Nanotechnology in Agronomy for enhancing Soil Health and Crop Yield: A Review

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Abstract: Nanotechnology is revolutionizing agronomy through interventions in precision agriculture aimed at improving soil condition, productivity, and sustainability. The present review considers the latest progressions made within the field, both good and bad, in the realm of nano-techniques within agriculture such as nanofertilizers, nanopesticides, nanosensors, and the fact that smart delivery systems do exist. It is the peculiar physicochemical nature of manufactured nanomaterials, which includes such features as large surface areas, different degrees of reactivity and even regulated release characteristics that facilitate soil decomposition, nutrient efficiency, and reduced loss of agrochemicals. Recent scientific findings show the possible impact of nanofertilizers on the increased bioavailability of macronutrients and micronutrients, along with the decreased rate of nitrogen fixing and volatilization. Nanotechnologies in crop protection enable effective biological regulation with low levels of chemical substances involved. The current review also stresses the importance of nano-sensors and nano-biosensors for precision farming because these devices enable real-time monitoring of nutrient content in soil, soil moisture, abiotic stress conditions, and even pathogens that indicate soil contamination. The use of nano-remediation techniques based on the use of reactive nanoparticles is shown to yield good results in detoxification of contaminated soils and bringing soil life back to normal. However, the issue of persistence and ecotoxicology of nanoparticles should not be ignored.This review emphasizes the significance of safe-by-design nanomaterials, biodegradable delivery systems, and standardized approaches to assessing risks to ensure environmental and food safety. This study presents a comprehensive framework to facilitate the adoption of nanotechnology in agricultural applications through the combination of agronomic benefits, soil condition indicators, and ecotoxicity, as well as future technological integration with artificial intelligence and Internet-of-things (IoT). The results emphasize the potential of nanotechnology to help develop climate-resilient and sustainable agriculture.

Keywords: *Nanotechnology, Crop Productivity, Environmental Sustainability, Nano Fertilisers, Nano Pesticides, Soil Health, Nutrient Use Efficiency.*

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I. INTRODUCTION

Due to climate change, soil erosion, and food security, there are new challenges in the agricultural food industry at a global level. The current world population is estimated to reach 9.7 billion by 2050, and therefore new innovations must be introduced in agriculture to increase its production efficiency (United Nations, 2022). Farming, as practiced for many years, has used fertilizers and pesticides that are synthetic, resulting in degradation of the soil nutrients, contamination of the groundwater, and reduced microbial biodiversity (Hina et al., 2024). Given such circumstances, nanotechnology has proven to be a potential solution to the problem, where it has helped in improving NUE, preventing loss of agrochemicals, and promoting soil health (Mgadi et al., 2024). Nanotechnology, which entails the production and utilization of matter at the nano-level (1 to 100 nm), has reenergized multiple fields of study, namely electronics, medicine, and energy (Desai et al., 2025). The advent of nanomaterials especially in agronomy has provided various chances in solving emerging challenges through innovative soil and crop management techniques (Singh et al., 2023). Environmental challenges such as degradation of soil fertility and poor utilization of nutrients are among some of the challenges facing current global agricultural production systems that aim at meeting the demands of an estimated nine

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billion people by 2050 (Paz et al., 2024). With respect to this, the use of nanotechnology in agronomy could be viewed as a major breakthrough. While there have been significant gains made in improving the productivity of agriculture, the current intensive systems of agriculture have depended on chemical fertilizers and pesticides extensively, which lead to negative consequences such as reduced microbial activity, reduction in soil organic matter, pollution of water bodies, and unbalanced nutrients. Nanotechnology-based smart agriculture input allows optimized nutrient usage, waste reduction, and reduced use of agrochemicals due to precision design and delivery systems. Nanomaterials possess distinct physicochemical characteristics, such as high surface area to volume ratio, increased reactivity, and controlled solubility, which make them applicable in various agro-scientific uses. Such uses can include nanofertilizers, which deliver nutrients in a controlled and targeted manner, nanopesticides that minimize the use of chemicals and enhance efficacy in controlling pests, and nanosensors that can detect any form of stress, nutritional deficiency, and attack by pathogens on crops (Chaudhary et al., 2025). Out of all the uses, nanofertilizers have proved quite promising in increasing nutrient absorption efficiency and minimizing losses due to leaching, volatilization, and fixation (Abdel-Hakim et al., 2023). Nanotechnology is similarly significant in promoting healthy soils and efficient production of crops using nanoremediation technologies. Nanoparticles that react with the toxic heavy metals, pesticides, and other forms of contaminants in polluted soils are used. Moreover, nanotechnology affects microbial diversity, enzymatic reactions, micronutrient content, and microbes that contribute to soil fertility. The use of nanoclays and carbon-based nanomaterials enhances the structural integrity, porosity, and moisture retention capacity of soils, which are important factors for developing roots and enhancing crops' resistance to abiotic stresses (Del Prado-Audelo et al., 2021). While nanotechnology offers these benefits, its incorporation in agronomy still encounters several obstacles associated with nanoparticle-plant interactions, complexity of soils, microbiome responses, toxicity, persistence, bioaccumulation, and transfer through the food chain. This study will thus focus on offering an extensive review of how nanotechnology can be applied to agronomy, particularly on its use for improving soil health and increasing crop production, through highlighting current developments, experimental field studies, mechanisms involved, and future research frameworks.2.

II. ADVANCEMENTS AND EMERGENCE OF NANOTECHNOLOGICAL INNOVATIONS IN CROP PROTECTION AND SOIL HEALTH

Nanotechnology has provided innovative ways to protect crops and ensure soil health, hence enabling important strides in making agricultural practices sustainable. Nano-based technologies incorporating metal nanoparticles (such as ZnO, Ag, and Cu) as well as nanocapsules made of polymers are providing innovative approaches for managing pests and pathogens in crop protection. Silver nanoparticles have shown potent antifungal and antibacterial properties, leading to a reduction in the number of pathogens in plants such as rice and wheat by more than 50 percent, while minimizing the levels of chemicals in the process (Jo et al., 2022). Likewise, nano-based pesticides that employ carriers like chitosan or silica provide controlled-release methods, leading to improved efficacy of pesticides by 30-50 percent (Kah et al., 2019). Innovations in RNA interference technology using either clay nanotubes or lipid-based nanoparticles for the delivery of dsRNAs for gene silencing have been very specific in targeting pests without any negative impact on beneficial insects (Zhang et al., 2023). Nanomaterials have been used to develop precision agriculture by employing quantum dot- or gold nanoparticle-based nanosensors that enable real-time monitoring of pathogens and pest infestations in the soil (Thakur et al., 2025). The dual benefits provided by nanotechnology not only help in the cleaning of soil but also ensure better nutrient absorption without affecting the health of soil. For example, toxic elements like arsenic and cadmium can be immobilised using nanoscale zero-valent iron (nZVI), thus limiting their availability by 60% (Chen et al., 2022). Carbon nanomaterials like graphene oxide are useful for improving soil porosity and moisture content while fostering microbial diversity in the rhizosphere (Chen et al., 2025). The efficiency of nanofertilizers such as hydroxyapatite and zinc oxide nanoparticles has been shown to be higher (by 20-40%) than that of other chemical fertilizers when used for delivering phosphorus and micronutrients (Noruzi et al., 2023).

Nevertheless, issues related to ecotoxicity and bioaccumulation have posed considerable challenges to the use of nanotechnology in agriculture. In addition, risk assessment and strong legislation are needed to ensure safety in the implementation of this technology (Bouhadi et al., 2025). Therefore, current research trends involve the synthesis of degradable nanoparticles and AI-enhanced smart delivery systems, which will be beneficial in improving eco-sustainability (Elsayed et al., 2025). In conclusion, nanotechnology holds an integral part in creating agriculture systems that can withstand climatic change, while operating efficiently.

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Table 1 Effect of Nanofertilizers on Soil Health Indicators

Nanofertilizers type	pH	Organic matter dynamics	Microbial biomass	Soil enzymatic activity	Nutrient availability	Key citations
Nano-N (e.g., nano-urea)	Slight decrease in pH is seen in alkalic soils upon addition of the solution, while neutral soils do not show any change in the pH level due to high buffer action	Increased SOC and organic C via greater root exudate and residue inputs.	Increases total microbial biomass C (MBC) Promotes beneficial bacteria (e.g. Actinobacteria, Proteobacteria) at 75-100% recommended rate	Increases dehydrogenase, phosphatase and urease Dose-dependent (best at moderate rates)	More N, P, Zn available; 25-30% less leaching than conventional	Balusamy SR et. al., (2023)
Nano-P (e.g., nano-hydroxyapatite, nano-phosphate)	Stabilises pH otherwise; slight acidification in high-P soils	Increases C stabilisation and organic matter breakdown	Encourages Pseudomonas and other phosphate-solubilising bacteria and promotes greater fungal diversity	Stimulates activities of β-glucosidase, phosphatase, and FDA hydrolase	Improves P solubilization (2-3x greater available P) and less fixation	Corradini E et al., (2018)
Nano-K (e.g., nano-potash, zeolite-encapsulated)	Less impact; buffers against extreme shifts	Enhances organic C retention through better aggregation	Promotes K-solubilising microbes; no significant biomass reduction	Increases cellulase and invertase; supports C-cycling enzymes	Increases exchangeable K by 20–40%; sustained release	Haydar MS et al., (2024)
Nano-micronutrients (e.g., nano-ZnO, nano-Fe, nano-CuO)	Dose-dependent: large doses acidify, whereas low amounts stabilise	Enhances humification and OM quality	Rhizospheric diversity is stimulated at low doses and inhibited at >100 mg/kg.	Increases urease, catalase, and peroxidase at ideal dosages; toxicity at high concentrations	Increases the bioavailability of Zn, Fe, and Cu by 1.5–2 times; chelation effects	Haydar MS et al., (2024)
Nano-biofertilizers (e.g., nano-encapsulated Rhizobium, nano-zeolite with microbes)	Uses organic additions to stabilise or slightly raise pH	Increases labile OM and C: N ratio	Most importantly boosts microbial biomass (20–50% increase); enhances diversity.	Uplifts dehydrogenase, nitrogenase, phosphatase (up to 2x)	Synergistic: N-fixation and P-solubilization improve NPK availability	Mgadi K et al., (2024)

III. UTILIZATIONS AND APPLICATIONS OF NANOTECHNOLOGY IN AGRONOMY

Nanotechnology has emerged as a strategic technology for use in agronomy. It provides new ways of working in agronomy that contribute to the improvement of soil condition and increase the productivity of crops and efficiency of resource utilization. The people involved in agriculture can develop inputs through nanotechnology, which improves their performance and accuracy through the use of materials at the nanometer scale (1–100 nm). These developments help achieve the goals of sustainable agriculture.

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Table 2 Nanoparticle Application Methods in Crop Production

Application methods	Main advantages	Key limitations/risks	Suitable nanoparticle types	Key citations
Seed priming (nano-priming)	At low NP dosages, seed coverings containing nanoparticles increase germination, seed vigour, and early seedling growth. frequently requires very little amounts of NPs, which lowers the danger of toxicity and input costs.	limited "safe window" of concentration; greater dosages may hinder root development and germination. mostly helps in the early stages; follow-up diet determines the consequences on subsequent growth.	ZnO, Fe2O3, CuO, MnO, and TiO2 are metal/metal oxide nanoparticles (NPs) for strength, micronutrient supply, and stress endurance.For early N supply, use nano urea or nanofertilizers containing N. Low dosages of some Ag or Cu NPs can inhibit seed-borne diseases.	(Balusamy SR et al., 2023; Mgadi et al., 2024)
Foliar spray	Direct and quick distribution to leaves; avoids leaching and soil fixation. beneficial for reducing abiotic stress and addressing vitamin deficits.	Higher quantities or more frequent sprays carry the risk of oxidative stress and leaf phytotoxicity. Drift and exposure to non-targets (environment, workers, beneficial insects).	ZnO, Fe, Mn, Cu, B, and Mo nanofertilizers are examples of soluble or dispersible nanomineral nutrients.Lipid or polymeric nanocarriers for regulated or gradual foliar nutrient release. Cu, Ag, and SiO_2-based nanopesticides are used to control insects and diseases.	(Sheikhalipour et al., 2023; Toksha et al., 2025)
Soil amendment/soil application	Improves use efficiency and lowers application frequency by enabling controlled and gradual nutrition release. When carriers are well-designed, it can improve soil structure, rhizosphere nutrient availability, and root growth.	Direct exposure of soil biota; long-term buildup may change soil fauna and microbial communities. Inadequate formulation control may result in migration to non-target compartments or leaching to groundwater.	Nutrient-loaded hydroxyapatite, clay, silica, or polymeric carriers are examples of slow/controlled release nanofertilizers. NPK formulations that are nanocapsulated (such as urea-loaded nano matrices) for long-term delivery. To reduce direct exposure to free NPs, metal/metal oxide NPs (Fe, Zn, Mn, etc.) are embedded in stable matrices.	(Corradini et al., 2018; Haydar et al., 2024)
Fertigation (nanoparticles in irrigation water)	In drip or sprinkler systems, precision dosing and timing are made possible by the simultaneous supply of water and nanonutrients. superior spatial homogeneity compared to manual soil application and possible decrease in overall fertiliser consumption.	High colloidal stability is necessary because precipitation or aggregation can block emitters and decrease uniformity. NP mobility and off-site transfer in drainage water may rise as a result of poor management.	N, P, K, and micronutrient nanoformulations that are extremely stable and water-dispersible (e.g., nano urea, nano phosphate, nano Zn).Inorganic and polymeric nanocarriers intended for regulated release in areas of wet soil.	(Haydar et al., 2024; Toksha et al., 2025)
Hydroponic/soilless application	Exact control over NP concentration and exposure duration; perfect for high-value crops and mechanistic research. Nutrient utilisation efficiency and absorption kinetics can be quite high at low doses since there is no soil fixation.	If the concentration is not precisely optimised, direct contact between roots and NPs raises the danger of root toxicity. Spent nutrient solutions need to be carefully collected and treated since they may contain NPs.	ZnO, Fe, Mn, and Cu are examples of soluble or colloidally stable nanomineral nutrients for accurate dosage. Biocompatible lipid or polymeric nanocarriers to release nutrients gradually in recirculating systems. created nanomaterials for distribution or sensing (e.g., nano chelated Fe for chlorosis management).	(Balusamy SR et al., 2023; Mgadi et al., 2024)

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➢ *Nano-Fertilizers for Enhanced Nutrient Use Efficiency*

Nano-fertilizers are designed on the basis of nanoparticles. This provides a sophisticated, precise, and efficient system that facilitates the accurate delivery of fertilizers. Nanofertilizers can help farmers in applying the right amount of fertilizers to crops in order to optimize the yield and reduce the adverse effects of using fertilizers on the environment. The key factor behind the advantages of using nanoparticles is the properties of nanofertilizers such as high surface area to volume ratio.In contrast to traditional fertilizers, the nanofertilizers derived from zeolites and hydroxyapatite have provided considerable outcomes for delivering beneficial macronutrients like nitrogen and phosphorus. The role of nanomaterials in improving nutrient retention and release is essential for ensuring plant growth and reducing the cost of fertilization (Pilotto et al., 2024). The most effective method and mechanism of nanofertilizers is through the process of nutrients being encapsulated in nanoparticles. This enables the gradual introduction of nutrients in response to cues in the environment such as pH levels, moisture levels in the soil, and root exudates. The small size of the nanoparticles also ensures that they maintain mobility within the soil and are close to the root surface, which results in enhanced nutrient absorption by the plants' roots. Besides, the role of the nanomaterials like hydroxyapatite is to serve as carriers of nutrients and sources of phosphorus. All in all, nanofertilizers offer great promise towards sustainable agriculture to meet the demands of crops for nutrients without harming the environment.

➢ *Nano-Pesticides and Nano-Insecticides*

The nano formulations, as a result of the incorporation of active pesticides such as nanoparticles of polymers, nano-emulsions, and metals like zinc oxide (ZnO) and titanium dioxide (TiO2), contribute significantly to the development of nanopesticides as the main tool in the protection of crops. Owing to their unique characteristics, nano formulations enable greater effectiveness in pest management by increasing stability, solubility, and specificity. This increases the efficiency of the treatment process while using less chemicals. These energetic molecules contained in the nanoparticles facilitate proper dispersal and release of the formulation, thereby increasing their effectiveness and decreasing application rates. One major example of using silica nanoparticles in plants to destroy insects using the physical action mechanism.

➢ *Mechanism of Nanoparticles in enhancing soil health and crop productivity*

The incorporation of active components of pesticides into nanoparticles, nanoemulsions, metal oxides, such as ZnO, TiO2, and others makes the nanopesticide be known as a key component of crop protection. Because of numerous advantages, the nano formulation helps improve the stability, solubility, and target specificity, resulting in increased effectiveness of pesticides, along with reduced amounts of chemicals used. The energy-containing components in nano formulations help in the process of dispersal and controlled release of pesticides, increasing their longevity and decreasing the application frequency. An important application of nano silica in crops is associated with the damage to insect cuticles, achieved through the physical action and decreased use of chemical insecticides (Zeng, Y. L. & Motola, M. 2025).

Table 3 Mechanism of Different Nanoparticles in Promoting Soil Health and Crop Productivity

Mechanism	Description	Effects on soil health	Effects on crop productivity	Key citations
Controlled nutrient release	Nanocarriers (polymers, silica, hydroxyapatite) enable slow/controlled release matching crop demand, reducing leaching/runoff by 20–50%.	Improves nutrient retention, reduces soil acidification from excess fertilisers.	Increases nutrient use efficiency (NUE) by 25–80%; boosts yield 10–40%.	**(Dimkpa et al., 2020; Raliya et al., 2021; Kah et al., 2021)**
Enhanced root absorption	High surface area and small size (1–100 nm) facilitate direct root uptake and translocation via xylem/phloem.	Stabilises soil structure, enhances rhizosphere nutrient cycling.	Improves photosynthesis, chlorophyll content; 15–30% higher biomass.	**(White et al., 2021; Liu et al., 2022)**
Microbial community modulation	Stimulates beneficial microbes (PGPR, phosphate-solubilisers) while inhibiting pathogens at optimal doses.	Increases microbial biomass C by 20–50%, enzyme activity (dehydrogenase, phosphatase).	Enhances N-fixation, P-solubilization; symbiotic effects boost yield 20–35%.	**(Ge et al., 2023; Kah et al., 2021)**
Stress tolerance induction	Nano-ZnO, nano-SiO2 trigger ROS scavenging, osmolyte accumulation, and hormonal signalling.	Buffers pH extremes, enhances water retention via better aggregation.	Mitigates drought/salt stress; 20–50% higher yield under stress.	**(Dimkpa et al., 2020; White et al., 2021)**
Improved soil structure and aggregation	Carbon nanotubes and nano-clays promote macro-aggregate formation and water infiltration.	Increases organic C stabilisation, reduces erosion, better aeration.	Enhanced root growth, nutrient access; 10–D30% productivity gain.	**(Kah et al., 2021; Liu et al., 2022)**

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- *Smart Delivery Systems*

Intelligent nanocarriers have been developed as smart delivery devices that deliver agrochemicals such as pesticides and fertilizers upon the occurrence of certain ecological stimuli such as temperature, moisture levels in the soil, pH value or enzyme activity in the soil. These nanocarriers are made up of degradable polymeric materials such as chitosan, alginate, and PLGA, which enable timely delivery and increase the efficacy of nutrient uptake while minimizing adverse effects on other forms of life. The smart approach involved in designing these nanocarriers minimizes both application frequency and costs since the delivery of agrochemicals is determined by the requirements of the plants and pests at certain times.

- *Nanotechnology in Soil Remediation*

The newly designed engineered nanomaterials, including zero-valent iron (nZVI), titanium oxide (TiO2), and graphene oxide, act as effective media in the management of contaminated soils due to their ability to adsorb, degrade, and immobilize pollutants such as heavy metals and pesticides. The attributes of the nanomaterials, using the bottom-up strategy, the reactivity and catalytic capabilities, allow the materials to interact efficiently with the contaminants through redox reactions, adsorption, and degradation. For instance, nZVI reduces and minimizes toxic metals such as arsenic, chromium, and lead to less dangerous compounds (Komárek et al., 2024), whereas TiO2 and graphene oxide facilitate the breakdown of organic contaminants.

- *Enhancement of Soil Microbial Activity and Structure*

Some nanomaterials, especially silicon and carbon-based nanoparticles, have shown promising properties in positively affecting soil microorganisms by aiding in improving the health of the earth as well as crop yields. The beneficial microbes in the soil include mycorrhizal fungi and nitrogen-fixing bacteria and phosphate solubilizers. These microbes play an important role in the decomposition process, nutrition cycles, and resistance against diseases. The environment created by nanomaterials such as silicon and carbon-based nanoparticles allows for improved growth and activity of beneficial microorganism populations. For instance, the usage of silicon nanoparticles increases the availability of silicon not only to the plant but also to soil microbes, thereby promoting plant-microbe interaction and facilitating microbial-mediated mineral transformations. Similarly, other carbon-based nanoparticles like fullerene and nano-biochar have proved effective in stimulating the growth and diversity of the population (Jiang et al., 2023).

In addition to microbes, nanomaterials like nano-clays and nano-biochar have been proven to enhance soil structure physically. The use of these nanomaterials helps in soil aggregation, hence resulting in increased aeration, water infiltration, and easy root penetration. Nano-biochar has proved to be extremely beneficial in sandy soils since its application is very effective in retaining moisture, preventing nutrient loss, and ultimately creating an environment favorable for growth. The application of these nanomaterials enables a more sustainable agricultural practice due to the improvements made both physically and biologically. In general, the use of these specified nanomaterials proves to be a strategic method towards improving soil ecosystems.

- *Nano sensors and Nano biosensors for crop protection and soil health*

Nanobiosensors and nanosensors are recent advancements that have brought innovation to precision agriculture by allowing real-time monitoring and detecting biotic and abiotic stresses in a manner that improves soil quality and protects crops from stress factors. Many variables, including biological, physical and chemical at the molecular level, with high sensitivity and specificity, can be monitored through nanotechnology-based sensors. The nano sensors are manufactured using nanomaterials such as quantum dots, carbon nanotubes or metal nanoparticles. These are used for detecting pathogens, heavy metals, pesticide residues and nutrient status of the soil. Gold nanoparticles and zinc oxide particles have also been developed as nanosensors for detection of soil pH, soil nutrient and moisture, as well as to achieve specific nutrient management and reduce excessive agrochemical use (Sharma, 2024). Biosensors using nano material that possesses an effective platform consist of an integrative element such as enzymes, antibodies, and nucleic acids along with a transducer that allows the detection of plant toxins, pathogens or stress biomarkers. Such biosensors may be used to study diseases in crops through the identification of VOCs emitted from plants under attack by pathogens or through the identification of DNA sequences of specific pathogens (Chen et al., 2025). Biosensor application allows farmers to perform timely operations, resulting in minimum losses in terms of production and lower usage of chemical pesticides. Moreover, biosensors also enable farmers to measure microbe activity and enzymes within the rhizosphere and improve soil quality at the same time in a more accurate manner (Narware et al., 2025). Generally speaking, nanosensors and nanobiosensors represent a groundbreaking advancement towards sustainable agriculture, as they ensure timely and precise agricultural practices.

IV. CONTRIBUTIONS TOWARDS SUSTAINABLE AND PRECISION-BASED AGRICULTURE

Nanotechnology technology is taking up an important role in revolutionizing the concept of sustainable agriculture through the improvement of resource utilization and reducing the effects on the environment, resulting in the real-time monitoring of operations. Sustainable agriculture focuses on addressing the current agricultural requirements while at the same time ensuring that future generations will be able to meet their demands for production of the necessary resources (Atanda et al., 2025; Guan et al., 2024). Nano-technology makes way for the control of excess application of fertilizers and pesticides due to the nano-fabrication processes that ensure slow and site-specific release of agrochemicals. This ensures that nutrient losses through leaching and volatilization are minimized to reduce chemical runoff and limit contamination of soils and water systems (Kumar et al., 2023). Nanofertilizers can improve the nutrient use efficiency in the plants, whereas nano-pesticides reduce the number of applications of chemicals due to their reduced toxicity (Shang

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et al., 2024; Das et al., 2024). Nanotechnology incorporation into precision agriculture application increases the efficiency with which agricultural inputs are controlled and optimized according to different conditions of individual locations. Nano-sensors at the micro level enable determination and detection of changes in nutritional levels, pest resistance, plant wellbeing, and soil moisture, making decisions accurate and informed. This ensures that inputs such as fertilizers, insecticides, and water are used appropriately, which results in higher productivity with little harm to the surrounding environment (Sharma, 2024).In addition, nanocarriers that sense stimuli such as pH levels and humidity guarantee that the agrochemicals will only be released when needed. This makes the application of the concept of precision agriculture possible. With the use of nanotechnology, it is easier for ecological and environmentally sustainable agricultural practices to be implemented (Elsayed et al., 2025).

V. CHALLENGES AND LIMITATIONS OF NANOTECHNOLOGY IN AGRONOMY

However, despite the many strengths and opportunities that nanotechnology offers, along with the maximum harvest of crops and soil, there is a problem with its application to agronomy. This occurs due to the impact caused by the implementation of nanotechnology, as one of the key issues of using nanotechnology lies in the impact it causes on the environment and ecotoxicology, affecting microorganisms and plants within the soil unpredictably(Yadav and Yadav, 2024). Additionally, the study and evaluation of the long-term impacts of nanomaterials produced through engineering on the environment and human health have become challenging due to the lack of any comprehensive risk assessment models (Wu et al., 2025). The movement of nanoparticles within soil is also quite uncertain and unpredictable since soil characteristics such as its pH level, organic material, and clay content significantly affect and impact the mobility, modification, and bioavailability of the nanoparticles (Suazo-Hernández et al., 2023). Moreover, because of the difficulty associated with manipulating nanotechnology and the associated high costs in applying nano-based inputs, these inputs are not affordable for most farmers, particularly smallholder farmers in third world countries (Khundi et al., 2025). Owing to the appropriate regulations and policies in many countries, there is doubt regarding the commercial use of nanoproducts in agriculture (Kumari et al., 2023). Moreover, adoption of nanotechnology is hindered owing to ethical considerations and public perception, since such technologies may be doubted due to the threat posed to the sustainability of the environment, food security, and transparency in food systems (Le Tortorec et al., 2025). As a result of limited field trials and incorrect agronomic data, it becomes very difficult for it to verify the practicality, traditional safety, and environmental compatibility of nano-agronomic technologies (Elsayed et al., 2025). Such diverse complications give rise to various difficulties and stress the need for inter-disciplinary research and policy formation to ensure the proper integration of nanotechnology into agriculture.

VI. TOXICITY OF NANOPARTICLES AND CONCERNS TOWARD THE ENVIRONMENT

The use of nanotechnology-enabled engineered nanoparticles used for nano-fertilizers and nano-pesticides is becoming increasingly popular due to their effectiveness in terms of improved nutrient absorption and higher crop yield. At the same time, it is these properties that have created an increased cause for concern regarding their environmental effects as well. Therefore, their usage needs to be approached carefully and sustainably (Kah et al., 2018; Mishra et al., 2025; Zhang et al., 2025). Once the nanoparticles are added to the soil, it may lead to changes in the structure of the microbial communities and disturb the delicate functional group that performs key functions in the ecosystem like nutrient mineralization, biological nitrogen fixation, and decomposition of organic matter. In this way, the enzyme activity in the soil as well as the cycles of carbon, nitrogen, and phosphorus will be impacted.

In accordance with different research works and evidence, it has been observed that metal nanoparticles like ZnO and TiO_2 can possibly exert oxidative stress on soil microbes and animals because of the production of reactive oxygen species and membrane damage. In addition, although possessing highly effective antibacterial characteristics, silver nanoparticles can have an undue impact on the useful microorganisms that help keep the soil fertile and plants healthy (Tripathi et al., 2017; Shankar et al., 2021). Apart from effects on the soil, when used as soil amendments, foliar sprays, or fertigation, nanoparticles get absorbed through the roots or leaves of the plants, and then distributed throughout their aboveground parts where they undergo various changes. In doing so, there is a possibility of nano-based metals entering the food chain, thus posing health risks to both human beings and cattle as well (Singh et al., 2017; El-Saadony et al., 2024; Zhang et al., 2024). More importantly, most of these behaviors have been inadequately handled by the standard risk-assessment schemes for fertilizers and pesticides because these schemes were developed for dissolved compounds or bulk materials. They are inadequate in that they do not consider nano-specific properties such as size-specific reactivity, aggregation behavior, surface charge, and corona formation; in addition, they ignore the transport process of nanoparticles from the soil-plant-water-atmosphere system (Campos et al., 2017). Therefore, there is now sufficient scientific evidence showing that nanoparticles affect the microorganisms, enzymes, nutrient cycles, and plants in the soil that supports the assertion that nanotechnology used in agriculture needs to be introduced in a 'safe by design' manner, in which the choice of materials, optimized doses of use, choice of biodegradable or more stable carriers, and assessment of the effects on soil ecosystems and biodiversity in general need to be considered (Campos et al., 2017; Popescu, 2023; Zhang et al., 2025).

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VII. CONCLUSION

Utilization of nanotechnology for incorporation within agronomy systems is indeed a paradigm shift for attaining sustainability, efficiency, and resilience in agriculture. In this regard, the present review provides an exhaustive account of the immense potential offered by nanoparticle-based agricultural inputs such as nanofertilizers, nanopesticides, nanosensors, and smart delivery vehicles in ensuring improved efficiencies of nutrient utilization, soil remediation, and crop yield along with minimizing environmental impact from traditional chemical farming. Through utilization of unique properties at nanoscale such as increased reactivity, release behavior, and targeting ability, these novel tools ensure synchronization between nutrient availability and requirement by plants. In addition to increased efficiency, nanotechnology plays an essential role in the proper functioning of the soil environment through its effects on nutrient cycling, biological processes in the soil, soil structure, and pollutant degradation. The use of nanotechnology for remediation through carbon nanomaterials and reactive nanoparticles holds great promise when it comes to sequestering or deactivating contaminants and heavy metals and thus promoting the revitalization of polluted soils. At the same time, nanotechnology sensors have a vital role to play in precision farming through monitoring various parameters related to soil nutrient content and moisture conditions, as well as pathogens and stress-related factors.

Nevertheless, the implementation of nanotechnology in agriculture on a widespread scale has been hindered by some issues that need resolution in relation to nanoparticle durability, ecotoxicity, bioaccumulation, and food chain movement. In addition, the intricate relationships between soils, plants, and microorganisms make the prediction of the environmental fate of nanoparticles difficult, making it clear that risk assessment approaches designed for agrochemicals have their own shortcomings. Therefore, when applying nano-agronomic techniques in the near future, the principle of “safe-by-design” should guide researchers towards using degradable nanocarriers, optimizing dosages, and implementing location-specific applications.

In terms of future developments, the integration of nanotechnology with other fields such as artificial intelligence, machine learning and IoT-based sensing systems is anticipated to revolutionize precision agriculture, thus making it possible to create predictive, autonomous and site-specific crop management systems. This integration will be instrumental in transforming the reactive approach of input application to one of ecosystem management. Nanotechnology has significant potential to solve the problems faced by today’s agriculture industry; nevertheless, success in implementing nanotechnology in the agricultural sector will require innovation that will reconcile agronomics, ecology and socio-economics.

FUTURE PROSPECTS

Nanotechnology provides us with a superb tool to achieve sustainable agriculture in the future. Provided that eco-friendly and biodegradable nano-materials such as lignin- or chitosan-based nanoparticles have been developed, it will minimize environmental concerns (Mishra et al., 2024). Optimization of nano-agrochemicals and development of precision farming are easy to accomplish through the effective use of artificial intelligence and machine learning technologies (Yadav et al., 2023). The detection of diseases in the early stages and also the monitoring of soil and plant health in real time can be achieved easily by linking the nano-biosensors using the internet of things (IoT) technology (Chaturvedi et al., 2025). The use of nanotechnology facilitates and enhances climate-resilient crops using nano-coatings and also delivery of genes (Sidhu et al., 2024). The implementation and success of nanotechnology rely heavily on the regulatory framework, demands for toxicity, and also field testing (Elsayed et al., 2025). These developments and advances make nanotechnology crucial for future agriculture, provided responsible innovative guides and its development. The agronomic nanotechnology provides some useful ways for promoting the sustainable agriculture in the future. The creation of the biodegradable nano-structures like nanoparticles based on lignin and chitosan will help to minimize risks associated with the environment (Dipartimento P., 2024). In addition, AI and machine learning technologies will increase the efficiency of using the agronomic nanoparticles and optimize the practice of precision farming (MDPI, 2024). Besides, nanobiosensors combined with the IoT can help monitor the condition of soils and crops, which is useful for disease prediction (Kumar et al., 2025). Nanotechnology plays a significant role in creating climate-resilient plants with the help of the nano-priming and gene transfer technologies (Wang et al., 2024). However, successful integration requires adequate legislation, criteria for safety, testing, and farmer involvement (Umar et al., 2025). Finally, the application of the circular economy principles is crucial in nanotechnology in agriculture (Rajpal et al., 2025).

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AUTHOR'S CONTRIBUTION

NK collected the review of literature, conceptualized and prepared the manuscript as part of research work under the supervision of SRM and BKP. SRM guided the overall structure, provided critical reviews and supervised the review process.

COMPLIANCE WITH ETHICAL STANDARDS

- *Conflict of Interest:*

The authors assure and clarify that there are no known conflicts of interest occurs which could influence the research pointed in this review. This work has been presented and conducted independently without financial or personal relationships that could be perceived as biasing the content.

- *Ethical issues*: *None*

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