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Application of Nanotechnology in Agriculture: Opportunities and Challenges in the Context of Environmental Sustainability

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Review Article

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ABSTRACT

Nanotechnology is an emerging field with immense potential to revolutionize agriculture by enhancing productivity, resource efficiency, and sustainability. Its applications span diverse areas, including nano-fertilizers for improved nutrient uptake, nano-pesticides for targeted pest control, and nanosensors for real-time monitoring of soil and crop health. These advancements address critical agricultural challenges, such as nutrient inefficiency, pest resistance, and environmental degradation. Nano-enabled smart delivery systems optimize the use of fertilizers and pesticides, reducing environmental contamination and improving yield. Nanotechnology also facilitates soil remediation, enhances microbial health, and provides innovative water purification techniques, making it instrumental in mitigating resource scarcity and pollution. Its role in precision agriculture, through IoT-integrated nanosensors, enables data-driven farming practices that improve decision-making and resource allocation. Despite its promise, the adoption of nanotechnology faces barriers, including potential toxicity of nanomaterials, long-term environmental risks, and concerns over food safety and human health. High production costs, limited scalability, and a lack of regulatory frameworks hinder widespread implementation, particularly in developing countries. Future research must focus on eco-friendly and biodegradable nanomaterials, scalable manufacturing methods, and the development of cost-effective technologies accessible to smallholder farmers. Robust policy frameworks, standardized safety guidelines, and public-private collaborations are essential to ensure the safe and ethical integration of nanotechnology in agriculture. Equally important are educational initiatives to enhance farmer awareness and build public trust in these innovations. By addressing these challenges, nanotechnology can play a transformative role in creating a sustainable, climate-resilient agricultural system capable of meeting the demands of a growing global population while protecting environmental and human health.

Keywords: Nanotechnology; nano-fertilizers; nano-pesticides; nanosensors; precision farming.

1. INTRODUCTION

A) Nanotechnology in Agriculture

Nanotechnology is the science, engineering, and application of materials or systems that operate at the nanoscale, typically ranging from 1 to 100 nanometers (nm). At this scale, materials exhibit unique physical, chemical, and biological properties that differ significantly from their bulk counterparts, enabling novel applications across a wide range of industries, including agriculture. In agriculture, nanotechnology primarily involves the design and use of nanomaterials, such as nanoparticles, Nano sensors, and nano-based delivery systems, to enhance crop productivity, improve soil health, and mitigate environmental challenges (Pathak et al., 2024). The application of nanotechnology in agriculture has its roots in the early 2000s when scientists began exploring the potential of nanomaterials for precision farming and pest control. Initial studies focused on using nano-fertilizers to enhance nutrient delivery and reduce wastage, as well as nano-pesticides for targeted pest management, which demonstrated improved efficiency compared to conventional methods. Over the years, advancements in nanotechnology have enabled the development of Nano sensors for real-time monitoring of soil and plant health, as well as nanofiltration systems for water purification (Kuhn et al., 2022). Today, nanotechnology is increasingly integrated into smart farming systems, enabling the adoption of precision agriculture practices aimed at optimizing resource use and minimizing environmental impact.

B) Importance of Agriculture for Global Sustainability

Agriculture remains the backbone of global food security, providing sustenance to billions of people. With the global population projected to reach 9.7 billion by 2050, the demand for food is expected to increase by 60%. This rising demand poses significant challenges to the agricultural sector, requiring innovative solutions to increase crop productivity while maintaining environmental sustainability. Nanotechnology offers transformative potential in this regard by improving the efficiency of inputs such as fertilizers and pesticides, which can help achieve higher yields without significantly expanding arable land. The agricultural sector is facing mounting environmental challenges, including soil degradation, water scarcity, and the impact of climate change. Traditional farming practices often rely on excessive use of chemical inputs, which contribute to pollution, eutrophication, and loss of biodiversity (Kumar et al*.,* 2019). Global agriculture accounts for approximately 70% of freshwater withdrawals, highlighting the urgent need for water-efficient practices. Nanotechnology can address these challenges through innovative solutions such as nanocarriers for controlled-release fertilizers and pesticides, nanofiltration systems for water conservation, and nanomaterials for soil remediation, thus supporting sustainable agriculture [44].

C) Objectives of the Review

The primary objective of this review is to provide a comprehensive overview of how nanotechnology is being applied to address critical challenges in agriculture. This includes exploring the role of nanotechnology in enhancing crop productivity, improving soil health, conserving water resources, and enabling precision farming techniques. The review aims to highlight recent advancements in the development of nano-based agricultural inputs, such as nano-fertilizers, nano-pesticides, and Nano sensors, and their potential to transform traditional farming practices (Yadav et al*.,* 2023). In showcasing the potential of nanotechnology in agriculture, this review seeks to critically examine the associated challenges. These include environmental and health risks posed by nanomaterials, high production costs, regulatory uncertainties, and limited adoption in developing regions. By identifying these opportunities and challenges, the review aims to provide insights into the future directions of agricultural nanotechnology research and development, with a focus on promoting sustainable and inclusive practices [45].

2. PRINCIPLES OF NANOTECHNOLOGY IN AGRICULTURE

A) Nanotechnology Basics and Tools

Nanotechnology in agriculture relies on the use of nanomaterials, which are materials with dimensions at the nanoscale range (1–100 nm). These nanomaterials exhibit unique physical, chemical, and biological properties compared to their bulk counterparts, such as increased surface-area-to-volume ratio, enhanced reactivity, and novel optical or magnetic behaviours (Table 1) (Khan et al*.,* 2022). These characteristics make them ideal tools for addressing the multifaceted challenges faced by modern agriculture, such as nutrient inefficiency, pest control, and environmental sustainability. Nanomaterials utilized in agriculture include nanoparticles, carbon nanotubes (CNTs), and Nano sensors. Nanoparticles, such as zinc oxide, silver, and silica nanoparticles, are widely applied in agriculture due to their ability to enhance nutrient delivery, pest management, and soil health. For example, zinc oxide nanoparticles significantly improve zinc bioavailability to plants, thereby boosting crop growth and productivity. Carbon nanotubes, with their high mechanical strength and electrical conductivity, play an emerging role in delivering agrochemicals directly to plant tissues and promoting plant growth through enhanced water and nutrient absorption. Nano sensors, on the other hand, are critical tools for precision agriculture. These devices detect and monitor environmental variables such as soil moisture, nutrient levels, and pest activity in real-time, enabling farmers to make informed decisions and optimize resource use (Yin et al*.,* 2021). The synthesis of nanomaterials is achieved through top-down and bottom-up approaches. Top-down methods involve breaking down bulk materials into nanoscale particles using physical techniques such as milling and laser ablation. Although effective, these methods are energy-intensive and can result in uneven particle sizes. In contrast, bottom-up approaches assemble nanoparticles from atomic or molecular precursors using chemical methods, including sol-gel processes, or biological methods involving plant extracts or microorganisms. Green synthesis has gained significant attention for being cost-effective and environmentally friendly, utilizing natural reducing agents to produce nanoparticles with minimal toxicity. Once synthesized, nanomaterials are characterized using advanced techniques such as scanning electron microscopy (SEM) and transmission electron microscopy (TEM) to determine their size and morphology. Spectroscopic techniques such as Fourier-transform infrared (FTIR) and UV-Vis spectroscopy are used to study their surface chemistry and optical properties, ensuring their suitability for agricultural applications (Petit et al*.,* 2018).

B) Mechanisms of Nanotechnology Functionality in Agricultural Systems

The functionality of nanotechnology in agricultural systems stems from the ability of nanomaterials to interact with soil, plants, and pests at the molecular level, leading to enhanced efficacy of inputs and improved agricultural outcomes. In soil systems, nanomaterials can improve soil health and nutrient availability. Nanoparticles like hydroxyapatite are used as carriers for phosphorus, enhancing its availability to plants while reducing phosphorus fixation in the soil. Nanoparticles are employed for soil remediation, where they break down pollutants and heavy metals, thus restoring soil fertility and quality. For plants, nanomaterials interact directly with biological systems. Nanoparticles can penetrate plant tissues through natural openings such as stomata and root hairs, delivering nutrients or agrochemicals precisely where needed. For example, zinc oxide nanoparticles have been shown to promote enzymatic activities and improve photosynthetic efficiency in plants. Carbon-based nanomaterials, such as graphene and carbon nanotubes, have demonstrated the ability to increase water uptake and improve plant tolerance to abiotic stresses, such as drought and salinity (Alabdallah et al*.,* 2023). In pest management, nanotechnology plays a critical role in minimizing pesticide use while maintaining efficacy. Nano-pesticides are engineered for controlled release and targeted action, ensuring that the active ingredients reach the pest while reducing off-target effects. Silver nanoparticles disrupt the cellular functions of pests, providing an eco-friendly alternative to traditional chemical pesticides. Silica nanoparticles are designed to adhere to pest surfaces, improving their toxicity while reducing the overall pesticide load on the environment. Nanotechnology also plays a significant role in enhancing biological and chemical processes within agricultural systems. Nano-fertilizers, are designed to release nutrients in a controlled manner, matching plant uptake patterns and reducing nutrient losses due to leaching or volatilization. Urea-coated nanoparticles are particularly effective in supplying nitrogen to crops while mitigating environmental impacts associated with excessive fertilizer use (Dimkpa et al*.,* 2020). Nanomaterials have been shown to improve plant stress tolerance by modulating physiological responses. For example, cerium oxide nanoparticles protect plants from oxidative stress by scavenging reactive oxygen species (ROS), enhancing plant survival under adverse environmental conditions.

C) Regulation and Ethics in Nanotechnology Use

Despite its transformative potential, the use of nanotechnology in agriculture raises critical regulatory and ethical concerns that must be addressed to ensure its safe and sustainable implementation. One of the primary concerns is the environmental safety of nanomaterials. While nanotechnology offers significant advantages, the long-term fate and behavior of nanomaterials in soil, water, and ecosystems remain poorly understood. Studies have shown that some nanoparticles, such as silver and titanium dioxide, may pose risks to non-target organisms, including soil microbiota and aquatic ecosystems. Effective risk assessment frameworks are needed to evaluate the environmental implications of nanotechnology and establish guidelines for its safe use. Another key issue is the potential impact of nanomaterials on human health. Exposure to nanomaterials through food products or occupational handling raises concerns about their toxicity and accumulation in the food chain. Although some studies have demonstrated the safety of nano-based products, comprehensive toxicological evaluations are required to assess their long-term effects on human health (Okeke et al*.,* 2022). The regulatory landscape for nanotechnology in agriculture is still evolving. Currently, there are no standardized regulations governing the production, use, and disposal of nanomaterials in most countries. International organizations, such as the Organization for Economic Co-operation and Development (OECD), have emphasized the need for harmonized regulatory frameworks to address these gaps and ensure the responsible use of nanotechnology in agriculture. Ethics also play a crucial role in shaping the adoption of nanotechnology. Concerns regarding the accessibility and affordability of nano-based agricultural innovations must be addressed to prevent technological disparities between developed and developing regions. Smallholder farmers, who constitute the majority of the agricultural workforce in developing countries, may face challenges in adopting expensive nano-enabled technologies. Ensuring equitable distribution of benefits and fostering inclusive growth are essential to the ethical development of nanotechnology in agriculture.

Table 1. Principles of Nanotechnology in Agriculture

Principle	Explanation	Applications in Agriculture	Examples
Nanoscale Manipulation	Materials engineered at 1–100 nm scale, exhibiting unique physical, chemical, and biological properties.	Enhanced efficiency of fertilizers and pesticides; improved plant uptake.	Nano-fertilizers for improved nutrient delivery.
Targeted Delivery	Encapsulation and controlled release of active ingredients to specific sites.	Precision application of pesticides, herbicides, and fertilizers.	Nano-encapsulated pesticides for specific pest control.
Enhanced Surface Area	Increased surface area-to-volume ratio leading to higher reactivity and efficiency.	Faster and more efficient absorption of nutrients and chemicals by crops.	Nano-silica in soil conditioners.
Controlled Release	Regulated release over time to ensure sustained availability of active ingredients.	Slow-release fertilizers and pesticides to minimize environmental damage.	Nano-clay for sustained nitrogen release.
Improved Solubility	Nanomaterials improve solubility and dispersion of poorly soluble compounds.	Better uptake of water-insoluble nutrients and agrochemicals by plants.	Nano-formulated zinc for micronutrient supplementation.
Bioavailability Enhancement	Nanomaterials improve the bioavailability of nutrients and agrochemicals to plants.	Improved nutrient use efficiency and reduction in fertilizer dosage.	Nano-chelated iron for correcting deficiencies.
Smart Sensing and Monitoring	Use of nano-sensors for real-time monitoring of agricultural parameters.	Precision farming for soil health, crop condition, and pest detection.	Nano-sensors for detecting soil nitrate levels.
Sustainable Practices	Reduced environmental footprint through efficient resource utilization.	Minimizing pesticide runoff and reducing nutrient leaching.	Nano-biosensors for monitoring pesticide residues.
Multifunctionality	Nanomaterials can perform multiple roles, such as nutrient delivery and pathogen protection.	Combining plant growth promotion with disease resistance.	Nano-silver particles for antimicrobial and growth-promoting effects.
Self-assembly and Biomimicry	Materials mimic natural biological systems to enhance compatibility and efficiency.	Biodegradable nanocarriers for eco-friendly applications in agriculture.	Lipid-based nano-carriers for agrochemical delivery.

(Sources: Khan et al., 2022, Okeke et al., 2022)

3. NANOTECHNOLOGY APPLICATIONS IN AGRICULTURE

A) Crop Production and Protection

Nanotechnology has revolutionized agricultural practices by improving crop production and protection methods. Among these, nano-fertilizers, nano-pesticides, and disease management technologies have garnered significant attention for their ability to enhance efficiency and minimize environmental impacts (Table 1) (Yadav et al., 2023). Nano-fertilizers represent a breakthrough in nutrient management, addressing inefficiencies associated with conventional fertilizers, such as nutrient loss through leaching, volatilization, or fixation in the soil. These fertilizers are engineered to release nutrients in a controlled manner, matching the plant's growth cycle and improving nutrient use efficiency. Urea-coated nanoparticles provide a slow and sustained release of nitrogen, reducing nitrate leaching and promoting uniform crop growth. Zinc oxide nanoparticles improve zinc bioavailability to plants, which is critical for enzymatic functions and chlorophyll synthesis. The adoption of nano-fertilizers has the potential to increase crop yields while reducing fertilizer application rates, thereby minimizing the environmental footprint of agricultural practices. Conventional pesticides often suffer from poor targeting, leading to excessive application and environmental contamination. Nano-pesticides address these limitations by providing targeted delivery of active ingredients to pests, enhancing efficacy while reducing chemical usage. Silica nanoparticles are used as carriers for hydrophobic pesticides, improving their solubility and reducing off-target effects (Zhang et al., 2023). Silver nanoparticles exhibit potent antimicrobial properties and are effective against a range of plant pathogens and pests. Furthermore, nano-pesticides can be designed for controlled release, ensuring prolonged pest protection and reducing the frequency of applications. These innovations contribute to sustainable pest management by reducing toxicity to non-target organisms and preventing pesticide resistance. Nanotechnology offers advanced solutions for managing plant diseases by enabling early detection and effective control. Nano-based formulations, such as copper nanoparticles, are used to control fungal and bacterial pathogens while minimizing the environmental impact of traditional fungicides. Nanosensors can detect plant pathogens at an early stage by identifying disease biomarkers or microbial metabolites, allowing for timely intervention. For example, carbon nanotube-based sensors have been used to detect viral infections in crops, enabling farmers to implement targeted disease management strategies. By integrating nanotechnology into disease management systems, agricultural productivity can be safeguarded with minimal ecological disturbance.

B) Soil Health Management

The use of nanotechnology in soil health management focuses on improving soil quality, enhancing nutrient availability, and restoring degraded land. Nano-formulations and amendments are critical tools in this domain (Goud et al., 2022). Soil contamination caused by industrial activities and excessive chemical input poses a significant threat to agricultural productivity. Nanotechnology offers innovative solutions for soil remediation, such as the use of iron oxide nanoparticles for the degradation of organic pollutants or the removal of heavy metals like arsenic and cadmium. Zero-valent iron nanoparticles (nZVI) have been extensively studied for their ability to remediate contaminated soils through redox reactions that neutralize toxic compounds. Titanium dioxide nanoparticles are used for photocatalytic degradation of pesticides and herbicide residues, thereby restoring soil fertility and reducing toxicity to crops. These nano-remediation techniques are cost-effective and environmentally friendly compared to conventional methods. Healthy soil microbial communities are essential for nutrient cycling, organic matter decomposition, and plant growth. Nano-enhanced amendments, such as biochar-coated nanoparticles or nano-fertilizers, improve microbial activity and diversity in the soil (Sahu et al., 2017). Silica and magnesium nanoparticles provide essential micronutrients to soil microbes, enhancing their metabolic functions and promoting plant-microbe symbiosis. Nanomaterials with antimicrobial properties can selectively target harmful pathogens while preserving beneficial microorganisms, thus maintaining a balanced soil ecosystem.

C) Water Management

Nanotechnology plays a crucial role in addressing water scarcity and contamination, two critical challenges in agriculture. Innovations in irrigation systems and water purification have enabled sustainable water use. Nanofiltration membranes are widely used in irrigation systems to optimize water quality and reduce wastage. These membranes selectively remove contaminants such as salts, heavy metals, and pathogens from irrigation water while retaining essential nutrients. Graphene oxide-based nanofiltration membranes exhibit high filtration efficiency and durability, making them ideal for desalination and water recycling in agriculture (Tiwary et al., 2024). By ensuring the availability of clean and nutrient-rich water, nanotechnology-based irrigation systems enhance crop productivity and reduce dependence on freshwater resources. Contaminated water poses a severe risk to both crops and human health.

Table 2. Applications of nanotechnology in agriculture

Nanotechnology Application	Nanomaterials Used	Purpose/Function	Examples
Nano-fertilizers	Nano-hydroxyapatite, Nano-clay	Enhanced nutrient use efficiency, slow and targeted nutrient release	Zinc nano-fertilizers for improved plant growth
Nano-pesticides	Nano-silica, Nano-copper	Targeted pest control, reduced pesticide application rates, and environmental safety	Nano-silica for controlling fungal infections
Nano-herbicides	Nano-encapsulated herbicides	Precision weed control, minimizing damage to non-target plants	Nano-glyphosate for effective weed management
Nano-sensors	Nano-carbon, Gold nanoparticles	Real-time monitoring of soil health, nutrient levels, pest infestations, and crop health	Nano-biosensors for detecting soil nitrate levels
Nano-encapsulation in delivery systems	Lipid-based nanocarriers, Nano-polymers	Protecting active ingredients, controlled release, and reduced environmental degradation	Nano-encapsulation of essential oils for pest management
Water management	Nano-membranes, Nano-porous materials	Improved water filtration and purification, reduction of water loss through evaporation	Nano-filtration membranes for irrigation systems
Plant disease management	Nano-silver, Nano-copper oxide	Antimicrobial properties for controlling plant pathogens	Nano-silver spray for bacterial wilt management
Nanotechnology in genetics	Nano-DNA delivery systems	Gene editing, transformation techniques for crop improvement	Nano-assisted CRISPR-Cas9 delivery for improved gene editing in crops
Soil remediation	Nano-zero-valent iron, Nano-clay	Removal of contaminants, heavy metal detoxification	Nano-zero-valent iron for arsenic remediation in agricultural soils
Post-harvest management	Nano-packaging materials, Nano-coatings	Prolonging shelf life, reducing spoilage, and preserving food quality	Nano-chitosan coatings for fruits and vegetables
Precision farming	Nano-sensors, Smart nanodevices	Advanced tools for precision agriculture including field mapping, automated irrigation, and nutrient management	Smart Nano-sensors for precision farming
Carbon sequestration	Nano-biochar	Enhancing soil carbon storage and mitigating greenhouse gas emissions	Nano-biochar for improving soil organic carbon levels
Crop yield enhancement	Nano-based growth promoters	Enhancing photosynthesis and stimulating plant growth	Carbon nanotubes for increased photosynthetic efficiency

(Source: Yadav et al., 2023, Goud et al., 2022)

Nanotechnology provides efficient solutions for water purification, such as the use of silver and titanium dioxide nanoparticles for the removal of pathogens and organic pollutants. Nano-adsorbents, such as carbon nanotubes and nanoclays, are used to remove heavy metals and pesticide residues from water sources. Photocatalytic nanomaterials can degrade harmful chemicals in water under sunlight, offering a sustainable approach to water treatment. These technologies ensure the availability of safe irrigation water while mitigating environmental risks.

D) Precision Agriculture

Precision agriculture leverages nanotechnology to monitor and manage agricultural inputs with unparalleled accuracy, leading to optimized resource use and reduced environmental impacts. Nanosensors are at the forefront of precision agriculture, enabling real-time monitoring of soil and crop health. These sensors detect variations in soil nutrient levels, moisture content, and pH, providing farmers with actionable data to optimize fertilizer and water use (Paul et al., 2022). Gold nanoparticle-based sensors can detect nitrogen and phosphorus levels in the soil, allowing for precise nutrient application. Nanosensors are used to monitor environmental factors such as temperature and humidity, helping farmers mitigate the effects of climate variability on crop growth. Smart delivery systems enabled by nanotechnology provide controlled and targeted release of agricultural inputs, such as fertilizers, pesticides, and herbicides. Encapsulation of active ingredients in polymeric nanoparticles or liposomes ensures their gradual release, matching crop demand and minimizing losses to the environment. For example, nano-clay carriers have been developed for the sustained release of fertilizers, reducing nutrient leaching and improving crop nutrient uptake. These systems contribute to efficient resource use and lower environmental pollution.

E) Post-Harvest Management and Food Security

Nanotechnology has immense potential to address post-harvest challenges by improving food storage, reducing spoilage, and ensuring food safety (Babu et al., 2022). Nano-packaging materials are designed to extend the shelf life of agricultural produce by providing antimicrobial protection and maintaining optimal storage conditions. For example, silver and zinc oxide nanoparticles are incorporated into packaging films to prevent microbial growth and reduce spoilage. Nano-packaging also includes oxygen and ethylene scavengers that delay the ripening of fruits and vegetables, ensuring longer storage durations. These innovations enhance food supply chain efficiency and reduce post-harvest losses. Nanosensors are used for the rapid detection of contaminants in food products, including pesticide residues, heavy metals, and microbial pathogens. For example, quantum dot-based sensors can identify trace amounts of harmful substances in fruits, vegetables, and grains, ensuring compliance with food safety standards (Xiong et al., 2022). Nanotechnology-enabled smart labels in packaging provide real-time information about food freshness, enabling consumers to make informed decisions. By enhancing food safety, these technologies contribute to improved public health and food security.

4. OPPORTUNITIES IN NANOTECHNOLOGY FOR AGRICULTURE

A) Potential to Improve Crop Yields and Reduce Resource Use

Nanotechnology presents significant opportunities to enhance crop yields while reducing the environmental footprint of agriculture. Through innovative input delivery systems and resilience-enhancing technologies, it provides a pathway for efficient resource use and sustainable farming practices. Conventional agricultural practices often involve the excessive use of fertilizers and pesticides, leading to nutrient loss, environmental pollution, and declining soil health. Nanotechnology addresses these issues by enhancing the efficiency of agricultural inputs. Nano-fertilizers and nano-pesticides are designed to release active ingredients in a controlled manner, ensuring their availability to plants when and where they are needed most. Nitrogen-based nano-fertilizers reduce nitrate leaching into groundwater and minimize volatilization, improving nitrogen use efficiency and reducing environmental contamination. Nano-pesticides enhance the targeting of pests, allowing for lower application rates while maintaining efficacy. For example, silica and chitosan nanoparticles serve as carriers for active ingredients, improving pesticide stability and penetration into pest tissues (Kashyap et al., 2015). This precision in input delivery reduces the reliance on excessive chemical applications and mitigates adverse environmental impacts. By improving the bioavailability and effectiveness of fertilizers and pesticides, nanotechnology can significantly increase crop productivity while reducing the consumption of limited natural resources, such as water and arable land. Nanotechnology has the potential to help agriculture adapt to the challenges posed by climate change. Extreme weather events, prolonged droughts, and soil salinization are increasingly affecting crop yields worldwide. Nanomaterials, such as carbon-based nanoparticles and cerium oxide nanoparticles, can enhance plant tolerance to abiotic stresses by modulating stress-response pathways and improving water and nutrient uptake. Carbon nanotubes have been shown to improve root water absorption under drought conditions, ensuring plant survival in water-scarce environments. Nanosensors can monitor and provide real-time data on soil moisture, temperature, and other environmental parameters, enabling farmers to implement climate-smart practices and reduce water usage (Gangwar et al*.,* 2024). Nano-coatings and films are also being developed to protect crops from extreme temperatures and UV radiation, further increasing their resilience to climate change. These applications demonstrate how nanotechnology can be instrumental in building a climate-resilient agricultural sector capable of sustaining global food production in the face of environmental challenges.

B) Boosting Global Food Security and Sustainable Development

Nanotechnology offers promising solutions for addressing the dual challenges of feeding a growing global population and achieving sustainable development goals. Its ability to improve agricultural productivity, optimize resource use, and integrate precision farming technologies makes it a key enabler of food security. With the global population projected to exceed 9.7 billion by 2050, agricultural output must increase by an estimated 60% to meet food demand. However, this increase must be achieved without exacerbating resource depletion or environmental degradation. Nanotechnology can enable this transition by increasing crop yields and reducing post-harvest losses. Nano-fertilizers and nano-pesticides provide precise nutrient and pest management, ensuring higher productivity with reduced input requirements (Tang et al*.,* 2023). Nano-packaging and nanosensors are being used to extend the shelf life of perishable produce and reduce food waste. Packaging films containing silver or zinc oxide nanoparticles inhibit microbial growth, preserving food quality and safety during storage and transportation. By enhancing the efficiency of agricultural production and post-harvest processes, nanotechnology contributes to sustainable food systems that can meet the needs of future generations. Precision agriculture, which relies on advanced technologies to monitor and manage farming practices, is a key enabler of sustainable development. Nanotechnology plays a central role in precision farming by providing tools for real-time monitoring and smart input delivery. Nanosensors, for example, can detect soil nutrient levels, moisture content, and pest activity, enabling farmers to make data-driven decisions and reduce resource wastage. Smart delivery systems based on nanomaterials, such as polymeric nanoparticles or nano-clays, ensure that fertilizers and pesticides are released gradually and efficiently, matching the crop's growth cycle (Singh et al*.,* 2024). These technologies optimize resource use, minimize environmental impacts, and enhance the economic viability of farming operations. As global agriculture transitions toward sustainable practices, the integration of nanotechnology into precision farming will play a pivotal role in achieving food security and environmental conservation.

C) Innovation and Economic Growth

Nanotechnology is not only transforming agricultural practices but also driving innovation and economic development. The emergence of agri-nanotechnology startups and the development of cost-effective solutions are creating new opportunities for growth and competitiveness in the agricultural sector. The growing demand for sustainable agricultural solutions has led to the rise of startups specializing in agri-nanotechnology. These companies are at the forefront of developing and commercializing innovative products, such as nano-fertilizers, nano-pesticides, and nanosensors. Several startups are focusing on the production of eco-friendly nano-based formulations that reduce environmental impact while improving crop yields. Agri-nanotechnology startups are collaborating with research institutions and governments to scale up their innovations and make them accessible to farmers. These partnerships are fostering the development of cutting-edge technologies that address critical agricultural challenges, such as soil degradation, pest resistance, and climate variability (Jose et al*.,* 2024). The growth of agri-nanotechnology startups is contributing to job creation, technology transfer, and the diversification of agricultural markets, enhancing the sector's resilience to global challenges. One of the key opportunities in nanotechnology for agriculture lies in its potential to develop cost-effective solutions that benefit smallholder farmers, who constitute the majority of the agricultural workforce in developing countries. Innovations such as green synthesis of nanomaterials and low-cost nanosensors are making nanotechnology more affordable and accessible. For example, green-synthesized nanoparticles using plant extracts or microorganisms reduce production costs while maintaining efficacy and environmental safety. Nano-enabled products, such as polymer-coated fertilizers and pest-resistant nano-formulations, can reduce the need for repeated applications, lowering input costs for farmers. Governments and international organizations are also investing in the dissemination of nano-agriculture technologies through subsidies, training programs, and demonstration projects, ensuring that the benefits of nanotechnology reach underserved farming communities. By empowering farmers with affordable and efficient tools, nanotechnology is driving inclusive economic growth and contributing to the broader goal of poverty alleviation (Harsh et al*.,* 2018).

5. CHALLENGES IN NANOTECHNOLOGY APPLICATIONS IN AGRICULTURE

While nanotechnology offers transformative potential in agriculture, its implementation is accompanied by a range of challenges. These challenges span environmental, health, technological, economic, and regulatory domains. Addressing these issues is critical to ensuring the safe, equitable, and sustainable application of nanotechnology in agricultural practices.

A) Environmental Concerns and Risks

One of the major environmental concerns regarding the application of nanotechnology in agriculture is the potential toxicity of nanomaterials to ecosystems. Nanoparticles, due to their small size and high reactivity, can persist in the environment and interact with non-target organisms. Studies have shown that silver nanoparticles, widely used for their antimicrobial properties, can adversely affect soil microbial communities by disrupting metabolic activities and reducing microbial diversity. Metal oxide nanoparticles such as titanium dioxide and zinc oxide can induce oxidative stress in aquatic organisms, impacting their growth and reproduction (Mawed et al*.,* 2022). The unintended accumulation of nanoparticles in agricultural soils can alter nutrient cycling and soil structure, potentially impairing soil fertility and productivity. For example, carbon-based nanomaterials such as fullerenes have been shown to alter the enzyme activity of soil microorganisms, which could have cascading effects on the ecosystem. This toxicity raises concerns about the long-term safety and ecological compatibility of nanomaterials used in agriculture. The long-term impacts of nanomaterials on soil, water, and biodiversity remain poorly understood, primarily due to the lack of comprehensive data on their environmental fate and behavior. Nanoparticles can leach into groundwater or run off into nearby water bodies, where they may accumulate and affect aquatic ecosystems. Zero-valent iron nanoparticles, used in soil remediation, have shown potential to disrupt the aquatic food web when released into water systems. In terms of biodiversity, concerns have been raised about the bioaccumulation of nanomaterials in plants and animals, which could affect higher trophic levels in the food chain. Prolonged exposure to certain nanomaterials, such as silver and copper nanoparticles, has been linked to reduced germination rates and phytotoxic effects in crops (Budhani et al*.,* 2019). These uncertainties underscore the need for robust risk assessment frameworks to evaluate the long-term environmental implications of agricultural nanotechnology.

B) Safety and Health Issues

The handling of nanomaterials during manufacturing, transportation, and application poses risks to human health. Due to their small size and high surface reactivity, nanoparticles can easily become airborne and be inhaled, leading to respiratory issues and systemic exposure. Workers involved in the production and application of nano-fertilizers and nano-pesticides are particularly vulnerable to inhalation or dermal exposure. Studies have suggested that certain nanoparticles, such as carbon nanotubes and metal oxides, may cause cytotoxicity, inflammation, and oxidative stress in human cells. Nanomaterials can enter the human body through ingestion or skin contact during agricultural activities. Improper handling of nano-pesticides can lead to accidental exposure, posing risks to farmers and applicators. These occupational health risks highlight the need for protective equipment, safety protocols, and adequate training for those working with nanomaterials in agriculture (Chelliah et al*.,* 2023). The introduction of nano-enhanced products into the agricultural system raises concerns about their potential transfer through the food chain. Nanoparticles used in fertilizers, pesticides, and soil amendments can be taken up by plants and accumulate in edible tissues, leading to the ingestion of nanoparticles by humans and animals. For example, zinc oxide nanoparticles applied as a fertilizer have been detected in plant tissues, raising questions about their long-term health effects when consumed in large quantities. The potential for bioaccumulation and biomagnification of nanomaterials through the food web remains a significant area of concern. Animal studies have demonstrated that certain nanoparticles, such as silver and titanium dioxide, can cross biological membranes and accumulate in vital organs, posing risks to human consumers at the top of the food chain. Comprehensive toxicological studies and labeling requirements are essential to ensure the safety of nano-enhanced agricultural products for consumers (Saikanth et al*.,* 2023).

C) Technological and Economic Barriers

The high cost of producing nanomaterials and integrating them into agricultural systems is a significant barrier to widespread adoption. Techniques for the synthesis of nanoparticles, such as chemical vapor deposition and sol-gel processes, often require expensive raw materials, energy-intensive processes, and sophisticated equipment. The formulation of nano-enabled agricultural inputs, such as smart delivery systems, further adds to production costs, making these products unaffordable for many farmers, especially in developing countries. The deployment of nanotechnology in agriculture also requires investments in infrastructure, training, and maintenance, which can deter small-scale farmers from adopting these technologies. Without significant cost reductions or government subsidies, the commercialization and accessibility of agricultural nanotechnology will remain limited (Hofmann et al*.,* 2020). The benefits of nanotechnology in agriculture are often concentrated in high-income countries and large-scale farming operations, leaving small-scale farmers and developing regions at a disadvantage. High upfront costs, lack of awareness, and limited technical expertise prevent smallholder farmers from adopting nanotechnology-based solutions. The lack of local manufacturing capabilities in many developing countries forces farmers to rely on imported nano-agricultural products, further increasing costs and limiting accessibility. Bridging this gap requires targeted initiatives, such as capacity-building programs, technology transfer, and the development of affordable nano-based products tailored to the needs of small-scale farmers.

D) Lack of Regulation and Public Awareness

The regulatory landscape for nanotechnology in agriculture remains fragmented and underdeveloped, creating uncertainty for stakeholders. Most countries lack specific guidelines for the production, application, and disposal of nanomaterials in agriculture, leaving potential risks unaddressed (Engelmann et al*.,* 2024). International organizations, such as the Organization for Economic Cooperation and Development (OECD), have called for the establishment of harmonized regulations to govern the use of nanotechnology. These regulations must address critical issues, including environmental safety, worker protection, and product labeling, to ensure the responsible and transparent use of nanomaterials in agriculture. However, the slow pace of regulatory development has hindered the adoption of nanotechnology and limited its market potential. The use of nanotechnology in agriculture raises ethical and social concerns that must be addressed to gain public trust and acceptance. Issues such as equity, accessibility, and transparency are critical to ensuring that the benefits of nanotechnology are distributed fairly. There is concern that large agribusinesses may monopolize nano-enabled technologies, marginalizing small-scale farmers and exacerbating existing inequalities in the agricultural sector. Public skepticism about the safety and environmental impacts of nanotechnology can hinder its acceptance. A lack of awareness and understanding of nanotechnology among farmers and consumers further exacerbates these concerns. Effective outreach programs, stakeholder engagement, and transparent communication are essential to address ethical issues and build public confidence in the safe use of nanotechnology in agriculture (Amutha et al*.,* 2024).

6. CASE STUDIES AND CURRENT RESEARCH TRENDS

Nanotechnology has seen significant advancements in agricultural applications, ranging from nutrient management and pest control to real-time monitoring and sustainability. Several case studies illustrate its successful application in improving agricultural productivity and environmental sustainability, while emerging research trends point to the development of more eco-friendly and efficient nano-based solutions. The adoption of nanotechnology in agriculture varies regionally and globally, driven by research priorities, market demands, and policy frameworks.

A) Successful Case Studies of Nanotechnology in Agriculture

Nano-fertilizers have emerged as a powerful tool for increasing nutrient use efficiency and improving crop productivity. Several case studies highlight their potential in real-world agricultural settings. One notable example is the application of zinc oxide (ZnO) nanoparticles as a nano-fertilizer. Studies conducted in India demonstrated that ZnO nanoparticles enhanced zinc bioavailability, leading to significant improvements in wheat crop yields compared to conventional zinc sulfate fertilizers (Singh et al*.,* 2021). The increased uptake of zinc also contributed to better chlorophyll content, photosynthesis, and plant health, demonstrating the superior efficacy of nano-fertilizers over traditional formulations.In another case study, urea-coated nanoparticles were applied to rice fields in China. The results showed a substantial reduction in nitrogen losses due to leaching and volatilization, coupled with a 15–20% increase in rice yield compared to conventional urea fertilizers. These studies highlight the potential of nano-fertilizers to address the inefficiencies of traditional fertilizers, reduce environmental contamination, and enhance food security by increasing crop production. Nano-pesticides are increasingly recognized for their ability to provide targeted pest control with minimal environmental impact. In a successful case study from Brazil, silica nanoparticles were used to deliver a widely used insecticide (lambda-cyhalothrin) to soybean crops. The nano-formulation exhibited higher pest mortality rates while significantly reducing the required pesticide dosage compared to conventional methods (Vishnu et al*.,* 2024). This study demonstrated how nano-pesticides can minimize chemical usage while maintaining or even enhancing pest control efficacy.Another noteworthy example is the use of silver nanoparticles for fungal disease management in tomato crops. A study conducted in Mexico found that silver nanoparticles effectively controlled *Fusarium oxysporum* infections, a major fungal pathogen, with no adverse effects on plant growth or soil microbiota. This case highlights the potential of nano-enabled pest management systems to tackle specific agricultural challenges while reducing the ecological risks associated with conventional chemical pesticides.

B) Emerging Research Areas

One of the most promising trends in agricultural nanotechnology research is the development of biodegradable and eco-friendly nanomaterials. These materials aim to address concerns about the environmental persistence and toxicity of conventional nanomaterials. For example, researchers are developing bio-based nanoparticles derived from natural polymers such as chitosan, starch, and cellulose. These biodegradable nanoparticles can be used as carriers for fertilizers, pesticides, or growth regulators, ensuring that they break down into non-toxic byproducts after use (Sarkar et al*.,* 2021). Another emerging approach involves the use of plant or microbial extracts for the green synthesis of nanoparticles. This method eliminates the need for hazardous chemicals in nanoparticle production, reducing their environmental impact. Researchers in India have successfully synthesized zinc oxide nanoparticles using *Azadirachta indica* (neem) leaf extract, which showed potential as a plant growth enhancer while being completely biodegradable. Such developments represent a shift toward more sustainable nanotechnology applications in agriculture. Nanosensors are a rapidly evolving area of research with significant implications for precision agriculture. Recent advancements have focused on enhancing the sensitivity, specificity, and durability of nanosensors for real-time monitoring of soil, crop, and environmental parameters. For example, carbon nanotube-based sensors have been developed to detect soil nutrient levels, such as nitrogen, phosphorus, and potassium, with high accuracy. These sensors provide farmers with actionable data to optimize input applications and improve crop yields (Paul et al*.,* 2022).Smart farming tools integrating nanosensors with Internet of Things (IoT) platforms are also being developed to enable remote monitoring and decision-making. A recent study in the Netherlands demonstrated the use of graphene-based nanosensors for detecting ethylene gas, a key indicator of fruit ripening, in greenhouses. These sensors were connected to IoT systems, allowing farmers to automate climate control and harvesting schedules based on real-time data. Such innovations are paving the way for more efficient and data-driven agricultural practices.

C) Regional and Global Trends in Nanotechnology Adoption

The adoption of nanotechnology in agriculture is influenced by regional research priorities, economic factors, and regulatory frameworks. Developed countries, such as the United States, Japan, and European nations, have taken the lead in developing and commercializing nano-based agricultural products. The U.S. Department of Agriculture (USDA) has invested heavily in nanotechnology research to address challenges such as nutrient management and pest resistance. European initiatives like the Horizon 2020 program have funded projects focused on sustainable nanotechnology applications in agriculture. Developing countries are increasingly exploring nanotechnology as a means to address pressing agricultural challenges, such as food security and resource scarcity. Countries like India and China have emerged as significant contributors to agricultural nanotechnology research. India, for example, has established dedicated research centers, such as the Nanotechnology Applications Centre at the Indian Institute of Technology, to develop affordable nano-fertilizers and nano-pesticides tailored to local farming needs (Ali et al., 2014). The adoption of nanotechnology in agriculture remains uneven globally. While developed countries have access to advanced technologies and well-established regulatory frameworks, developing regions often face barriers such as high costs, limited infrastructure, and a lack of awareness among farmers. To address these disparities, international collaborations and technology transfer initiatives are being promoted to ensure that the benefits of agricultural nanotechnology reach all regions equitably.

7. CONCLUSION

Nanotechnology offers transformative opportunities for agriculture by enhancing crop productivity, improving resource efficiency, and enabling sustainable practices. From nano-fertilizers and pesticides to smart sensors and eco-friendly nanomaterials, its applications promise to address global challenges such as food security, climate resilience, and environmental degradation. However, the integration of nanotechnology into agriculture faces significant challenges, including potential environmental toxicity, health risks, high costs, and regulatory gaps. Future advancements must prioritize the development of biodegradable and cost-effective nanomaterials, supported by robust policies and global collaborations. Equally critical are educational and outreach initiatives to empower farmers and build public trust in these innovations. By fostering sustainable and inclusive approaches, nanotechnology can play a pivotal role in transforming agricultural systems, ensuring equitable access to its benefits while protecting human and environmental health.

8. RECOMMENDATIONS

The future of nanotechnology in agriculture lies in addressing existing challenges and advancing innovations that contribute to sustainable and inclusive agricultural systems. While nanotechnology holds immense potential to revolutionize farming practices, its full-scale implementation requires targeted research, robust policy frameworks, and effective public engagement.

A) Research Priorities in Agricultural Nanotechnology

The environmental and ecological implications of nanotechnology must be addressed by prioritizing the development of sustainable and eco-friendly nanomaterials. The synthesis of biodegradable nanoparticles, derived from natural resources like chitosan, starch, and cellulose, is an emerging area of research. Such materials degrade into non-toxic byproducts, minimizing environmental risks associated with persistent nanomaterials (Rani et al., 2018). For example, bio-based nanoparticles synthesized using plant extracts or microbial agents offer a greener alternative to traditional chemical synthesis methods. Recent studies have demonstrated the potential of neem-derived zinc oxide nanoparticles as both eco-friendly fertilizers and pest control agents. The use of nanotechnology to develop materials that contribute to circular agriculture systems, such as nano-biochar composites that enhance soil fertility while reducing waste, is gaining traction. Future research should focus on integrating life cycle assessments (LCAs) into the development process to evaluate the sustainability of nanomaterials from production to disposal. This approach can ensure that agricultural nanotechnology aligns with global sustainability goals, including the United Nations’ Sustainable Development Goals (SDGs). High production costs and scalability limitations currently hinder the widespread adoption of nanotechnology in agriculture. Therefore, research must prioritize the development of cost-effective synthesis methods that enable large-scale production without compromising quality or functionality. Green synthesis methods, which use renewable biological materials such as plant extracts and agricultural residues, offer significant cost advantages over conventional approaches and should be further explored (Saratale et al., 2018). Nanotechnology research should focus on simplifying formulations and delivery mechanisms to reduce manufacturing complexity. The use of nano-clays as carriers for agrochemicals has been shown to be both scalable and economically viable due to the abundant availability of raw materials. Public and private sector investments in pilot programs and industrial-scale production facilities can accelerate the commercialization of affordable nanotechnology-based products. Collaborative efforts between academia, industry, and governments can further facilitate technology transfer and reduce costs for end users, particularly smallholder farmers in developing countries.

B) Policy and Regulatory Development

The absence of comprehensive and harmonized regulatory frameworks remains a significant barrier to the safe and ethical implementation of nanotechnology in agriculture. Establishing standardized guidelines for the production, use, and disposal of nanomaterials is critical to addressing environmental, health, and safety concerns (Lee et al., 2010). These guidelines should be based on rigorous scientific evidence and address critical issues such as nanoparticle toxicity, environmental persistence, and bioaccumulation.Governments and international organizations, such as the Food and Agriculture Organization (FAO) and the Organization for Economic Co-operation and Development (OECD), must work together to develop global standards for agricultural nanotechnology. These standards should include labeling requirements for nano-based products, clear protocols for risk assessment, and regulations for nanomaterial disposal. Regulatory oversight must also account for regional variations in agricultural practices and environmental conditions to ensure context-specific safety measures. Effective policy implementation requires strong collaboration between governments, researchers, and industry stakeholders. Governments can play a pivotal role by funding research and development (R&D) initiatives, incentivizing innovation through subsidies and grants, and creating platforms for public-private partnerships. Industry participation is crucial for scaling up innovations and bringing them to market. Companies specializing in agricultural inputs, such as fertilizers and pesticides, should collaborate with researchers to develop nano-enabled products that meet regulatory standards while addressing farmers' practical needs. By creating multi-stakeholder networks, policymakers can ensure that nanotechnology is developed and deployed in a manner that maximizes benefits while minimizing risks (Tawiah et al., 2024).

C) Educational and Outreach Initiatives

Farmers are the primary beneficiaries of agricultural nanotechnology, yet many lack the knowledge and resources to adopt these innovations effectively. Education and capacity-building programs are essential to bridge this gap. Governments, agricultural extension services, and non-governmental organizations (NGOs) must work together to provide training on the safe and effective use of nano-enabled products.These programs should focus on practical aspects such as the application of nano-fertilizers and nano-pesticides, the operation of nanosensors, and the interpretation of real-time data for precision farming. Demonstration farms and field trials can serve as powerful tools for showcasing the benefits of nanotechnology and building trust among farming communities. Partnerships with cooperatives and farmer organizations can help disseminate information and resources to smallholder farmers in remote areas.Efforts must also be made to ensure that educational materials are accessible and culturally relevant. For example, instructional content should be translated into local languages and delivered through channels familiar to farmers, such as radio broadcasts, mobile applications, and community meetings (Caine et al., 2015). These initiatives will empower farmers to make informed decisions about adopting nanotechnology and contribute to its successful integration into agricultural systems. Public skepticism about the safety and ethical implications of nanotechnology can hinder its acceptance and adoption. Transparent communication and proactive engagement with consumers, environmental groups, and other stakeholders are necessary to build trust in nanotechnology. Public awareness campaigns should highlight the benefits of nanotechnology for food security, environmental sustainability, and climate resilience while addressing common misconceptions and concerns.Engaging the public in discussions about nanotechnology’s risks and benefits can foster an open dialogue and encourage informed decision-making. Citizen forums and stakeholder consultations can provide valuable insights into public perceptions and priorities, helping to shape research agendas and policy framework. Labeling nano-enabled products and providing clear information about their composition and safety can enhance consumer confidence. Governments and industry stakeholders must also work together to establish ethical guidelines that prioritize equity and inclusivity, ensuring that the benefits of agricultural nanotechnology are accessible to all, particularly marginalized communities (Aziza et al*.,* 2023).

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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