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NANOTECHNOLOGY IN AGRICULTURE: A MODERN REVOLUTION

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Abstract

Nanotechnology has emerged as a transformative approach in modern agriculture, addressing key challenges such as declining soil fertility, pest resistance, water scarcity, and environmental pollution. The integration of nanomaterials-such as nanofertilizers, nanopesticides, and nanosensors-enhances nutrient delivery, crop protection, and soil health through precise and controlled mechanisms. Nano-enabled fertilizers improve nutrient uptake efficiency, while nanocarriers ensure targeted pesticide release, reducing chemical waste and ecological damage. Furthermore, nanosensors provide real-time monitoring of soil and plant conditions, enabling data-driven and sustainable farming practices. Applications such as nanocoatings on produce also help extend shelf life and minimize post-harvest losses. Despite its immense potential to boost productivity, sustainability, and profitability, challenges remain, including high production costs, regulatory gaps, and uncertain long-term ecological impacts. Overall, nanotechnology holds great promise for transforming agriculture into a more efficient, eco-friendly, and resilient system for the future.

Keywords: Nanotechnology, Agriculture, Nanofertilizers, Nanopesticides, Nanocomposites, Agricultural innovation.

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pests with minimal chemical usage to enhancing soil health and monitoring crop conditions in real time. Through these innovations, nanotechnology holds the potential to make agriculture more sustainable, resilient, and productive, addressing some of the most pressing challenges faced by farmers and the global food system today [1].

Introduction

Agriculture is the backbone of the global economy, providing food, raw materials, and livelihoods for billions of people worldwide. Despite its crucial role, conventional agricultural practices face numerous challenges, including declining soil fertility, pest infestations, inefficient use of water and fertilizers, and the growing impacts of climate change. These limitations not only reduce crop yield and quality but also threaten global food security. In this context, nanotechnology the science and engineering of materials at the nanoscale, typically between 1 and 100 nanometersemerges as a promising tool to revolutionize modern agriculture. By manipulating matter at such a minute scale, nanotechnology enables the development of advanced fertilizers, pesticides, sensors, and delivery systems that are more efficient, precise, and environmentally friendly. Its applications range from improving nutrient absorption in plants and controlling

Nanotechnology in Agriculture

Nanotechnology in agriculture involves the use of nanomaterials and nanoscale processes to enhance farming techniques [2]. Nanofertilizers and nanopesticides release nutrients and protect crops more efficiently than traditional methods. For example, nanofertilizers improve nutrient absorption in plants, reduce wastage, and prevent environmental pollution.

The merits of nanotechnology include precision farming, reduced chemical usage, improved crop yield, and enhanced soil health. Smart delivery systems using nanoparticles allow fertilizers or pesticides to act only where needed, minimizing harmful effects on non-target organisms. Nano-sensors can also monitor soil moisture, nutrient levels, and pest attacks in real time, helping farmers make data-driven decisions.

However, there are also demerits and concerns. The production of nanoparticles may be costly, and their long-term environmental impact remains under study.

Unregulated use may lead to soil or water contamination and unintended effects on beneficial organisms. Hence, careful assessment and regulation are essential before mass adoption.

Another promising aspect of nanotechnology is post-harvest management. Nanocoatings on fruits and vegetables extend shelf life and prevent microbial contamination. Such applications can reduce food waste and improve food security globally [3].

Nanotechnology in Agriculture: Revolutionizing Crop Production

Nanotechnology in Crop Protection

Nanotechnology enables controlled and targeted delivery of pesticides and herbicides using nanocarriers such as nanoparticles and nanocapsules [Fig 01]. This approach minimizes chemical use, reduces environmental contamination, and protects non-target organisms like pollinators. Nano-formulations-including nanogels, nanocapsules, and nanoparticles-enhance solubility, stability, and slow release of agrochemicals, reducing toxicity and frequency of application. Nanobiosensors allow early pest detection, enabling timely interventions and reducing overall pesticide use.

Nanotechnology in Crop Production: A Transformative Approach

Crop production is fundamental to food security and economic stability worldwide. However, conventional agricultural methods face numerous challenges, including soil degradation, inefficient nutrient use, water scarcity, and the impacts of climate change. Nanotechnology, the science of materials at the nanoscale (1-100 nanometers), offers innovative solutions to enhance crop productivity while promoting sustainability [4].

Nano-Enabled Fertilizers: Revolutionizing Nutrient Delivery

One of the most significant advancements in crop production through nanotechnology is the development of nano-fertilizers. Unlike traditional fertilizers, which often suffer from low nutrient use efficiency leading to leaching, volatilization, and environmental pollution nano-fertilizers provide controlled and targeted nutrient delivery. The nanoparticles encapsulate essential nutrients such as nitrogen, phosphorus, potassium, and micronutrients, releasing them gradually in response to plant needs and environmental triggers. [4,6,10] This slow and controlled release minimizes nutrient loss and enhances nutrient uptake by plant roots, leading to improved fertilizer use efficiency and better crop yields. Field trials have demonstrated that nano-fertilizer application can increase yields by 15–30% compared to conventional fertilizers while simultaneously reducing the amount of fertilizer required by 20–40%. For example, in rice and wheat cultivation, nano-fertilizers have shown to improve tiller numbers, grain quality, and overall plant health [5].

Nanohydrogels: Enhancing Water Retention and Efficiency

Water scarcity is a critical limiting factor for crop productivity, especially in arid and semi-arid regions. Nanohydrogels, composed of polymeric nanoparticles, exhibit exceptional water retention capabilities. These hydrogels can absorb and store water up to several hundred times their weight and release it gradually to crops during dry periods. When incorporated into soil, nanohydrogels improve soil moisture levels, reduce irrigation frequency, and enhance plant survival and growth under water-stress conditions.

In addition to water retention, nanohydrogels can also encapsulate and slowly release nutrients, integrating water and nutrient management effectively. Studies have reported up to 50% increase in water use efficiency in crops treated with nanohydrogels, greatly benefiting both crop resilience and resource conservation [5].

Precision Farming through Nanosensors

Precision agriculture is being revolutionized by nanosensor technologies that allow continuous, real-time monitoring of critical parameters such as soil moisture, nutrient availability, and plant stress signals. These nanosensors, often based on carbon nanotubes, quantum dots, or metal nanoparticles, transmit valuable data wirelessly to farmers or automated irrigation/fertilizer systems.

By enabling data-driven decision-making, nanosensors optimize resource application, reduce input waste, and enhance crop health. For instance, farmers can irrigate only when and where needed or apply fertilizers in precise dosages aligned with crop growth stages. This approach not only boosts crop productivity but also reduces environmental impacts associated with over-application of water and agrochemicals [5].

Challenges and Future Directions

While nanotechnology offers promising solutions for boosting crop production, challenges remain. The high cost of producing nanomaterials may limit accessibility for smallholder farmers, especially in developing regions. Additionally, the long-term environmental and ecological impacts of nanoparticles are still under thorough investigation. Regulatory frameworks to ensure safe and responsible use are essential as these technologies scale up. Future research is directed toward developing cost-effective, biodegradable, and eco-friendly nanomaterials, advancing smart delivery systems, and integrating nanosensor data into comprehensive farm management platforms. These advancements will accelerate the transition to sustainable, high-efficiency agriculture that meets global food demands without compromising environmental health.

Nanotechnology in Fertilization

Nano-fertilizers release nutrients slowly and efficiently, reducing leaching and improving soil health. Nanocarriers deliver nutrients in sync with plant growth, improving uptake and minimizing losses. In precision agriculture,

nano-sensors optimize fertilizer application, cutting costs and environmental impact [6].

Nanotechnology in Soil Health

Nanoparticles such as nanoscale zero-valent iron remediate polluted soils by adsorbing and neutralizing toxic substances. Nano-enhanced soil amendments improve water retention, nutrient availability, and microbial activity. Nano-sensors track pH, moisture, and nutrients in real time, supporting smarter irrigation and soil management [6].

Nanotechnology in Plant Growth and Development

Nanoparticles like zinc oxide, silica, and carbon-based materials enhance seed germination, root development, and stress tolerance. Nanocoatings and sprays protect plants from pests, diseases, and environmental stressors, reducing reliance on chemical pesticides. Nanotechnology also boosts photosynthesis efficiency through materials such as carbon nanotubes and quantum dots, leading to higher yields with fewer inputs. Nanotechnology has emerged as a powerful tool to enhance plant growth and development by manipulating various physiological and biochemical processes at the nanoscale. Nanoparticles can interact with plants in unique ways that allow for improved germination, nutrient uptake, stress tolerance, and overall productivity.

Effects on Seed Germination and Root Development

Nanoparticles such as zinc oxide (ZnO), silicon dioxide (SiO₂), and carbon-based nanomaterials positively influence seed germination and root growth. These nanoparticles enhance water absorption and stimulate enzymatic activity essential for seed germination. When seeds are treated with appropriate concentrations of nanoparticles, faster germination rates and improved seedling vigor are observed. Furthermore, nanoparticles can promote root elongation and proliferation, increasing the root surface area. This expansion improves the root system's capacity to absorb water and nutrients efficiently, contributing to better plant establishment and growth.

Stress Tolerance Enhancement

Nanoparticles improve plant tolerance to abiotic stresses such as drought, salinity, and heavy metal toxicity. For instance, silica nanoparticles strengthen plant cell walls and improve water retention, helping plants withstand drought stress. Zinc oxide nanoparticles are known to enhance antioxidant enzyme activities, reducing oxidative damage caused by environmental stressors. Carbon nanotubes can penetrate plant cell walls, facilitating the efficient transport of water and nutrients under unfavorable conditions. These effects collectively enable plants to maintain physiological and metabolic functions, even under stress [6].

Boosting Photosynthetic Efficiency

Certain nanomaterials such as carbon nanotubes and quantum dots enhance photosynthesis by improving light absorption and energy transfer within chloroplasts. By facilitating electron transport in photosystems, these nanoparticles increase photosynthetic rates, resulting in higher biomass accumulation and crop yields. This enhanced photosynthesis also translates into improved carbon assimilation and better resource use efficiency within plants, contributing to sustainable crop production [6].

Nano-Coatings and Sprays for Protection and Growth Enhancement

Nano-coatings applied as foliar sprays create a protective barrier on plant surfaces against pests, diseases, and environmental stressors. These coatings can contain antimicrobial nanoparticles like silver or copper, which suppress pathogens and reduce the need for chemical pesticides. Additionally, nano-sprays delivering growth regulators or micronutrients directly to leaves improve nutrient uptake and stimulate growth-promoting processes. Such targeted delivery systems reduce input wastage and environmental contamination [6].

Nanomaterials in agriculture

Types of Nanomaterials

Nanomaterials are materials with structural features at the nanoscale, typically between 1 and 100 nanometers, which give them unique physical, chemical, and biological properties. These materials have gained considerable attention in agriculture because of their ability to enhance productivity, improve nutrient use efficiency, control pests and diseases, and reduce environmental impact. Various types of nanomaterials are currently used or being explored for agricultural applications, each with distinct properties that make them suitable for specific purposes [7].

Nanoparticles

Nanoparticles are among the most widely studied and utilized nanomaterials in agriculture. Their small size and high surface area allow them to interact more effectively with plants, soil, and microorganisms, offering enhanced reactivity and novel behaviors compared to conventional bulk materials. Nanoparticles can be designed to deliver nutrients, agrochemicals, or bioactive compounds precisely where they are needed, thereby reducing waste and environmental contamination.

Metal Nanoparticles

Metal nanoparticles, such as silver, zinc oxide, and copper nanoparticles, are popular in agricultural applications due to their antimicrobial properties. Silver nanoparticles, for instance, are effective against a wide range of plant pathogens and pests, providing an environmentally friendly alternative to conventional chemical pesticides. Zinc oxide nanoparticles not only protect plants from diseases but also enhance nutrient uptake and overall growth. Copper nanoparticles can be used to manage

fungal infections and improve soil fertility, offering additional benefits to plant health and productivity [7].

Carbon-based Nanoparticles

Carbon-based nanoparticles, including carbon nanotubes and graphene, possess exceptional mechanical, electrical, and thermal properties. Carbon nanotubes are often incorporated into fertilizers, pesticides, and sensors to enhance material performance, improve delivery mechanisms, and monitor environmental conditions. Graphene, with its high surface area and excellent conductivity, is particularly useful in Nano sensors for precision agriculture. These sensors can detect changes in soil moisture, nutrient levels, and plant health, enabling farmers to make informed decisions and optimize resource use.

Polymer-based Nanoparticles

Polymeric nanoparticles are composed of biodegradable materials and are widely used for controlled-release applications. They can encapsulate fertilizers, pesticides, or plant growth regulators, releasing them slowly over time to ensure sustained availability to plants. This reduces the need for repeated applications, decreases environmental pollution, and improves the efficiency of agricultural inputs. Polymeric nanoparticles also offer the flexibility to deliver multiple active compounds simultaneously, promoting plant growth, resilience, and overall productivity.

Silica and Clay-based Nanoparticles

Silica and clay nanoparticles are naturally abundant and environmentally friendly. They are used to enhance soil water retention, improve nutrient availability, and provide protection against pests and diseases. Silica nanoparticles, for example, can strengthen plant cell walls, making crops more resistant to environmental stress and pathogens. Clay-based nanomaterials can act as carriers for fertilizers

and pesticides, ensuring slow and targeted release, which reduces input losses and supports sustainable farming practices.

Lipid-based Nanoparticles

Lipid-based nanoparticles, such as liposomes and solid lipid nanoparticles, are biocompatible carriers that can transport water-soluble and fat-soluble nutrients or agrochemicals directly to plant tissues. These nanoparticles improve the stability and bioavailability of the encapsulated compounds, allowing for more efficient absorption and utilization by plants. Their use also reduces the negative impact of chemical inputs on soil and water systems [7].

Hybrid Nanoparticles

Hybrid nanoparticles combine properties of two or more materials, such as metal-organic frameworks, polymer-metal composites, or carbon-metal hybrids. These multifunctional nanoparticles can simultaneously deliver nutrients, regulate growth, and protect against pests. They are particularly valuable in precision agriculture, where integrated solutions are required to optimize crop performance while minimizing environmental impact [7].



Fig 01: nanotechnology in modern agriculture

Table 01: benefits and challenges in nanotechnology in agriculture [8]

Nanotechnology In Agriculture	Benefits of Nanotechnology	Challenges Of Nanotechnology
Enhances Nutrients absorption with nanofertilizers Nanopesticides reduce chemical use and environmental pollution. Nano-sensors Monitor soil nutrients, moisture and pests in real time. Smart Delivery System target only Specific Plants or Areas. Nanocoating extend shelf life of fruits and sustainability. Improve precision farming and Sustainability. Support climate-resistant and stress-tolerant agriculture.	Increase efficiency of fertilizer and pesticides. Reduce water waste using nano-sensors in irrigation. Improves crop yield with fewer chemical inputs. Minimizes soil and water contamination. Decrease greenhouse gas emissions and carbon footprint. Reduces post-harvest food wastage through nanocoating. Supports premium eco-friendly and high-value.	High cost of nanoparticles production. Uncertain long-term environmental effects. Risk of soil and water contamination if unregulated. Potential harm of beneficial organisms. Limited awareness and adoption among farmers Scalability issues in rural and resource-limited areas Need to strict regulation and safety assessments.

Nanointervention

Nano-Fertilizers

Nano-fertilizers represent a groundbreaking advancement in modern agriculture, offering a solution to the inefficiencies associated with conventional fertilizers. These fertilizers are engineered at the nanoscale to optimize nutrient delivery by controlling the timing, location, and rate at which essential macro- and micronutrients are made available to plants. Traditional fertilizers often suffer from significant nutrient losses due to leaching, volatilization, or runoff, which not only reduces crop yield but also contributes to environmental pollution. In contrast, nano-fertilizers enhance nutrient use efficiency by ensuring that nutrients are absorbed in a form readily available to plants, minimizing waste and promoting healthy growth. The targeted delivery mechanism of nano-fertilizers allows for precise application, reducing the overall quantity of fertilizer required, lowering costs for farmers, and decreasing the risk of soil and water contamination. Additionally, these fertilizers contribute to maintaining soil health by preventing the overaccumulation of salts and harmful compounds, which can degrade soil structure over time. By integrating nanotechnology into nutrient management practices, sustainable crop production becomes achievable, ensuring higher yields while conserving natural resources. This approach is particularly significant in regions facing soil degradation, water scarcity, or intensive farming pressures, highlighting the role of nanotechnology in advancing sustainable agriculture [9].

Nano-Pesticides

Nano-pesticides are a transformative innovation in pest management that leverage nanotechnology to enhance the effectiveness, precision, and environmental safety of agricultural chemicals. Unlike conventional pesticides, which often disperse broadly and affect non-target organisms, nano-pesticides encapsulate or bind active pest-control agents within nanomaterials, allowing controlled and targeted delivery to specific pests or pathogens. This precise targeting reduces the quantity of chemical needed while increasing the efficacy against the intended pests, thereby limiting harmful impacts on beneficial insects, soil microorganisms, and surrounding ecosystems. Additionally, nano-pesticides often exhibit improved stability and solubility, enabling them to persist in the field longer and act more efficiently under varying environmental conditions. The controlled-release properties of these formulations ensure that active ingredients are released gradually, reducing the frequency of application and labor costs for farmers. By minimizing chemical drift, runoff, and environmental contamination, nano-pesticides contribute significantly to sustainable agriculture practices. Furthermore, their reduced toxicity to humans and wildlife enhances food safety and public health outcomes. As agricultural demands continue to rise in response to global population growth, nano-pesticides offer an essential tool for achieving high crop productivity

while preserving ecological balance and mitigating the adverse effects associated with conventional pest control methods [9].

Nano-Sensors

Nano-sensors are an emerging technology that revolutionizes agricultural monitoring by providing precise, real-time data on crop and soil conditions at an unprecedented scale. These highly sensitive devices operate at the nanoscale, enabling the detection of minute changes in soil composition, moisture levels, nutrient content, and environmental stressors, which traditional monitoring techniques may overlook. By integrating nano-sensors into agricultural systems, farmers gain actionable insights into plant health, irrigation needs, and nutrient requirements, facilitating more informed decision-making. For example, soil moisture sensors can optimize irrigation schedules, reducing water wastage, while nutrient sensors help fine-tune fertilization practices to prevent overuse or under-application. When combined with digital agriculture platforms, such as precision farming or smart irrigation systems, nano-sensors support automated adjustments in real time, enhancing efficiency, crop yield, and resource conservation. Additionally, these sensors can detect early signs of disease, pest infestations, or environmental stress, allowing for timely interventions that reduce crop losses. The deployment of nano-sensors ultimately contributes to sustainable agriculture by maximizing productivity, reducing input costs, and minimizing the ecological footprint of farming practices. As global agriculture faces challenges from climate change, water scarcity, and population growth, nano-sensor technology provides a powerful tool for optimizing resource use and ensuring resilient food systems [10].

Nanocomposites

Nanocomposites are engineered materials that integrate nanoparticles with conventional matrices such as polymers, metals, or ceramics, resulting in unique properties that surpass those of their individual components. The incorporation of nanoparticles into these matrices imparts superior mechanical strength, thermal stability, chemical resistance, and functional versatility, making nanocomposites particularly valuable in agricultural applications. For instance, nanocomposites can be used to fabricate durable packaging materials, water-retentive soil amendments, or protective coatings for seeds and equipment. Their enhanced structural and chemical properties allow for longer-lasting performance, reducing material consumption and maintenance costs. In crop protection, nanocomposites can encapsulate agrochemicals such as fertilizers, herbicides, or pesticides, enabling controlled and targeted release over time, which improves efficacy while minimizing environmental contamination. Moreover, the customizable nature of nanocomposites allows scientists to design materials with specific functionalities, such as antimicrobial activity or UV resistance, further supporting sustainable agricultural practices. By integrating nanocomposites into modern

farming systems, efficiency, productivity, and environmental stewardship are significantly enhanced. The potential of nanocomposites extends beyond conventional applications, as ongoing research continues to explore their use in soil remediation, water purification, and smart delivery systems, positioning them as a critical tool in the advancement of precision and sustainable agriculture. [11]

Nano-Enhanced Fertilizers

Nano-enhanced fertilizers represent an innovative application of nanocomposites in agriculture, designed to improve nutrient delivery and maximize crop productivity while reducing environmental impact. By embedding essential nutrients within a nanocomposite matrix, these fertilizers provide controlled and gradual nutrient release directly to the plant root zone. This slow-release mechanism ensures that nutrients are available over extended periods, minimizing losses due to leaching, volatilization, or surface runoff, which are common challenges associated with conventional fertilizers. Consequently, plants can absorb nutrients more efficiently, leading to healthier growth, increased yields, and reduced fertilizer consumption. Nano-enhanced fertilizers also support soil health by maintaining optimal nutrient levels without causing chemical imbalances that degrade soil structure. Their targeted action reduces the risk of water and soil contamination, aligning with sustainable agricultural practices and environmental protection goals. Additionally, these fertilizers can be tailored for specific crops or regional soil conditions, making them highly adaptable and efficient. In regions with heavy rainfall, poor soil retention, or nutrient-deficient soils, nano-enhanced fertilizers provide a strategic solution to maintaining soil fertility and improving crop resilience. Overall, they represent a critical advancement in precision agriculture, offering both economic benefits for farmers and ecological sustainability for global food systems [11]. These were outlined in the Fig 02.

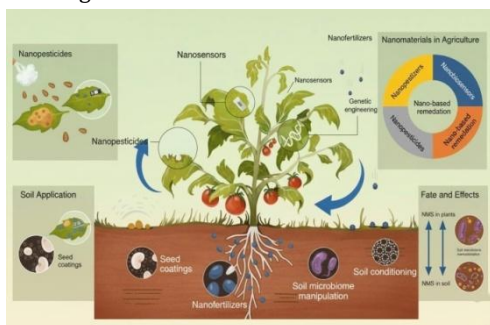


Fig 02: Nanointervention in agriculture

Benefits of nanotechnology in agriculture

Nanotechnology is revolutionizing agriculture by making farming more efficient, sustainable, and profitable. Through nano-formulations, sensors, and smart delivery systems, it improves how inputs like fertilizers, pesticides,

and water are used-reducing waste and boosting productivity.

Increased Efficiency and Productivity

Precision Inputs: Nano-fertilizers and nano-pesticides enable targeted delivery to plants, releasing nutrients or chemicals only where needed. This minimizes waste, reduces pesticide drift, and ensures optimal crop health.

Smart Water Use: Water-absorbent nanoparticles and nano-sensors help monitor soil moisture and regulate irrigation, reducing water waste and enhancing plant growth [12].

Environmental Sustainability

Less Pollution

Nano-formulations reduce excessive fertilizer and pesticide use, preventing soil and water contamination and protecting beneficial organisms.

Lower Carbon Footprint

Controlled nutrient release and precision farming decrease energy consumption and greenhouse gas emissions.

Water and Soil Conservation

Nano-filtration systems improve irrigation water quality, while nano-sensors and amendments prevent soil degradation, salinization, and erosion [12].

Enhanced Crop Yield

Nanotechnology supports higher yields with fewer resources. Slow-release nano-fertilizers and improved pest control promote healthier plants and higher productivity [13].

Economic Benefits

Cost Savings:

Farmers spend less on fertilizers and pesticides due to the higher efficiency of nano-formulations.

High-Value Crops:

Precision farming with nanotech improves crop quality and marketability, opening opportunities for premium, eco-friendly produce.

Market Edge:

Nano-packaged and nano-enhanced agricultural products appeal to consumers seeking sustainable, safe, and longer-lasting foods [13].

Advantages of nanotechnology in agriculture

Enhanced Nutrient Efficiency

Nano-fertilizers can release nutrients in a controlled manner, reducing losses through leaching or volatilization. Plants absorb nutrients more efficiently, which improves crop yield and quality [13].

Reduced Chemical Usage

Nano-pesticides require smaller doses due to targeted delivery. Minimizes the environmental impact of conventional agrochemicals on soil, water, and non-target organisms.

Improved Crop Protection

Nanoparticles can act as carriers for fungicides, herbicides, and pesticides, enhancing their stability and effectiveness. Helps control pests and diseases more precisely.

Water Conservation

Nanotechnology-based materials can improve soil water retention.

Reduces irrigation needs and supports farming in arid regions.

Soil Health Management

Nanomaterials can help detect and neutralize soil contaminants.

Supports sustainable soil management practices [14].

Precision Agriculture

Nano-sensors can monitor soil conditions, nutrient levels, and plant health in real time.

Enables data-driven decisions for efficient resource utilization.

Post-Harvest Benefits

Nanotechnology can enhance food packaging with antimicrobial coatings, extending shelf life. Reduces post-harvest losses [14].

Disadvantages of nanotechnology in agriculture

High Cost

Development and large-scale production of nanomaterials can be expensive.

Small farmers may find it unaffordable without subsidies or support.

Potential Environmental Risks

Nanoparticles may accumulate in soil and water, affecting beneficial microorganisms and aquatic life.

Long-term ecological effects are not yet fully understood.

Health Concerns

Inhalation or ingestion of certain nanoparticles could pose risks to human health.

Proper handling and safety measures are necessary.

Regulatory and Ethical Issues

Lack of standardized regulations for nanomaterials in agriculture.

Ethical concerns over unknown long-term impacts on ecosystems and food safety.

Technical Complexity

Requires advanced knowledge and technology for effective use.

Small-scale farmers may face difficulty adopting these methods.

Uncertain Long-Term Impact

Limited studies on the long-term effect of nanomaterials on soil fertility and biodiversity.

Risk of bioaccumulation in plants and animals [15].

Challenges and consideration

Despite the potential benefits, the use of nanomaterials in agriculture also raises concerns regarding safety, environmental impact, and regulatory oversight. The toxicity of certain nanoparticles to non-target organisms, their accumulation in soil and water, and potential health risks to humans must be carefully assessed. Proper handling, testing, and regulation are essential to ensure that nanotechnology contributes positively to sustainable

agriculture without causing unintended harm. Ethical considerations, public awareness, and adherence to environmental standards are equally important in the responsible adoption of nanomaterials in food production systems [16].

Soil Remediation

Nanocomposites play an important role in soil remediation, addressing issues such as heavy metal contamination, pesticide residues, and other pollutants. By incorporating nanoparticles with materials capable of adsorbing or neutralizing contaminants, nanocomposites can clean polluted soils efficiently. These materials bind toxic substances, prevent their absorption by plants, and improve soil quality, making land more suitable for cultivation. In addition, nanocomposites can enhance soil water retention and nutrient availability, further supporting sustainable farming practices [17].

Pesticide Delivery

Nanocomposites are also highly effective as pesticide delivery systems. By combining nanoparticles with polymers or other supportive matrices, pesticides can be stabilized and protected from degradation due to sunlight, temperature, or microbial activity. This ensures that the active ingredients remain effective until they reach the target pests. Additionally, nanocomposites can be engineered to release pesticides only under specific environmental conditions, reducing exposure to non-target organisms and minimizing ecological disruption. This precision delivery not only enhances crop protection but also reduces the overall quantity of pesticides needed [17].

Water Retention and Nutrient Stabilization

Certain nanocomposites are designed to improve water retention in soil and stabilize nutrients. These materials can absorb and hold water, releasing it slowly to plant roots during dry periods. At the same time, they prevent rapid nutrient loss by binding nutrients within the composite structure. This dual functionality helps crops withstand drought stress and supports more efficient fertilization practices [18].

Environmental Protection

The controlled release and targeted delivery features of nanocomposites contribute to environmental protection by reducing the overuse of chemical inputs. They prevent excessive accumulation of fertilizers and pesticides in soil and water bodies, thereby mitigating pollution and maintaining ecosystem balance [18].

Interference

The development and implementation of nanotechnology in agriculture can sometimes face interference from various biological, chemical, and environmental factors. These interferences can influence the performance, stability, and safety of nanomaterials used in farming practices [19].

Environmental Interference

Environmental conditions such as temperature, humidity, and soil pH can affect the reactivity, solubility, and degradation of nanoparticles, thereby altering their intended efficiency in soil or plant systems [19].

Biological Interference

Interactions between nanoparticles and soil microorganisms, plant root exudates, or enzymes can modify the behavior of nanomaterials, influencing nutrient availability and toxicity levels.

Chemical Interference

The presence of organic matter, ions, and other agrochemicals in soil or water can lead to aggregation or transformation of nanoparticles, which may reduce their activity or cause unexpected reactions. [20]

Analytical Interference

During research and application, accurate measurement of nanoparticles in complex biological matrices (like soil or plant tissue) may be hindered by overlapping signals or background noise, making detection and quantification challenging.

Regulatory and Human Interference

Lack of standardized safety guidelines, improper handling, and uncontrolled application of nanomaterials by farmers can interfere with both environmental safety and crop productivity outcomes [20].

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Conflict of Interest

None Declared

Author Contribution

Both Authors contributed equally

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Ethical Approval and Inform Consent

Not Applicable

Conclusion

Nanotechnology represents a powerful frontier in modern agriculture, enabling a transition from conventional farming to a more precise, sustainable, and intelligent agricultural system. Through the integration of Nano fertilizers, Nano pesticides, Nano sensors, and Nano-based delivery systems, farmers can achieve optimal resource utilization and improved crop productivity while minimizing environmental degradation.

The ability of nanoparticles to enhance soil fertility, control pests effectively, and monitor real-time field conditions has opened a new era of smart and sustainable farming. Moreover, nanotechnology holds potential in post-harvest preservation, packaging, and food quality enhancement, thereby strengthening global food security.

However, the rapid adoption of nanotechnology must be balanced with comprehensive safety assessments and ethical regulations. Continuous research is necessary to understand the long-term ecological and health impacts of nanomaterials. With proper management, awareness, and policy support, nanotechnology can revolutionize agriculture fostering a greener, safer, and more resilient future for the planet.

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