INTERNATIONAL JOURNAL OF RESEARCH AND INNOVATION IN APPLIED SCIENCE (IJRIAS)
ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume XI Issue VI June 2026

A Review on Nanotechnology in Agricultural Systems.

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DOI: https://doi.org/10.51584/IJRIAS.2026.11060230

Received: 28 June 2026; Accepted: 04 July 2026; Published: 13 July 2026

ABSTRACT

Nanotechnology has appeared as a transformative approach in modern agriculture, by providing innovative solutions to enhance productivity, sustainability and resource efficiency. Nanotechnology involves the manipulation and application of materials at nanoscale (1-100nm), where unique physicochemical properties enhance performance compared to conventional material. In agriculture, nanotechnology has facilitated the development of innovative product such as nanofertilizers, nanopesticides, nanoherbicides, nanosensors and nano-enabled delivery systems. The application of Nano materials such as silver, gold, zinc oxide and iron oxide in agricultural systems enables targeted delivery of fertilizers, pesticides and nutrients, reducing environmental pollution and improving crop yield. Nano-enabled sensors and diagnostic tools facilitate precise monitoring of soil health, plant growth and pest infestations, promoting informed decision-making and precision farming. However, the comprehensive risk assessment, proper regulation and sustainable application strategies are essential for the safe integration of nanotechnology into the agricultural system. This review examine the use of nanotechnology to the development of smart packaging, post-harvest preservation, water management strategies, ensuring food security and quality in Agriculture. Despite its promising potential, the adoption of nanotechnology in agriculture requires careful assessment of its environmental impact, toxicity and regulatory frameworks. Overall, integrating nanotechnology into agricultural systems represents a significant step toward sustainable, efficient, high-yield farming practices and food security.

Keywords: Nanotechnology, Nanofertilizers, Nanopesticides, Nanoherbicide, Nano-materials, Agriculture.

INTRODUCTION

Agriculture has been the backbone of human civilization, providing food, raw materials and economic sustenance for centuries [1]. However, the agricultural sector is facing significant challenges due to population growth, climate change, resource scarcity, pest infestations and soil degradation [2]. To meet the increasing global food demand, there is a need for innovative and sustainable solutions to improve productivity, reduce losses and minimize environmental impact [3].

Application of Nanotechnology in agriculture that help in manipulation of matter at the atomic and molecular scale (1-100 nanometers), has emerged as a groundbreaking technology with the potential to revolutionize agricultural practices [4]. By utilizing Nano scale materials and devices, nanotechnology offers new tools to optimize resource utilization, enhance crop yields and promote environmental sustainability [5]. This integration of nanotechnology into agriculture, termed "Nano -agriculture," is seen as a transformative approach to achieving global food security [6].

Aims and Objectives.

The primary aim of integrating nanotechnology into agricultural systems is to revolutionize traditional farming practices by introducing precision, sustainability and innovation. The specific objectives include:

a) **Enhancing Resource Efficiency**: To develop Nano-based fertilizers, pesticides and water management systems for efficient use of resources.

b) **Improving Crop Productivity**: To increase crop yield and quality through the targeted delivery of nutrients and protection against biotic and abiotic stresses.

c) **Promoting Sustainable Agriculture**: To reduce environmental pollution by minimizing the overuse of chemical inputs and promoting eco-friendly alternatives.

d) **Advancing Precision Farming**: To use Nano-sensors and devices for real-time monitoring of soil, crop, and environmental conditions.

e) **Reducing Post-Harvest Losses**: To enhance food storage and safety using Nano-packaging, coatings and smart monitoring technologies.

Applications of Nanotechnology in Agriculture

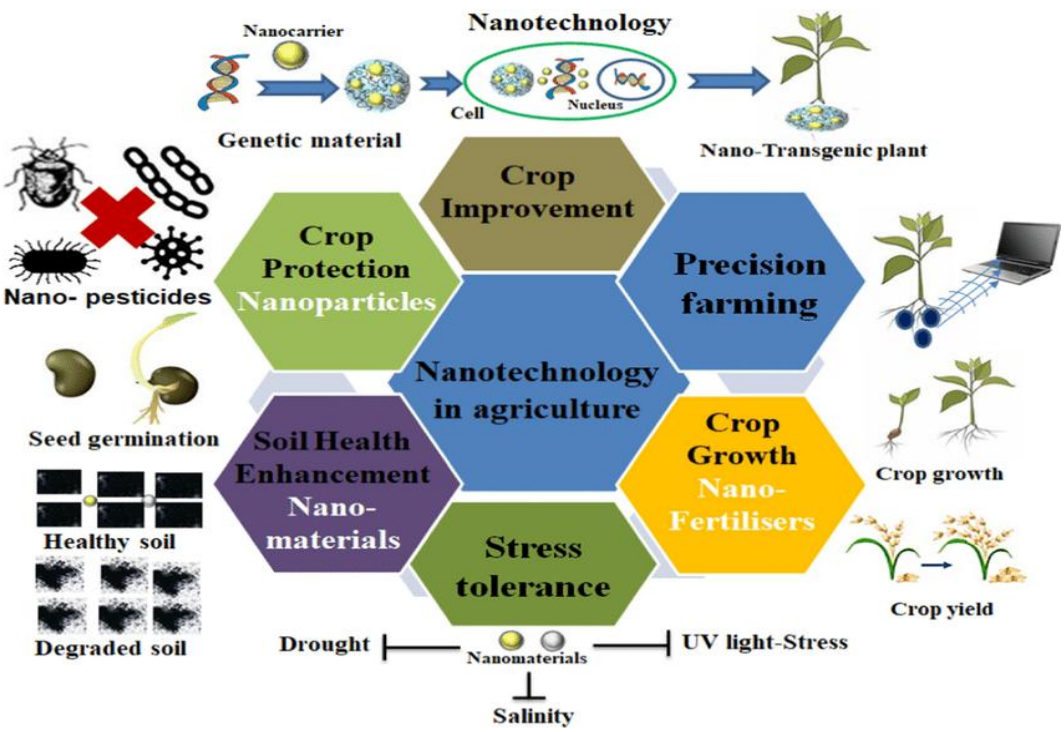

Figure 1 : Shows some application of Nanotechnology in Agriculture.

The (Fig.1) illustrates the major applications of nanotechnology in agriculture, highlighting how engineered nanomaterial's improve crop productivity, soil quality, precision farming, stress tolerance, crop protection and genetic improvement. These interconnected applications contribute to sustainable agricultural production while minimizing environmental impacts.

1. **Crop Protection (Nanoparticles and Nano-pesticides)**: The left side of the (Fig.1) shows the use of nano-pesticides for controlling insects, bacteria, fungi and other plant pathogens. Nanoparticles serve as carriers that enhance the stability, targeted delivery and controlled release of pesticides. Compared with conventional pesticides, nano-pesticides require lower application rates, reduce chemical residues and minimize environmental contamination while improving pest control efficiency. [7]

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2. **Crop Improvement through Nanotechnology**: The upper section demonstrates how nanocarriers transport genetic materials (Deoxyribonuclic acid, Ribonucleic acid or genes) into plant cells and eventually the nucleus, resulting in nano-transgenic plants. Nanotechnology facilitates efficient gene delivery without relying solely on traditional transformation methods, improving crop breeding, disease resistance, drought tolerance and nutrient efficiency[8].

3. **Precision Farming**: The right section illustrates precision agriculture, where nanosensors frequently monitor soil moisture, nutrient availability, plant health and disease development. The information and data collected from these sensors is transmitted to computers or digital platforms, allowing farmers to apply fertilizers, pesticides and irrigation only where needed. This increases resource-use efficiency while reducing production costs and environmental pollution[9].

4. **Crop Growth through Nano-fertilizers**: The yellow hexagon explains the role of nano-fertilizers in promoting crop growth and increasing yield. Nano-fertilizers provide slow and controlled nutrient release, improve nutrient uptake, reduce nutrient losses through leaching and volatilization, and enhance nutrient-use efficiency. Consequently, plants exhibit improved root development, biomass accumulation and grain yield compared with conventional fertilizers [10].

5**. Stress Tolerance**: The green hexagon at the bottom indicates that nanomaterials enhance plant tolerance to environmental stresses such as drought, salinity and ultraviolet (UV) radiation. Nanoparticles stimulate antioxidant defense systems, improve photosynthetic activity, regulate osmotic balance and reduce oxidative damage caused by reactive oxygen species. These physiological improvements enable crops to survive adverse environmental conditions more effectively [11].

6. **Soil Health Enhancement**: The purple hexagon represents the application of nanomaterials for promoting soil health. Nanotechnology enhances soil fertility by improving nutrient retention, increasing microbial activity, immobilizing heavy metals and restoring degraded soils. Nanomaterials also improve soil structure and water-holding capacity, thereby supporting sustainable crop production.[12]

7. **Seed Germination**: The (Fig.1) also shows improved seed germination, where nanoparticles penetrate seed coats, enhance water uptake, stimulate enzyme activity and accelerate metabolic processes. These effects promote faster germination, stronger seedling emergence and more vigorous plant establishment.[13]

Finally, at the center of the (Fig.1) is Nanotechnology in Agriculture, emphasizing that all these applications are interconnected. Nanotechnology integrates nano-fertilizers, nano-pesticides, nanosensors and nanocarriers to improve agricultural productivity while reducing fertilizer losses, pesticide residues, water consumption and environmental pollution. Collectively, these technologies support climate-smart, eco-friendly and sustainable agricultural systems capable of meeting future food security demands.

Additionally, nanotechnology offers a wide range of applications that address challenges encountered at every stage of the farming process such as :

1. **Nano-Fertilizers:** Traditional fertilizers often suffer from low nutrient-use efficiency, leading to significant nutrient losses to the environment. Nano-fertilizers are engineered to deliver nutrients in a

controlled and precise manner [14].

2. **Nano-Pesticides:** Chemical pesticides often affect non-target organisms and contaminate the environment [15]. Nano-pesticides offer a targeted and efficient alternative [4].

3. **Nano-Sensors for Precision Agriculture:** Precision agriculture relies on real-time data to optimize farming practices [5]. Nano-sensors are highly sensitive devices that monitor soil, plant and environmental parameters [16].

4. **Water Management Systems:** Water scarcity is a major concern in agriculture. Nanotechnology provides innovative solutions for efficient water use[17].

5. **Post-Harvest Management and Food Safety:** A significant portion of agricultural produce is lost during storage and transportation. Nanotechnology addresses this through:

i. **Nano-Coatings**: Protective coatings for fruits and vegetables extend shelf life by preventing microbial growth and moisture loss.

ii. **Nano-Packaging**: Smart packaging systems monitor food freshness and detect spoilage.

iii. **Contaminant Detection**: Nano-sensors identify toxins, heavy metals and pathogens in food.

6. **Genetic Engineering and Nanobiotechnology:** Nanotechnology facilitates genetic improvement in crops by acting as carriers for biomolecules like Deoxyribonucleic Acid (DNA), Ribonucleic Acid (RNA) and proteins.

Benefits of Nanotechnology in Agriculture.

(a). Enhanced Productivity: Higher Crop Yields through Improved Input Efficiency.

One of the primary goals of nanotechnology in agriculture is to improve productivity by increasing crop yields [1]. This is achieved by enhancing the efficiency of essential agricultural inputs like fertilizers, pesticides and water [4].

Nanotechnology plays a key role in boosting productivity such as:

i. **Nano-Enhanced Fertilizers**: Traditional fertilizers often suffer from poor nutrient uptake efficiency, leading to significant nutrient loss through leaching, runoff, or volatilization. Nanotechnology enables the development of Nano-fertilizers that have a controlled release mechanism. By encapsulating nutrients in nanoparticles, these fertilizers slowly release nutrients over time, making them more readily available to plants. This controlled release minimizes waste, ensures efficient nutrient uptake, and promotes healthy plant growth, which translates to higher crop yields.

ii. **Targeted Nano-Pesticides**: Conventional pesticides can harm beneficial organisms and often lead to pesticide resistance. Nano pesticides are engineered to deliver active ingredients more precisely, targeting pests and diseases without affecting non-target organisms. For example, Nano-particles can penetrate the pest's exoskeleton more effectively, ensuring that the pesticide works more efficiently with a smaller dose. This reduces the amount of chemical used and improves pest control outcomes, ultimately enhancing crop yield.

iii. **Nano-Coatings on Seeds**: Nanotechnology can be used to coat seeds with Nano-materials that improve germination rates, protect against pathogens, and provide essential nutrients for initial plant growth. This leads to more uniform crop emergence and better overall productivity.

iv. Water and Irrigation Management: Nano-coatings on irrigation systems or soil treatments can help retain moisture and ensure that plants receive consistent water supply, especially in drought-prone areas. Efficient water usage means crops grow under optimal hydration conditions, increasing yield potential.

(b). Sustainability: Eco-Friendly Practices That Protect the Environment.

Nanotechnology promotes sustainability in agriculture by offering environmentally friendly solutions that minimize the use of harmful chemicals and reduce environmental pollution. These sustainable practices not only benefit the environment but also improve long-term agricultural productivity [18]. However nanotechnology act as ecofriendly in the following ways:

i. **Reduced Chemical Usage**: Nanotechnology allows for the development of "Nano-pesticides" and "Nano-fertilizers," which are more efficient in terms of delivery and application. These products are designed to release active ingredients in a controlled manner, targeting only the plants or pests that need attention. This reduces the over-application of chemicals, which can lead to soil degradation, water contamination, and harm to non-target organisms.

ii. **Environmentally Friendly Nano-Materials**: Nano materials used in agricultural applications (e.g., nano-pesticides or nano-fertilizers) can be engineered to degrade safely in the environment, unlike traditional chemical inputs that may persist and accumulate in the soil and water. For instance, some nanoparticles used in fertilizers can break down into non-toxic elements, reducing the risk of soil and water pollution.

iii. **Nano-Sensors for Environmental Monitoring**: Nano-sensors can detect changes in soil quality, moisture levels, or pest infestations early, allowing farmers to take preventive measures and apply interventions only when needed. This helps avoid unnecessary chemical usage and ensures that interventions are more targeted and precise, reducing the ecological footprint of farming practices.

(c). Resource Optimization: Efficient Use of Water, Nutrients And Energy.

The efficient use of resources is a critical challenge in agriculture, especially with growing environmental concerns and limited access to water and nutrients. Nanotechnology offers solutions to optimize the use of key resources—water, nutrients, and energy—leading to more sustainable and efficient farming practices[3].

i. **Water Efficiency**: In regions suffering from water scarcity, efficient irrigation is crucial. Nano-based water management systems such as hydrogels and nano porous materials can absorb and retain water for longer periods, ensuring that crops receive consistent hydration while reducing water wastage. Nanotechnology can also be used in nano-filtration systems to purify water sources, removing contaminants and making water safer for agricultural use.

ii. **Nutrient Optimization**: Traditional fertilizers often result in nutrient loss due to evaporation or leaching, which can pollute groundwater and harm ecosystems. Nanotechnology improves nutrient delivery by encapsulating them in nanoparticles that can release the nutrients in a controlled manner. This controlled release allows crops to absorb nutrients more efficiently, reducing the need for excessive fertilizer application and minimizing nutrient runoff.

iii. **Energy Efficiency**: Energy use in agriculture, particularly in irrigation and heating, can be optimized with nanotechnology. For instance, nano-enhanced coatings on greenhouse materials can help reduce energy consumption by improving thermal insulation, maintaining optimal temperature conditions for plant growth while minimizing the need for external energy inputs.

(d). Improved Food Quality: Safer And More Nutritious Agricultural Produce.

Nanotechnology can enhance the quality of food by improving the nutritional value, safety, and shelf life of agricultural produce [19]. Bellow are ways in which nanotechnology contributes to food quality:

i. **Enhanced Nutrient Content**: Nanotechnology can help increase the bioavailability of essential nutrients in food. For example, Nano encapsulation techniques can be used to deliver micronutrients (like vitamins or minerals) directly to the plant, making them more readily absorbed and utilized by the human body when consumed. This can lead to more nutritious crops, particularly in regions where nutrient deficiencies are prevalent.

ii. **Better Food Safety**: Nanotechnology can be used to enhance food safety by detecting pathogens or contaminants in agricultural products. Nano-sensors are capable of identifying harmful microorganisms like bacteria, fungi, or viruses early in the food supply chain, ensuring that contaminated products are detected and removed before they reach consumers. Nano materials can also be used to coat foods with antimicrobial properties, protecting them from spoilage and contamination.

iii. **Extended Shelf Life**: Nano-coatings and nano-packaging can protect food from spoilage caused by microbial growth or oxidation. These coatings provide a barrier against moisture loss, which helps maintain food freshness and quality for longer periods. For example, nano-packaging materials can be designed to slowly release preservatives or antimicrobial agents, thereby preventing spoilage without the need for excessive chemical additives.

iv. **Smart Packaging**: Nanotechnology can be used to create "smart" packaging that not only improves food preservation but also alerts consumers when food products are no longer safe to consume. For example, nano-sensors embedded in food packaging can monitor the freshness of the food and provide visual cues when the product is nearing expiration or has been compromised.

Future Prospects of Nanotechnology in Agriculture

Nanotechnology is poised to revolutionize the agricultural sector in the coming decades, offering innovative solutions to some of the most pressing challenges facing the industry. As the world grapples with population growth, climate change, resource scarcity, and environmental degradation, nanotechnology can play a crucial role in shaping the future of sustainable agriculture Nanotechnology is poised to revolutionize the agricultural sector[5]. Below is a detailed exploration of the future prospects of nanotechnology in agriculture:

(a). Smart Farming Systems: Integration of Internet of Things (IoT) and Nano-Sensors for Data-Driven Farming

The future of agriculture is increasingly data-driven, with technology enabling farmers to make precise, informed decisions. Nanotechnology plays a key role in enhancing the functionality and efficiency of these smart farming systems through the integration of Internet of Things (IoT) and nano-sensors.

i. **IoT and Nano-Sensors for Real-Time Monitoring**: The IoT allows for the interconnection of devices and systems that collect and share real-time data. When combined with nano-sensors, this technology can revolutionize farming by providing highly sensitive, precise, and continuous monitoring of environmental and crop conditions. Nano-sensors can detect subtle changes in soil quality, moisture levels, pH, temperature, and nutrient content at the nanoscale. This allows farmers to make immediate, data-driven decisions about irrigation, fertilization, pest control, and crop management, improving efficiency and reducing waste. The IoT allows for the interconnection of devices[16].

ii. **Precision Agriculture**: Nano-sensors embedded in soil or attached to plants could measure parameters such as nutrient deficiencies, soil acidity, moisture levels, and temperature fluctuations. This precise monitoring allows for precision farming, where interventions (e.g., watering, fertilizing, or pest control) are applied only when and where needed. By optimizing inputs, smart farming systems ensure higher crop productivity while minimizing costs and environmental impact. Nano-sensors embedded in soil could measure parameters [20].

iii. **Automation and Artificial intelligent (AI) Integration**: IoT-enabled devices and nano-sensors could be integrated with Artificial Intelligence (AI) to automate routine tasks. For example, sensors could alert farmers about when to apply fertilizers or pesticides, and AI could analyze the collected data to recommend optimal solutions. This integration ensures that every step of the farming process is as efficient as possible, improving overall yield and sustainability. IoT-enabled devices could be integrated with artificial intelligence[4].

iv. **Remote Monitoring**: Farmers could use smartphone apps or web-based platforms to access data from their farms remotely. This means they can monitor soil moisture, weather conditions, and crop health in real time, even from a distance, enhancing decision-making and management efficiency Farmers could use smartphone apps to access data[1].

(b). Climate-Resilient Solutions: Development of Nano-Products to Combat Extreme Weather Conditions.

Climate change poses a significant challenge to agriculture, with rising temperatures, unpredictable rainfall, floods, droughts and storms impacting crop growth and food security. Nanotechnology offers climate-resilient solutions that can help farmers adapt to extreme weather conditions and mitigate some of the adverse effects of climate change.

i. **Drought Resistance**: Nanotechnology can be used to develop nano-encapsulated water retention systems, such as hydrogels or nanoparticles, which help soil retain moisture during drought conditions. These water-storing nano-materials can be mixed into soil to maintain hydration levels for plants, reducing the need for frequent irrigation and conserving water resources. Nanotechnology can be used to develop nano-encapsulated water retention systems [17].

ii. **Heat-Resistant Crops**: Heat-stress-resistant crops can be developed[21]. Through nanotechnology, heat-stress-resistant crops can be developed by delivering specific genetic material to plants via nanoparticles, or by using nanoparticles that protect plants from the damaging effects of high temperatures. This could significantly improve crop survival and productivity in regions with rising temperatures or areas prone to heat waves.

iii. **Flood Control**: Nano materials, such as nano-coated membranes and super hydrophobic coatings, can be used in agricultural systems to manage water effectively, preventing flooding by absorbing and storing excess water during heavy rainfall. Nano materials can be used in agricultural systems to manage water [18]. These systems could help stabilize water levels in irrigation systems or agricultural land.

iv. **Pest and Disease Management in Changing Climates**: Nano-pesticides can respond quickly to emerging threats [4]. Nano-pesticides and nano-biosensors can be tailored to respond quickly to emerging threats posed by new pests or pathogens due to shifting climatic patterns.

(c). Biodegradable Nano materials: Eco-Friendly Nano materials That Reduce Environmental Concerns.

As concerns about the environmental impact of synthetic chemicals and non-degradable materials grow, the future of nanotechnology in agriculture includes a strong focus on biodegradable Nano materials that can reduce environmental pollution while maintaining high levels of efficiency.

i. **Biodegradable Nano-Fertilizers and Pesticides**: One of the major environmental concerns with traditional fertilizers and pesticides is that they often remain in the environment for long periods, leading to pollution of soil, water and air. Biodegradable nanomaterial offer a promising alternative[6]. Biodegradable nanomaterial's offer a promising alternative, as they break down into non-toxic substances after use. Nano-formulations of fertilizers or pesticides can degrade safely in the environment, leaving no harmful residues or chemical pollutants behind.

ii. **Eco-Friendly Nano-Packaging**: Nano-composite films made from biodegradable materials could be developed [19]. Another major area where biodegradable nanomaterial's are crucial is in food packaging. Traditional plastic packaging often contributes to pollution and waste. Nano-composite films made from biodegradable materials could be developed to protect agricultural products while being environmentally friendly. These nanomaterial's would decompose naturally and could be made from renewable plant-based sources, reducing the reliance on petroleum-based plastics.

iii. **Reduction of Non-Biodegradable Waste**: Nanotechnology can help reduce the amount of waste produced [20]. For example, nano-coatings on agricultural tools and machinery could extend their lifespan, and nano-reinforced composites could replace non-biodegradable synthetic materials, leading to less plastic and synthetic waste.

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume XI Issue VI June 2026

(d). Global Food Security: Large-Scale Adoption of Nanotechnology to Meet the Growing Food Demand Sustainably.

As the global population continues to rise, the demand for food will increase exponentially, and traditional farming methods may not be sufficient to meet this demand in a sustainable manner. Nanotechnology can help address this challenge by improving agricultural efficiency and enabling large-scale production of food with fewer resources.

i. **Increased Crop Yields**: The use of nano-enhanced fertilizers can lead to higher crop yields [1]. This increase in yield can help meet the growing food demand, particularly in regions with limited land and water resources.

ii. **Enhanced Nutritional Value of Crops**: Nanotechnology can be used to fortify crops [21] with essential nutrients, such as vitamins and minerals, improving food security in areas that suffer from malnutrition. Through nano-encapsulation, essential micronutrients can be delivered directly to plants, ensuring that the food produced is more nutritious and beneficial for human consumption.

iii. **Optimized Food Distribution and Storage**: Nanotechnology can help address the issue of food spoilage [19] and waste during transportation and storage. Nano-packaging materials can extend the shelf life of perishable food items, while nano-sensors can detect early signs of spoilage, preventing the loss of food during the supply chain process.

iv. **Sustainable Agricultural Practices**: Integrating nanotechnology with sustainable farming practices [18], such as precision agriculture and eco-friendly pest control, it is possible to increase food production while minimizing the environmental impact. This makes nanotechnology a critical tool in achieving long-term global food security. The deployment of nanosensor technologies enables farmers to make informed management decisions, reducing unnecessary applications of water, fertilizers, and pesticides. This enhances agricultural productivity while conserving resources and minimizing environmental impacts. The integration of nanosensors with digital agriculture and artificial intelligence platforms further strengthens sustainable farm management practices.[18].

Challenges of Nanotechnology in Agriculture.

Despite the enormous potential of nanotechnology to transform agricultural production through nano-fertilizers, nano-pesticides, nanosensors and smart delivery systems, several challenges limit its large-scale adoption.

1. **Nanoparticle toxicity to plants and soil microorganisms**: One of the major concerns is the toxicity of engineered nanoparticles to crops and beneficial soil organisms. Excessive concentrations of nanoparticles such as silver (AgNPs), zinc oxide (ZnO), and copper oxide (CuO) nanoparticles can induce oxidative stress, inhibit seed germination, reduce root growth, impair photosynthesis, and negatively affect beneficial soil microorganisms responsible for nutrient cycling. These adverse effects may ultimately reduce soil fertility and agricultural sustainability [23 &24].

2. **Environmental persistence and bioaccumulation**: The environmental fate of nanoparticles remains insufficiently understood. After application, nanoparticles may aggregate, dissolve, transform chemically, or accumulate in soils and aquatic ecosystems depending on soil properties and environmental conditions. These

transformations influence their mobility, persistence, and potential transfer into the food chain, raising concerns about long-term ecological impacts[25].

3. **Human health concerns**: Agricultural workers and consumers may be exposed to nanoparticles during production, application, or consumption of nano-enabled agricultural products. Due to their Nano scale dimensions, some nanoparticles can penetrate biological membranes, accumulate in tissues, and generate reactive oxygen species, potentially leading to inflammation or cellular damage. However, long-term human exposure studies remain limited[25] .

4. **Lack of regulatory frameworks**: Most countries lack comprehensive regulations governing the manufacture, application, labeling, monitoring and disposal of nano-enabled agricultural products. Existing fertilizer and pesticide regulations were developed for conventional agrochemicals and are often inadequate for engineered nanomaterial’s, creating uncertainty for manufacturers and end-users[24].

5**. High production and commercialization costs**: Although green synthesis has reduced manufacturing costs, large-scale production of nanoparticles still requires sophisticated equipment, quality control, purification and characterization techniques. Consequently, nano-enabled agricultural products remain more expensive than conventional fertilizers and pesticides, limiting adoption by smallholder farmers [24] .

6. **Limited field-scale validation** : Most studies on agricultural nanotechnology have been conducted under laboratory or greenhouse conditions. Long-term field experiments across different soil types, climatic regions, and cropping systems remain scarce. Therefore, the consistency of nanoparticle performance under practical farming conditions has not been fully established [25].

7. **Variable performance under different environmental conditions**: The efficiency of nanoparticles depends on particle size, concentration, coating material, soil pH, organic matter, moisture, temperature and crop species. Consequently, a nanoparticle formulation that performs well under one condition may exhibit reduced effectiveness elsewhere, making universal recommendations difficult [23].

8. **Low public awareness and acceptance**: Limited knowledge among farmers and consumers regarding the safety and benefits of nanotechnology has slowed its adoption. Concerns regarding food safety, environmental contamination and insufficient extension services contribute to public skepticism toward nano-enabled agricultural products [24].

9. **Difficulty in monitoring nanoparticles**: Detecting and quantifying nanoparticles in soil, water, and plant tissues requires sophisticated analytical techniques such as transmission electron microscopy (TEM), scanning electron microscopy (SEM), dynamic light scattering (DLS) and inductively coupled plasma mass spectrometry (ICP-MS). These methods are expensive and not readily available in many developing countries, limiting environmental monitoring [24].

10. **Standardization challenges**: There is currently no universally accepted protocol for nanoparticle synthesis, characterization, dosage, application methods, or environmental risk assessment. Differences in nanoparticle composition, morphology, and surface chemistry frequently produce inconsistent research findings, making commercialization and regulatory approval more difficult [25].

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume XI Issue VI June 2026

CONCLUSION

In conclusion, nanotechnology represents a significant leap forward in the field of agriculture. By enhancing productivity, improving efficiency and providing resilience against climate change, nanotechnology has the potential to transform the agricultural sector. While safety concerns, high costs, and public perception issues remain hurdles to widespread adoption, these challenges are not insurmountable. With continued investment in research, transparent communication, and collaborative efforts, nanotechnology can be seamlessly integrated into agricultural practices as It holds the promise of playing a pivotal role in achieving global food security and promoting sustainable agricultural practices.

Abbreviations

	Io Internet of a Things TEM Transmission Electron Microscopy DLS Dynamic Light Scattering SEM Scanning Electron Microscopy ICP-MS Inductively Coupled Plasma Mass Spectrometry
	AI Artificial intelligent

Author Contributions

Author's full name1: (Awodiran Festus Tunde) conceptualized the study, conducted the literature review and drafted the manuscript. He also coordinated the overall structure and revision of manuscript.

Author's full name2: (Kareem Saliu Adeyemi) assisted in literature collection, and critical review of the manuscript for scientific quality .

Author's full name3: (Alade Ayodele Adesoji) contributed to manuscript revision , proofreading and final validation**.**

Acknowlegement : All authors read, reviewed and approved the final manuscript and agreed to be accountable for all aspect of the work.

ACKNOWLEDGMENTS

We appreciate the guidance and valuable contributions of our supervisors and colleagues, whose insights and expertise greatly improved the quality of this work.

Funding

This review received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this review article.

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ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume XI Issue VI June 2026

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