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NANOTECHNOLOGY FOR A SUSTAINABLE FUTURE: INNOVATIONS IN AGRICULTURE AND ENVIRONMENTAL MANAGEMENT

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Abstract

Nanotechnology has come out as a revolutionary in curbing issues of world problems in agriculture and environmental sustainability. Its introduction to the agricultural industry increases the yield of crops, improves the transportation of nutrients, and offers effective control of pests and diseases. In the meantime, environmental uses of nanotechnology allow the control of pollution, wastewater treatment, as well as green remediation. Nano fertilizers, nano pesticides, and nano sensors are nano-enabled materials that help to facilitate precision agriculture, reduce losses and environmental degradations. Besides, nanomaterials have become crucial in reducing the emission of greenhouse gases as well as improving the quality of water and soil. Along with these benefits, there are still issues when it comes to the toxicity of nanoparticles, their environmental stability, and regulations. This review discusses recent developments in the application of nanotechnology in sustainable agriculture and environmental protection, with emphasis made on contemporary developments. The focus is put on the mechanisms, advantages, constraints, and perspectives to reach the UN Sustainable Development Goals (SDGs) based on nanobiotechnology-oriented solutions.

1. INTRODUCTION

The twenty-first century has posed great troubles to the world agriculture and the environment mainly because of population increase, fast urbanization, and climate change impacts. Like the population of globe is projected to attain 9.7 billion by 2050, the problem of the need to grow food supply and reduce the impact of environmental degradation is urgent (FAO, 2022). Traditional methods of agriculture, which are intensive and use chemical pesticides and fertilizers, have boosted production at the expense of soil infertility, water pollution, reduction in biodiversity, and greenhouse gases (Arora et al., 2022). Therefore, there has been an urgent need to develop sustainable agricultural systems that are sustainable in the production as well as safeguard

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the natural resources around the world. The primary promising approach to tackling these interrelated problems has been nano-technology, or the skill of dealing with materials ranging in size between 1 to 100 nanometers (Farooq et al., 2022). Nanotechnology is also used in the agricultural sector to create nanofertilizers with controlled release of nutrients, nano-pesticides to manage pests, nanosensors to detect soil nutrients and pathogens in real-time (Arora et al., 2022).

These inventions have the potential to transform the agri-food industry into a more accurate, resource-saving, and eco-friendly production industry. In addition to agriculture, nanotechnology is also important in making the environment sustainable. Examples of nanomaterials used in the cleanup of contaminated water and soils, heavy metals' extraction, and the breakdown of organic contaminants include carbon nanotubes (CNTs), zinc oxide (ZnO), and titanium dioxide (TiO_2) (Farooq et al., 2022). Nanotechnology enables biotechnology, information technology, and smart farming strategies to provide new opportunities to attain sustainable environmental management and food security (Arora et al., 2022). Nanotechnology brings about economic sustainability and ecological sustainability by increasing agricultural output, minimizing wastes, and alleviating pollution (Farooq et al., 2022). Recent studies also note that biodegradable and environmentally friendly nanomaterials should be developed to make the use safe in the long term (Pan et al., 2023). Nevertheless, even with its tremendous potential, the application of nanotechnology to agriculture and environmental uses is limited due to the fact that the toxicity, accumulation, and regulatory aspects of nanoparticles are still unclear (Arora et al., 2022). Thus, the purpose of this review is to thoroughly investigate the usage of nanotechnology in the agricultural industry and environmental sustainability, concentrating on the recent developments, and comment on the obstacles, safety concerns, and regulations.

2. Nanotechnology Applications in Agriculture

Nanotechnology has brought new horizons in the field of agriculture because it has developed the tools that serve the purposes of increasing the productivity, minimizing the environmental effects, and increasing the efficiency of the resources use. Major ones are nanofertilizers, nano-pesticides, nano-sensors, seed treatment and nano-management of post harvesting.

2.1 Nanofertilizers

Nanofertilizers are designed substances that can be used to deliver nutrient to crops in a regulated and effective way. They have been found to release nutrients slowly and gradually compared to traditional fertilizers and reduce the losses through leaching and volatilization (Arora et al., 2022). As an example, the Indian Farmers Fertiliser Cooperative (IFFCO) produced nano-urea; it proved to be more efficient in the use of nitrogen and had better crop yields at lower environmental pollution (Arora et al., 2022).

Table 1: Examples of Nanofertilizers and their Applications

Nanofertilizer Type	Active Component	Application/Benefit	Reference
Nano-urea	N (Nitrogen)	Enhances nitrogen-use efficiency	Arora et al., 2022
ZnO nanoparticles	Zinc	Corrects micronutrient deficiency	Fincheira et al., 2021 and Dimkpa & Bindraban, 2018
Fe_2O_3 nanoparticles	Iron	Promotes chlorophyll synthesis	Fincheira et al., 2021
Nano-hydroxyapatite	Phosphorus	Slow release of phosphate	Arora et al., 2022
SiO_2 nanoparticles	Silicon	Improves stress tolerance	Fincheira et al., 2021

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In the same manner, ZnO and iron oxide nanoparticles enhance incorporation of micronutrients and rectification of deficiencies in crops (Fincheira et al., 2021) (Dimkpa & Bindraban, 2018). Nanofertilizers can also be used in foliar delivery, in which nanoparticles are able to enter foliage cuticles and reach plant tissues to accelerate nutrient absorption (Fincheira et al., 2021). The strategy improves photosynthetic, root growth, and plant metabolism.

2.2 Nanopesticides

Nanopesticides are the type of formulations that involves the use of nanoparticles in enhancing the solubility, stability and targeted delivery of pesticides. They save on the amount of chemical required, and toxicity on the non-target is minimized. Silver (AgNPs) and chitosan-based nanoparticles are, as an example, effective when it comes to bacterial and fungal pathogens (Rai & Ingle, 2012). The pesticides contained in the polymeric nanoparticles (lambda-cyhalothrin or azadirachtin) are encapsulated to maintain a slow release and extended protection against the pests (Nuruzzaman et al., 2016). Notably, they minimize runoffs and erosion as compared to traditional formulations.

2.3 Nanosensors

Nanosensors allow the real time monitoring of soil nutrients, moisture, pH, and the health of crops. They act as the foundation of precision agriculture, which enables farmers to use inputs in the place and time when needed (Muhammad, Haijiao et al., 2024). Nanosensors based on carbon nanotubes (CNTs) are utilized to detect the concentration of nitrogen and phosphorus in the soil and those based on gold and zinc oxide to detect the presence of pesticide residues and pathogens (Miguel-Rojas & Pérez-de-Luque, 2023). The blend of nanosensors and artificial intelligence and Internet of Things allows making irrigation, fertilization, and pest control decisions based on data (Muhammad, Haijiao et al., 2024). Such systems enhance yield of crops, reduce wastage and encourage sustainable agricultural activities.

2.4 Nanotechnology in the treatment of Seeds and growth promotion of Plants

Nanoparticles improve the germination of seeds, resistance to disease, and stimulation of growth because they increase water and nutrient uptake (Shelar et al., 2023). ZnO or TiO_2 nanoparticle-treated seeds have a higher germination rate and abiotic stress tolerance, such as drought and salinity (Shelar et al., 2023). Nanomaterials additionally cause the stress-related genes to be expressed as well as lead to the lengthening of roots (Shelar et al., 2023). Moreover, plant hormones, growth regulators, or genetic material can be delivered with the help of nanocarriers to improve the quality of crops and their resistance (Balusamy et al., 2023).

Table 2: Key Applications of Nanotechnology in Post-Harvest Management

Nanomaterial	Application	Outcome	Reference
AgNPs	Antimicrobial packaging	Prevents microbial spoilage	Herrera-Rivera et al., 2024
TiO_2 nanoparticles	Photocatalytic films	Extends shelf life	Herrera-Rivera et al., 2024
ZnO nanoparticles	Active coatings	Maintains fruit firmness	Herrera-Rivera et al., 2024
CNT sensors	Smart packaging	Detects spoilage gases	Herrera-Rivera et al., 2024

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2.5 Post-Harvest Management

Nanotechnology also helps in minimizing the post-harvest losses through improvement of food preservation systems as well as food packaging. Films made of nanocomposite that include silver or titanium nanoparticles are highly antimicrobial thus inhibiting spoilage and shelf life (Herrera-Rivera et al., 2024). Integrated nano-biosensors in packaging may identify elements of food spoilage like ethylene gas or bacterial waste to guarantee food security and traceability (Herrera-Rivera et al., 2024).

3. Nanotechnology for Environmental Sustainability

One of the most topical problems of the twenty-first century in the world has become environmental degradation because of industrialization, excessive use of chemicals, and unsustainable use of resources. Nanotechnology offers new measures to prevent pollution and ensure that natural resources are used carefully and ensure ecological equilibrium. High surface area, catalytic reactivity, and morphology control are nanoscale characteristics, which can result in nanomaterials being useful environmental remediation and monitoring agents. The most recent trends focus on the widespread application of nanomaterials in the subsequent areas: purification of water, soil cleanup, air cleaning, and waste disposal, all serving to mitigate environmental sustainability.

3.1 Water Treatment and Water Purification

Heavy metals, pesticides and pharmaceutical contamination of water is a great threat to human health and biosphere. Nanotechnology is a way to provide cutting-edge water purification by adsorption, filtration, photocatalysis, and antimicrobial activity .Graphene oxide (GO), zinc oxide (ZnO) and Titanium dioxide (TiO_2), are nanomaterials with outstanding photocatalytic and adsorption properties, which allow decomposing stubborn organic pollutants (Shams Forruque, Mofijur et al., 2022). Copper oxide nanoparticles (CuO NPs) and Silver nanoparticles (AgNPs) can also be used due to their high antimicrobial properties against pathogens by water. Also, nanocomposites membranes with carbon nanotubes (CNTs) or graphene contribute to the increase in permeability and selectivity of the desalination and wastewater remediation systems (Shams Forruque, Mofijur et al,. 2022). The membranes are effective in extracting heavy metals, such as lead (Pb^{2+}), arsenic (As^{3+}), and cadmium (Cd^{2+}) in polluted water, thus they are essential equipment in contemporary environmental engineering.

3.2 Soil remediation and Fertility enhancement

Agricultural sustainability is becoming a major concern due to soil pollution by heavy metals and organic toxins. Nanomaterials are critical in immobilizing poisonous metals, increasing the activity of microbes, and replenishing soil fertility (Ahmed et al., 2024). Indicatively, iron oxide (Fe_3O_4) and zero-valent iron (nZVI) nanoparticles are an effective way to eliminate chromium (Cr) and cadmium (Cd) in soil, based on adsorption and redox reactions (Jawed et al., 2023). Similarly, nanoparticles that are supported on biochar enhance microbial biomass and biochemical processes in the soil, leading to healthier eco-systems (Ahmed et al., 2024). The recent studies

Table 3: Common Nanomaterials Used in Soil and Water Remediation

Nanomaterial	Application	Mechanism	Reference
TiO_2 nanoparticles	Water purification	Photocatalytic degradation of organics	Armaković et al., 2023
Fe_3O_4 nanoparticles	Soil remediation	Adsorption and redox reactions	Jawed et al., 2023
Graphene oxide (GO)	Wastewater treatment	Heavy metal adsorption	Liu et al., 2023
AgNPs	Pathogen removal	Antimicrobial activity	Shahid et al., 2023
Biochar-supported ZnO	Soil fertility restoration	Microbial activation	Ahmed et al., 2024

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have been interested in green-synthesized nanoparticles with plant extracts or agricultural wastes, to make them ecologically safe. The nanomaterials produced using such environmentally friendly substances are naturally decomposed, reducing the risk of secondary pollution (Gebre, 2023).

3.3 Air Pollution Control

Nanotechnology in air pollution control entails filtration, catalysis and sensing. Catalytic converters incorporate nanocatalysts including TiO_2, CeO_2 and MnO_2 nanoparticles to catalyze the degradation of nitrogen oxides (NO), carbon monoxide (CO), and volatile organic compounds (VOCs) (Ali et al., 2021). Nano-fibers that have been manufactured through electrospinning, in particular those containing metal oxides, are used in air filters to trap small particulates ($PM_{2.5}$ and PM_{10}) (Haleema, Syed Javaid et al., 2022). Moreover, nanosensors allow the real-time air quality monitoring of toxic substances such as ozone, ammonia, sulfur dioxide, etc., at very low levels (Haleema, Syed Javaid et al., 2022). Incorporation of nanosensors into smart systems helps in early warning systems to the management of industrial and urban air quality.

3.4 Waste Management and Circular Economy

Nanotechnology has been helping in sustainable waste management through recycling, recovery, and conversion of wastes to useful products. The nanocatalysts can transform plastic and organic waste into fuels and chemicals that are useful (Dermatas et al., 2018). Furthermore, the agricultural residues produce nanostructured adsorbents that are useful in the removal of industrial effluents and can be used to facilitate a cyclical bioeconomy (Dermatas et al., 2018). Magnetic nanoparticles (MNPs) are also used to reclaim heavy metals and dyes in wastewater treatment plants to minimize the use of resources (Dermatas et al., 2018). Similarly, chitosan or cellulose-based nano-enabled biosorbent exhibits superior performance in the removal of pollutants using low amounts of energy.

3.5 Nanotechnology to Climate-resilience

Indirectly, Nanotechnology can help mitigate climate change by enhancing the ability to capture carbon, renewable energy systems, and reduction of greenhouse gases. Graphene and CNTs are carbon-based nanomaterials that have an outstanding potential in CO_2 adsorption (Mustafa, 2026). Nano-coatings on solar panels and wind turbine parts can help improve their efficiency and efficiency and prolong their lifespan, help them transition to clean energy systems (Mustafa, 2026). In the farming sector, nanomaterials can be used as a way of minimizing the release of nitrous oxide caused by the use of fertilizers and enhancing the ability of soils to store carbon (Arora et al., 2022).

4. Safety, Toxicity, and Regulatory Aspects

Although nanotechnology has immeasurable opportunities in the agricultural sector as well as environmental sustainability, the issue of the possible hazards of nanotechnology on human health, soil ecology and ecosystems have become a major topic in the past few years. The small diameter, high reactivity and surface energy of nanoparticles which contribute to their functionality also casts doubt over its safety, bioaccumulation and environmental fate. Sustainable innovation of nanomaterials requires responsible and ethical use of nanomaterials.

4.1 Nanotoxicity and Biological Effects

Nanomaterials are toxic based on their size, shape, surface charge, solubility, and concentration (Lowry et al., 2019). Nanoparticles are able to enter biological membranes, cross blood-brain barrier and accumulate in organs, which may cause oxidative stress, DNA damage, and inflammation (Nel et al., 2009). To provide an example, silver nanoparticles and zinc oxide nanoparticles have been demonstrated to possess a high level of antimicrobial activity, yet high concentrations may disrupt positive microbial activity in soil and enzyme mechanisms (Kah et al., 2018). Nanoparticle exposure can influence photosynthesis, chlorophyll level and root length in the plants depending on dose and the type of

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metal (Rastogi et al., 2017). The small amount of nanoparticles can result in growth and stress resistance, and the large amounts can cause cytotoxicity and genotoxicity (Rastogi et al., 2017). Research has cited that TiO_2 and CeO_2 nanoparticles are capable of producing oxidative damage in the plant tissues by forming reactive oxygen species (ROS) (Rastogi et al., 2017). In addition, nanoparticles can get into the food web via plant absorption and distribution to greater trophosomes. When incorporated into the living systems they can interact with biomolecules distorting cell signaling and protein functions (Lowry et al., 2019). Thus, the long-term risks can be studied by evaluating nanomaterial exposure by analyzing acute and chronic toxicity tests.

4.2 Environmental and Ecological Neighborhood Hazards

Nanomaterials may also be retained in the soil and water systems in the environment, where they interact with organic matter, minerals and microorganisms (Kah et al., 2018). The interactions affect their mobility, change and bioavailability. Fe_3O_4 and TiO_2 engineered nanoparticles are capable of aggregating and modifying the soils structure, which in turn influences the interactions between plants and microbes and nutrient cycling (Kah et al., 2018). Aquatic habitats are the most susceptible as nanoparticles may be carried through runoffs or waste water. It has been revealed that AgNPs and CuO nanoparticles can cause oxidative stress emergence in aquatic organisms such as algae, fish, and crustaceans (Lowry et al., 2019). Moreover, nanoparticles also have secondary exposure risks to human beings and animals as a result of bioaccumulating in aquatic food webs (Lowry et al., 2019). Considering these possible ecological consequences, the use of green synthesis and biodegradable nanomaterials is a necessity, and it degrades without risk and provides the minimum pollution in the long term (Kah et al., 2018).

4.3 Human Health Concerns

The physical contact of humans with nanoparticles could happen during the manufacturing process, or when using infected food and water (Lowry et al., 2019). The most common methods of exposure are inhalation, dermal contact and ingestion. The laboratory research has shown that inhaled nanoparticles can lead to respiratory discomfort and pulmonary inflammatory processes (Nel et al., 2009). Systemic circulation of nanoparticles might also cause cardiovascular and neurological problems in case of chronic exposition (Donaldson & Poland, 2013). It should, however, be noted that most of these results are based on laboratory models with concentrations that are more than those that are experienced in the real environment. In this way, special caution is needed to apply the results to the situation in the field with the help of the life-cycle assessment (LCA) and risk-benefit analysis (Lowry et al., 2019).

4.4 Regulatory Frameworks and Risk assessment

On the international level, different agencies have launched systems of controlling nanomaterials with most of them still in a developing stage. The EFSA and EPA of U.S., have documented the regulations to define the safety of nanoparticles in agriculture and the environment (EFSA Scientific Committee, 2021; U.S. EPA, 2022). The REACH regulation on nanomaterials built by the European Union currently has labeling, toxicity testing, and environmental impact assessment nano-specific provisions (ECHA, 2022). Even in developing countries such as Asian countries, the regulatory environment is still underdeveloped, and there is a necessity of standard methodologies to assess the nanomaterial behavior in the local ecosystems (Lowry et al., 2019). Data sharing and harmonized safety standards can be supported with the help of the creation of nanotoxicity databases and international cooperation.

4.5 New Towards the safe and sustainable nanotechnology

Safe-by-design principles are the future of nanotechnology, and they combine safety concerns throughout the entire design process, including synthesis, use, and disposal (Wang et al., 2026). There is a growing interest in biogenic nanoparticle synthesis with the help of microorganisms, plants, or natural polymers

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which are environmentally friendly (Shah et al., 2025). Moreover, life-cycle assessment (nLCA) methods are applied to forecast the environmental impact of the use of nanoproducts during their use period and post-use degradation (Ramadan et al., 2024). The establishment of international regulatory agreement and creation of awareness initiatives to the population will be a significant step in fostering trust and making sure that nanotechnology is applied ethically and sustainably in the fields of agriculture and the environment.

5. Future Prospects and Challenges

Nanotechnology has already become a revolutionary device in sustainable agriculture and environmental security but its usage on a large scale has yet to be comprehensively addressed with a number of scientific, ethical, and regulatory issues. With the world agricultural systems trying to balance between the productive and the sustainable, nanotechnology provides a new avenue of growth, though in case it is safe, affordable and environmentally friendly.

5.1 Nanotechnology in Agriculture: New Sideways

The latest developments have put emphasis on biogenic and functionalized nanomaterials, which exhibit less toxicity and specificity as opposed to the traditional engineered nanoparticles (Lowry et al., 2019). Due to the polymer-coated nanofertilizers and stimuli responsive nanosystems, the nutrient release can be controlled according to the environmental factors (soil pH or moisture) (Kah et al., 2018). In the same way, smart sensors embedded in irrigation systems will be able to track the health of a plant, nutrient levels and soil parameters in real-time (Pérez-de-Luque, 2017).

Precision agriculture along with artificial intelligence (AI) will facilitate the use of nanotechnology to help farmers develop decisions that are made based on data to maximize fields and minimize losses (Mohd, Abid et al. 2022). In addition, nano-enabled CRISPR systems and gene delivery nanocarriers are creating a new horizon in crop enhancement, which offers efficient and non-viral viral gene editing (Demirer et al., 2019). It is also likely that the future of agriculture will be based on multi-functional nanocomposites which can deliver nutrients, monitor pests, and detect the environment, all on the same platform (Lowry et al., 2019). These combined systems will be a leap towards smart farming systems that will foster productivity and environmental sustainability.

5.2 Environmental Nanotechnology: To a Circular Bioeconomy

The field of environmental nanotechnology is progressing at a fast pace towards a circular and regenerative bioeconomy (Mohanta et al., 2026). Nanocatalysts are novel and better at degrading persistent organic pollutants, and graphene-based nanomembranes are becoming more efficient at purifying water (Ali, 2024). Magnetic nanocomposites are also easy to recover and reuse after adsorbing the contaminants, and secondary wastes are not produced (Yang et al., 2025). Moreover, carbon capture materials, including metal-organic frameworks (MOFs), are in development as nano-enabled to capture CO_2, which is emitted by industries, and can be utilized to reduce the outcomes of change in climate (Mittal et al., 2024). The green synthesis strategies, which apply plant extracts or microbial systems, are also ensuring that production processes comply with the principles of sustainability (Nikam et al., 2025). Nevertheless, to switch to large-scale environmental nanotechnology, it is necessary to engage nanoscientists, agronomists, environmental engineers, and policymakers (Dabare et al., 2025). A combination of these technologies and renewable energy systems can also be used to encourage a low-carbon, energy-saving society.

5.3 Implementation Problems with Large-Scale Implementation

Although nanotechnology has promising results in labs, in the field level, there are several challenges to its implementation. Other significant bottlenecks are cost-effectiveness, scalability and regulatory uncertainty (Kah et al., 2018). The

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production of nanomaterials with a consistent quality and stability at the industrial scale is also a technological problem (Lowry et al., 2019). In the developing world, the infrastructure is limited, and skilled human resources are not widely available (Lowry et al., 2019). The farmers must also be well trained and sensitized on effective use of nano-enabled products safely. In addition, the problem of the perception of the word nano in society may cause distrust in people and impede the adoption (Satterfield et al., 2009). This is further complexified by the lack of a common world regulatory framework. Although such organizations like the FAO, EPA, and EFSA have presented the first guidelines, there is yet to be a unified approach to toxicity testing or environmental risk assessment that can be applied to all types of nanoparticles (EFSA Scientific Committee, 2021; U.S. EPA, 2022).

5.4 Research gaps and Future directions

Future studies need to focus on to achieve the maximum potential of nanotechnology in sustainable agriculture and environment.

1. Mechanistic insights into nanoparticle-plant-microbe interactions in order to achieve efficiency and reduce toxicity (Zaman et al., 2025).
2. Preparation of bio-degradable nanomaterials with natural polymers, i.e., chitosan, cellulose, lignin (Mosavikia et al., 2020).
3. The life-cycle analysis (LCA) of the total sustainability and carbon footprint of nanoproducts (Ramadan et al., 2024).
4. Mathematical modeling of prediction of the transport, transformation, and persistence of nanoparticles in ecosystems using data (Wang et al., 2024).
5. Partnerships between the public and the private in the context of scaling up innovation by funding, educating, and transferring technology (Ogwu & Kosoe, 2025).

These gaps can be bridged by nanotechnology, which can be made a pillar of sustainable intensification and can be able to produce more yields and cleaner environment without damaging the natural resources.

5.5 Vision for the Future

The vision of nanotechnology at long term is to construct climatically smart, resource efficient and resilient agro-ecosystems (Lowry et al., 2019). Nanotechnology is also expected to be used together with synthetic biology, IoT-based sensors, and renewable energy networks in the future to form an autonomous agricultural network to maximize production without depleting biodiversity (Pérez-de-Luque, 2017). The way ahead needs to take into consideration the fact that innovation should not be ahead of safety. The interactive systems between researchers, regulators and the people will be key in creating credibility and making nano-enabled solutions fair in the global arena. Responsible use of nanotechnology in other words is not only a technological change but an ethical promise to the future generations - to do more and less and maintain the ecological balance of the planet.

6. Conclusion and Future Recommendations

Nanotechnology has proved to have an enormous potential of transforming agriculture and environmental management as it creates the possibility of sustainable, efficient and accurate solutions. Nanofertilizers improving the efficiency of nutrient use to nanopesticides that reduce the amount of chemical wastes, nano-based interventions are changing the traditional farming method into a more resource wise and environmentally friendly one. Equally at the environmental system level, nanomaterials are also being used to control pollution, treatment of waste water and soil repair using sophisticated adsorption, catalysis, and sensing processes. All these technologies are in line with the global sustainability agenda, especially SDG 2, SDG 6 and SDG 13 (FAO, 2022). But even with such success there are scientific and economic, and regulatory hitches when it comes to adopting nanotechnology in large scale. The complexity of nanomaterials behavior in the living systems and ecosystems casts doubts on the possibility of bioaccumulation, toxicity, and the long-term effects. Recent studies also do not have a coherent view of the interaction of nanoparticles with plants and microbes in different field scenarios (Lowry et al., 2019). On the same note, risk assessment and trust of the people cannot be made in the face of uneven international regulatory frameworks, paucity of field data, and standardization (Lowry et al., 2019; EFSA Scientific Committee, 2021). The way to sustainable nanotechnology should involve a combination of innovation and safety and ethics. The next generation of nanomaterials should be biodegradable and biogenic and synthesized by green methods relying on renewable biological synthesizing agents such as microorganisms, plant extracts, and natural polymers (Rajput et al., 2025). These green materials have similar functionality at a lower environmental persistence. Simultaneously, a life-cycle assessment (LCA) should become a standard component of nanoparticles design, and production, usage, and disposal need to produce ecological footprints as minimal as possible (Ramadan et al., 2024).

In addition, multi-disciplinary teamwork will be required. To bring the research of nanotechnology into practical and safe application, scientists, policymakers, agricultural engineers, and farmers should collaborate. Capacity building, public awareness and farmer training programs can also be positively invested in to hasten adoption particularly in developing nations. Increased transparency and accountability can also be achieved by setting up international databases of nanoparticle safety and developing global harmonized guidelines (EFSA Scientific Committee, 2021). In the future, integrative systems that integrate nanotechnology with synthetic biology, Internet of Things and artificial intelligence are expected to have an important part in the future of nanotechnology in the agricultural and environmental sustainability (Mohd, Abid et al. 2022; Lowry et al., 2019). It is the convergence of this that will allow instant tracking of soil, water and health of crops- supporting data-directed, adaptive management strategies. To sum up, nanotechnology is a disruptive innovation between innovation and sustainability. It can be defining in terms of climate-resilient agriculture and healing global environmental health with accountable governance, moral innovation and unremitting interdisciplinary cooperation. How well humanity can utilize the nanoscale to guarantee food security, environmental resilience, and sustainable prosperity in future generations, will be determined in the next decade.

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