike other fertilizers, nano-fertilizers are made to pass straight into the cells of plants, offering nutrients exactly as they need them (Kumar et al., 2021). There is less waste since nutrients are not released as fast like with conventional agriculture. Assuming studies, introducing nano-fertilizers into farming may result in nutrient efficiency improving to 80% which is a useful improvement for farmers (Easwaran et al., 2024). Nano-fertilizers are flexible enough to be adapted to fit the needs of every plant. Nutrients in soil can be made available by soil pH, temperature or moisture. Plants can get the nutrients they need most during important growth stages, so their yield is high and they require less frequent fertilizing. Using nano-fertilizers in precision agriculture systems improves both the usefulness and the benefits they provide to the environment and the economy (Iqbal, 2019).

Many traditional ways to apply fertilizer led to large amounts of nutrients being lost and the environment being polluted. Nano-fertilizers help solve the problems that traditional techniques can't address. These advanced materials are designed to give plants nutrients more exactly, making plant nutrition management better (El-Saadony et al., 2021).

Nano-fertilizers have the ability to make nutrient use more efficient. Conventional fertilizers are spread everywhere and can be wasted, unlike nanoparticle-based fertilizers which are designed to work with plant cells (Das & Das, 2019). Both silicon dioxide (SiO_2) and zinc oxide (ZnO) nanoparticles are known to help improve how the body uses nutrients and its metabolic functions (Zafar et al., 2024).

Nano-fertilizers have many different advantages. It has been demonstrated that nano-fertilizers can improve nutrient absorption by as much as 80% which means crops grow better and there is less harm to the environment. In addition, nano-fertilizers make it possible to release nutrients in a controlled way. Nano-fertilizers are different in that they can be set up to release nutrients slowly which fits the plant's schedule and helps avoid losses. This helps your body use nutrients better and also reduces harm to the environment (Ayenew et al., 2024).

Nano-fertilizers are able to overcome important agricultural issues. These new methods help crops by cutting back on chemicals and improving how nutrients are given, creating a more sustainable way to feed them. It has been found in field trials that using nano-fertilizers can cut fertilizer use by half without affecting or increasing crop yields (Goswami et al., 2024).

2.5 Nano-pesticides: Targeted Pest Control with Reduced Environmental Impact

Broad spectrum conventional pesticide use is usually with chemicals that can harm 'beneficial' organisms and disturb the functioning of ecosystems. On the other hand, however, nanotechnology includes new pest control technologies that are specific and effective. Long lasting efficacy results from their sustained and controlled release mechanisms yet these do not harm non target organisms. The nano–pesticide, for example, could be engineered to degrade after it targets the insect, thereby, reducing residual contaminant (Yousef et al., 2023). In addition, nano-particles are able to 'target' delivery of active ingredients to pest sites thereby increasing efficacy at lower concentrations. In addition, nanotechnology allows biodegradable carriers that minimize environmental persistence and, in turn, reduce long term ecological effects. More recently, new development includes smart nano formulations that will only release active ingredients under appropriate environmental conditions, i.e. presence of pests. In addition to optimizing effectiveness, this also minimizes waste, just as well as global efforts to minimize chemical dependence and to adopt curiosity for sustainable crop protection practices (Zainab et al., 2024).

In addition to pest management, nanotechnology holds promise in disease control through nanoscale delivery of antimicrobial agents and vaccines. These treatments can prevent diseases from developing and curtail the spread of pathogens, significantly reducing crop losses (Biswas et al., 2023). This targeted approach also reduces the risk of pests developing resistance to pesticides.

Gacem et al. (2022) research showed how effective nano-pesticides are. For example, inhibition of agricultural pests like a wide range of insects was shown by copper oxide nano-particles. These nano-formulations represent an important asset as they allow more targeted pest control with much less environmental persistence than with conventional pesticide formulations (Gacem & Chaibi, 2022).

The critical benefits afforded from nanoscale pesticides are due to their distinctive features. As a result, their small size makes them better able to enter directly into plant tissue for improved pest control. Additionally, nanoparticles can be modified for sustained, controlled release and the quantities of chemicals that need to be administered for successful pest control are greatly reduced. A reduction in chemical usage of 40â??65% while maintaining or improving pest control efficacy has been shown in studies of nano-pesticides. It's a big step toward sustainable agricultural practice aimed at eliminating the use of chemicals that contaminate and harm the environment (Zhang et al., 2023).

2.6 Soil Health Monitoring and Improvement

Sustainable crop production requires healthy soil which however experiences degradation by soil erosion, nutrient depletion and contamination. One-way nanotechnology can enhance soil health is by offering tools to will allow you to monitor soil conditions — such as pH, moisture and nutrient levels in real time. Furthermore, the use of nano-materials can help improve soil quality; elevating microbial activity, increasing nutrient availability and decreasing the incidence of harmful pollutants. For instance, certain nano-particles can link to extra metals or solids in the soil to make them more easily extracted and seem less dangerous (Yadav et al., 2023).

3. Nano-sensors: Real-time Crop Health Monitoring and Early Disease Detection

Innovations in nano-sensors have helped to revolutionize the way crop health is looked after in agricultural monitoring. These small sensors can quickly monitor plant physiology without harm, giving farmers new ways to take care of crops. Ibrahim and others (2024) built sensors using carbon nano-tubes that show very good sensitivity for plant pathogen detection. Such nano-sensors monitor soil nutrients, plant stress, initial signs of disease and environmental changes all at the same time (Ibrahim et al., 2024).

Nano-sensors allow us to spot agricultural risks early, well before any damages become noticeable. Traditional approaches to crop monitoring which depend on visual examinations after much of the damage has appeared are different from nano-sensor methods which give fast and correct data needed for action beforehand (El-Abeid et al., 2024). According to Khattak et al. (2024), nano-sensors are able to detect gentle changes in plant metabolism, how they handle nutrients and their reactions to stress accurately. By using real-time data, farmers are able to deal with issues before they get too serious, turning reactive habits into predictions (Khattak et al., 2024).

Teaming up nano-sensors with advanced data analytics raises their ability to solve problems. Farmers can learn about possible crop health problems in real time, so they can take quick action. After finding molecular signs suggesting the presence of pathogens, they can warn those in agriculture about possible hazards early on. The ability to spot risks early on greatly improves how we protect our crops (Shaw & Honeychurch, 2022). Nano-fertilizers, nano-pesticides and nano-sensors all work together to transform agriculture, as can be seen in Table 1. They provide new, precise ways to deal with issues farmers have for a long time faced which can make food production more efficient and friendly to the environment (Singh et al., 2024). Monitoring agricultural conditions in real time is needed if proactive management is to work. With nano-sensors, farmers can track nutrients in their soil, look after the health of their crops, observe for diseases early on and test for drought or salt conditions. Because the sensors give information instantly, farmers can make the right choices to save their crops and use resources efficiently (Alam et al., 2024).

4. Genetic and Cellular Interventions

With nanotechnology, interventions can be done accurately at the gene and cell level to drive new developments in crops. The use of nanotechnology supports gene transfer to make plants more tolerant of drought, less vulnerable to pests or better at using nutrients. Adding coatings to seeds made from nano-materials improves their ability to grow and ensures a strong beginning to crop growth (Kumari et al., 2023).

Zinc oxide nano-particles have demonstrated that they may help crops resist stresses and improve their yields. With nanotechnology, scientists are able to address targeted changes to crops by delivering their genetic material. With such progress, we now have more opportunities to grow crops that are adaptable in situations facing climate change (Inam et al., 2024).

5. Enhanced Water and Nutrient Use Efficiency

Scarcity of water is a serious problem all over the world, since water generation is heavily used in agriculture. Nanotechnology provides new answers for this challenge using nano-engineered water storage materials, advanced irrigation methods and nano-membranes for water reuse (Muhammad et al., 2025).

These hydrogels in soil improve its ability to hold water, so crops continue to get the moisture they need, even when drought occurs. Their use can lead to as much as 40% more soil retention on site, providing a lasting way to handle water challenges. Also, incorporating nano-materials into drip irrigation helps spread water more evenly prevents wastage and supports good farming techniques in dry and semi-dry areas (Vedovello et al., 2024). Nano-enabled filters also help purify polluted water so it can be used for irrigation and means less reliance on fresh water. As a result of these technologies, we can address water challenges and there is a continuous supply for irrigation. Nutrient use efficiency is also enhanced by nanotechnology. Nano-fertilizers can increase nutrient absorption by 80% than conventional methods (Pramanik et. al, 2020). The significant advantage of these advanced nano-formulations for modern agricultural practice is being able to deliver nutrients precisely to the plants. They are unlike conventional fertilizers in that they reduce loss of nutrient through leaching, holding the essential elements available to crops for longer time. Further, their nano-scale size promotes uptake of nutrients at the cellular level leading to healthier, more efficient plant health and growth. The key mechanism is that nano-particles (SiO_2 and ZnO) interact directly with plant cellular structures driving better nutrient uptake and metabolic processes (El-Saadony et al., 2022).

Table 1: Nano-fertilizers and Nano-pesticides: Key Characteristics, Applications, and Environmental Impacts with Nanoparticle Examples.

Category	Aspect	Details	Nanoparticles	Findings	References
Nano-Fertilizers	Precision Nutrient Delivery	Nanoparticles enable direct nutrient penetration into plant cells.	ZnO NPs, Fe_3O_4 NPs, Carbon-based NPs	Nano-fertilizers improve absorption efficiency by up to 80%.	(Abdel-Hakim et al., 2023)
		Nutrients are released gradually based on environmental triggers.	Chitosan NPs, Hydroxyapatite NPs	Responsive release based on soil pH, moisture, and plant growth stages.	(Shaghaleh et al., 2022)
		Nano-fertilizers minimize nutrient loss through leaching and volatilization.	TiO_2 NPs, Silica NPs	95% reduction in nitrogen runoff compared to traditional methods.	(Xia et al., 2020)
		Higher bioavailability of nutrients for plants.	ZnO NPs, Calcium Phosphate NPs	Improved crop yield and reduced need for reapplication.	(Hammerschmitt et al., 2021)
	Targeted Pest Control	Nanoparticles enable precise delivery of active ingredients to pest-affected areas.	Silver NPs (Ag NPs), Graphene Oxide NPs	Quantum dots release active compounds in response to pest activity.	(Ibrahim et al., 2021)
		Active ingredients are released only under specific environmental conditions.	Copper NPs, Chitosan NPs	Moisture-sensitive pesticides that activate during high humidity levels.	(Huang et al., 2018)
		Nano-encapsulation enhances stability and prolongs the activity of pesticides.	Polymeric NPs, Carbon Quantum Dots	Longer-lasting pest control compared to conventional formulations.	(Sarmah et al., 2024)
		Nanopesticides reduce the likelihood of pest resistance development.	Titanium Dioxide NPs, Silver NPs	Gradual and controlled release decreases exposure to sub-lethal doses.	(Pan et al., 2014)
		Reduced impact on non-target organisms and ecosystems.	Zinc Oxide NPs, Silica NPs	Lower toxicity to beneficial insects and soil microbes.	(Rashid & Chung, 2017)

6. Chemical Usage Reduction through Targeted Nano-interventions

For a long time, the industry has struggled against the environmental harm caused by overuse of pesticides and other agrochemicals. Large-scale use of chemicals on farms normally causes problems for the environment and wastes many resources. Nanotechnology creates a new way to deal with these challenges by offering precise treatment methods (Gallardo, 2024). Targeted intervention at the nano level was found in experiments to help reduce chemical use. Such chemicals deliver nutrients and pesticides extremely well, enabling farmers to treat problems in specific areas rather many open areas. Using this strategy reduces negative impact on the environment and increases performance. As reported by Saritha et al. (2022), the use of nano-based agriculture might help reduce chemicals used by up to 60-75%, compared to traditional techniques. Experimentally, zinc oxide nano-particles outperform in pest control and planting; the solutions they provide are narrowly designed to safeguard the environment from further contamination (Saritha et al., 2022).

7. Sustainability Improvements: A Deeper Dive into Nanotechnological Innovations

7.1 Advanced Mechanisms of Chemical Reduction

Agriculture for decades has required great amounts of chemicals, leading to major environmental damage. Nanotechnology gives a precise means to use less chemical, ensuring greater effectiveness. The use of nano-encapsulation in chemicals reduces chemical leaching by about 90% and sharply lowers pollution (Sharma et al., 2023).

Nano-particles built for agriculture are designed using technology that includes smart changes to their surface, ways they release their content and the ability to connect with specific materials. As an example, by setting up certain requirements in the soil, quantum dot nano-

particles will only deliver the nutrients or pest control products that are required. Precision application in farming eliminates waste and harmful excess use of agricultural chemicals (Mittal et al., 2020).

7.2 Advanced Solutions for Water Management

Farmers everywhere are struggling with drought, but nanotechnology offers solutions that are beyond traditional options. If we immerse nano-hydrogels in water, they turn into reservoirs that release moisture to plants over time (Shemer et al., 2023). They guide the water to where it's needed, stop it from slipping out and offer plenty of moisture to the roots. Because of this technology, less water is used and crops are better able to handle different environmental problems. Because they use less traditional watering methods, nano-hydrogels improve the management of water resources (Vundavalli et al., 2015).

7.3 Broader Ecological Implications

Apart from boosting productivity, nanotechnology affects the way we manage agricultural ecosystems. Introducing these measures raises biodiversity, toughens ecosystems and reduces the amount of chemicals entering the environment. So, new farming methods are allowing us to address problems stemming from climate change and a lack of resources (Ezeonu et al., 2012).

8. Technological Mechanisms Driving Nanotechnological Innovations

8.1 Nanoparticle-Mediated Genetic Material Transfer

The innovations made possible by nanotechnology are really changing how we look after our farms. A highly useful application of nanoparticles is their ability to deliver DNA into plant cells more precisely than any other technique. By using this approach, cells are modified efficiently and plant integrity is protected as little cellular disruption takes place. Also, the genetic material enclosed in nanoparticles becomes more stable and precise, cutting down the chance of unplanned genetic changes. Unlike earlier genetic engineering, using nanotechnology produces crops that are more productive, genetically improved and can last longer, with less impact on the environment (Mmbando, 2024).

8.2 Controlled Release Systems for Agrochemicals

The usual use of agrochemicals is known to cause ineffective use and environmental damage since too much is often spread not only targeted. Advanced controlled-release systems developed using nanotechnology address these problems by increasing both accuracy and sustainability. Nano-agriculture has developed a key feature where nanoparticles react to pH, moisture or temperature changes, so that agrochemicals are released only in suitable weather or soil. Using this technique increases the timing and purpose of the active ingredients and also significantly cuts down the possibility of these ingredients seeping into surrounding areas. By targeting the chemicals only to where they are needed such systems increase their effectiveness and help decrease the effect on the environment (Kumar et al., 2021)

8.3 Nano-encapsulation for Enhanced Protection

Applying nano-encapsulation to agrochemicals makes them resist damage from the environment and stay stable. The use of herbicides improves the application rate and reduces waste. Furthermore, as a result of this technique, agrochemicals can remain active for a longer time, so less needs to be applied, lessening harm to the environment (Pateiro et al., 2021).

8.4 Integrated Technological Mechanisms

The greatest benefits of using nanotechnology in farming appear when its various techniques are combined into one system. When we mix genetic material transfer, controlled-release technologies and nano-encapsulation, we have the potential to handle more than one agricultural complication. With this strategy, there's better use of resources, an improvement in productivity and crops become abler to withstand environmental problems. Besides, it greatly lowers the environment's burden from farming which in turn helps to maintain sustainability and boost efficiency (Mahra et al., 2024).

Conclusion

Overall, nanotechnology could greatly benefit agriculture, though the main issue is how to tackle problems of scaling, expense, access fairness and public reaction. Working to ensure that smallholder farmer's gain from these advances means making nano-solutions practical and inexpensive. At the same time, strict laws, informing people and close teamwork make sure smart technology is used safely. In this way, nanotechnology can help build an agricultural field that is both eco-friendly, efficient and withstands problems.

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