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Nanotechnology Revolutionizing Agriculture: From Nanofertilizers to Eco-friendly Solutions and Agrochemical Remediation: A Review

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ABSTRACT

For decades, fertilizers have boosted agricultural productivity but at high economic, environmental and health costs. Nano-fertilizers offer a sustainable and cost-effective alternative by serving as efficient nutrient carriers with controlled release and targeted delivery, thereby reducing the need for excessive agrochemicals. Their integration with microorganisms as nano-biofertilizers further enhances soil fertility and crop yield. With potential to cut conventional fertilizer use by 50%, nanomaterials also interact uniquely with plant systems through stomatal entry or vascular penetration. This review highlights the production, mechanisms, soil interactions and environmental implications of nano-fertilizers, emphasizing their role in mitigating biodiversity loss, biomagnification and soil fauna decline caused by agrochemicals. Finally, it underscores the need for advanced research and policymaking to harness nanotechnology for sustainable agriculture and agrochemical remediation.

Key words: Agrochemicals, Nano biofertilizers, Nanoremediation, Seed science, Vermicompost.

Pollutants are hazardous substances introduced into the environment by humans in excess of natural levels (Jurado *et al*., 2012). Heavy metal accumulation from urbanization, sewage sludge, industry and population growth has intensified environmental toxicity. To meet rising food demand, developing countries like India are increasingly reliant on agrochemicals, despite the obsolescence of traditional practices such as integrated pest management. Since their introduction, pesticides and related chemicals (fungicides, herbicides, insecticides, rodenticides, avicides, *etc*.) have transformed agriculture but also disrupted ecosystems. Notably, developed nations consume about 80% of global agrochemical production, while excessive use has fostered pest resistance, resurgence and non-target impacts. In India, fungicide use ranks second among agrochemicals, with expenditures rising by 44.17% from 2014 to 2020 (FAOSTAT, 2023).

To address these challenges, research is advancing remediation strategies, with nanotechnology gaining prominence. By converting bulk matter into nanoparticles (<100 nm) *via* physical, chemical, or biological methods, nanotechnology yields materials with unique electrochemical, optical, thermal and catalytic properties (Laurent *et al*., 2010; Taghizadeh *et al*., 2013). These distinctive attributes make nanomaterials a promising tool for mitigating the adverse effects of chemical pollutants.

Methodology: Literature selection criteria

The literature for this review was collected from peer-reviewed journals, books and authoritative databases including Scopus, Web of Science and PubMed. Keywords such as *nanotechnology, nano-fertilizers, agrochemicals, pollutants, remediation and sustainable agriculture* were used in various combinations. Studies published between [2010-2023] were prioritized to ensure inclusion of recent advancements, while seminal works were retained for conceptual clarity. Articles were included if they (i) addressed the environmental or agricultural applications of nanomaterials, (ii) discussed impacts of agrochemicals or pollutants, or (iii) provided experimental or review-based evidence relevant to remediation strategies. Non-peer-reviewed sources, duplicate records and publications lacking sufficient methodological detail were excluded. The final selection was guided by relevance, credibility and contribution to the research objectives.

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Nanotechnology-assisted remediation

Bio- and phytoremediation have been primary alternative remediation techniques aided by nanotechnology. Plants, in addition to absorbing water and nutrients from the soil, can rapidly take up contaminants from the soil and water, effectively removing them from the food chain (Li *et al.,* 2016). Agrochemicals' fate in soil includes their half-life and transformation into less toxic residues, which can affect soil microflora and fauna (Nayak *et al.,* 2018). In recent years, agricultural remediation has seen improvements through the direct or indirect application of nanotechnology, including nanofertilizers and nanopesticides.

Nanoremediation, a cost-effective and environmentally friendly method for detoxifying pollutants and toxins from soil and other environmental compartments, is gaining prominence. Notably, nano-bioremediation has been developed, combining various nanoparticles with microorganisms to remove hazardous environmental pollutants, offering an efficient and environmentally benign approach to building sustainable habitats (Chaudhary *et al.,* 2023). Various methods, including adsorption, catalysis (heterogeneous), nanoremediation (electro, nano-bio) and photodegradation, are employed in nanoremediation to remove or immobilize pollutants from soils (Ahmed *et al.,* 2021). Carbonaceous nanomaterials (carbon nanotubes, graphene nanosheets, graphene oxide nanosheets), metallic nanoparticles (CuO, ZnO, Fe_xO_y, TiO_2 and MgO-NPs) and polymeric nanoparticles (chitosan-NPs and alginate-based NPs) have been extensively studied for cleaning up polluted environments such as soil and water. Nanomaterials find diverse applications, from pollutant removal to the development of nanosensors for pollutant detection and even the production of nanopollutants under certain conditions (Bouyahya *et al.,* 2022). Concerns about nanopollution have arisen due to unsustainable nano manufacturing in various industries, leading to increased research interest in addressing this issue (Cárdenas-Alcaide *et al.,* 2022).

Nano-phytoremediation

Nano-phytoremediation is an environmentally beneficial approach that has gained global recognition and validation (Srivastav *et al.,* 2018). This method offers advantages such as technical simplicity, one-time investment and long-term returns, making it a driving force in sustainable development (Mahar *et al.,* 2016). Nano-phytoremediation involves the cultivation of economically valuable crops, such as herbs, that leave minimal waste, including biomass and biofuel. For instance, the remnants of lavender plants, after extracting essential oils through distillation, can be repurposed into biopellets (Kumari *et al.,* 2022). To address the time-intensive nature of traditional phytoremediation, Nwadinigwe and Ugwu (2018) have proposed a multidisciplinary approach to nano-phytoremediation.

Nano-bioremediation

Nano-bioremediation employs microorganisms in bioreme- diation to combat environmental contaminants (Singh *et al.*, 2020). Traditional bioremediation (phytorem ediation) methods are often challenged by high pollutant concentrations (Azubuike *et al.,* 2016). Combining these two techniques into nano-bioremediation has shown promise in mitigating these limitations. Numerous nanomaterials (NMs), including nZVI NPs, sodium oleate-nZVI, palladium/nZVI bimetallic NPs, palladium NPs, Fe_3O_4 NPs, MWCNTs and MgO NPs, have been employed to significantly enhance bioremediation processes.

Sustainable agriculture enabled by nanotechnology

Sustainable agriculture empowered by nanotechnology has been a subject of extensive research and documentation (Khot *et al.,* 2012). One innovative concept involves the intelligent release of fertilizer particles in response to specific signals. Nano biosensors, embedded in a biopolymer that coats fertilizer particles, can detect signals generated by the plant's root system in response to its nutrient requirements (Keswani *et al.,* 2020). Recent research has witnessed a surge in interest in nanotechnology's applications across various agricultural domains. Notably, nanomaterials (NMs) have been explored for their potential in promoting and protecting plant growth (Mejias *et al.,* 2021). Researchers in agricultural technology strive to develop methods and innovations that enhance crop yields while minimizing environmental impact. Nanofertilizers (NFs) are gaining popularity due to their reduced reliance on chemical fertilizers and the associated benefits. These NFs, including AgNPs, TiO_2 NiNPs, silica nanoparticles, CNTs and various metallic nanoparticles, have been studied for their effects on plant growth and yield (Kamal and Mogazy, 2021). NFs offer several advantages, including enhanced nutrient utilization, reduced fertilizer doses, improved solubility, controlled nutrient release, lower eco-toxicity compared to traditional fertilizers and efficient nutrient retention in the soil-plant system. Nanopriming, nanofoliar application and nano-root nourish-ment are among the various application methods for NFs.

Hormonal effects in plants

Hormonal effects in plants are influenced by regulators like Nano-5, nano-gro and Primo MAXX, which are widely employed globally (Ndlovu *et al.,* 2020). For example, Fe_2O_3 treatment has been shown to increase the levels of indole acetic acid and abscisic acid in the roots of both transgenic and non-transgenic rice varieties (Yang *et al.,* 2017).

Secondary metabolites exploitation

The exploitation of secondary metabolites, such as alkaloids, phenolics and terpenoids, produced by plants as natural defense mechanisms against insects, is an area where nanotechnology plays a role. Nano-conveyors

can detect these valuable metabolites and nanostructures can assist in their identification. Additionally, nano-polymers can enhance the catalytic activity of plant cells, leading to increased protein production. Conversely, nanostructured polymer layers can be used to detect toxic secondary metabolites, such as mycotoxins produced by fungi (Sertova, 2015).

Agrochemical's efficient delivery

Efficient delivery of agrochemicals is achieved through nano biosensors that utilize carbon nanotubes or nano-cantilevers to capture and transport tiny molecules and individual proteins (Abd-Elrahman and Mostafa, 2015). The horticultural industry benefits from smart sensors and delivery systems, resulting in reduced pesticide and herbicide dosages. Nano-encapsulated insecticides, for example, enhance the solubility of active chemicals and enable gradual release, reducing toxicity to non-target organisms. To implement controlled nanoparticulate delivery devices, a specific delivery approach based on the life cycle and behaviour of microorganisms or pests is necessary (Jatav and De, 2013). Researchers have found that nanoparticles of various metals are a reliable and cost-effective means of controlling insects and pests, significantly improving agrochemical distribution (Kumar, 2020).

Nanomanagement of Agro-wastes

Nanomanagement of agro-wastes addresses environmental issues stemming from agricultural practices that generate significant pollution, particularly in developing nations (El-Ramady *et al.,* 2022). This approach offers numerous advantages, including increased crop productivity and soil fertility, reduced reliance on mineral-based fertilizers and fossil fuels, the creation of protein-rich animal feedstocks, the generation of bioactive substances, the production of nanoparticles and nanomaterials and the potential for pharmacological applications, fermentation industries and environmental remediation. Silica nanoparticles and lignin nanomaterials have proven effective in mitigating environmental pollution caused by crop residues, such as straw (rice, wheat), shells (groundnut, walnut), husks (coconut) and peels (banana, orange), due to their high biogenic silica content. Additionally, they find applications in environmental cleanup, water treatment and nano-remediation (Yadav *et al.,* 2023). Addressing agri-food waste is essential, as improper handling can pose health and environmental risks. A substantial portion of global food production is wasted, contributing to environmental degradation. To achieve sustainable development goals, it is crucial to explore methods for converting agricultural waste into energy using nanotechnology-based processing (Sonu *et al.,* 2023).

Nano-agrochemicals for fertilization

Nano-agrochemicals for fertilization play a critical role in modern agriculture, exerting significant control over crop production, particularly in intensive farming. Fertilizers come in various forms, including conventional, biofertilizers and nanofertilizers. Bio- and nanofertilizers, especially biologically synthesized nanofertilizers, offer environmentally friendly alternatives to traditional fertilizers, positively impacting both the economy and the environment. Smart fertilization/irrigation systems, which adjust fertilizer and water application based on weather and soil conditions, are becoming increasingly prevalent in agriculture. These systems incorporate nanotechnology, allowing for precise control over nutrient release and reducing ecological impact. Smart nanofertilizers offer advantages such as high nutrient efficiency, reduced fertilizer doses, enhanced solubility, controlled nutrient release, lower eco-toxicity, simplified delivery and decreased nutrient leaching and volatilization. They can be applied through nanopriming, nanofoliar application, or nano-root nourishment (Thorat *et al.,* 2023).

In conclusion, nanotechnology has a transformative impact on various aspects of agriculture, from remediation of environmental contaminants to sustainable crop production, hormonal regulation, secondary metabolite exploitation, agrochemical delivery, management of agro-wastes and smart fertilization/irrigation practices. These advancements hold the potential to enhance agricultural sustainability, minimize environmental impact and increase food production to meet the demands of a growing global population.

Seed science

In the realm of seed science, the aging process of stored seeds is intimately associated with the emission of volatile aldehydes. These aldehydes have a significant impact on various seeds, potentially leading to degradation. To address this issue, biosensors have emerged as valuable tools for the detection of these volatile aldehydes. By utilizing biosensors, it becomes possible to differentiate between healthy seeds and those exhibiting signs of degradation before they are employed for various purposes (Reddy *et al.,* 2016).

Similarly, nano-sensors have found applications in precisely detecting the presence of insects or fungi within grains stored in agricultural storage facilities. These advanced sensors enable the early identification of infestations, thereby assisting in the preservation of grain quality (Sekhon, 2014). Furthermore, the utilization of silver nanoparticles has been employed to sterilize the surfaces of seed crops and apply seed dressing, contributing to improved seed quality and protection (Chhipa, 2019). Researchers are actively exploring the potential of carbon nanotubes and metal oxide nanoparticles to enhance the

germination and growth of rainfed crops, as indicated in Table 1.

Genetic manipulation and crop improvement, crop production

In the realm of genetic manipulation and crop improvement, nanotechnology offers promising avenues for enhancing crop traits and bolstering resistance to various environmental stressors. By manipulating the genetic components of plants at the nanoscale, plant breeders can develop improved crop varieties with heightened tolerance to conditions such as salinity, diseases, cold and drought (Ndlovu *et al.,* 2020).

Nanotechnology has also greatly advanced the field of gene sequencing, facilitating the efficient exploration and utilization of plant genetic resources. Nano-genomics-based technology allows nanomaterials to serve as carriers of DNA or RNA, directing genes to specific cellular locations for precise gene expression control. This technology has substantial implications for plant breeding by enabling the creation of genetically enhanced crops (Ndlovu *et al.,* 2020).

Additionally, nanofertilizers have emerged as a means to enhance crop productivity and quality while improving nutrient efficiency. They contribute to sustainable agriculture by reducing production costs and environmental nutrient runoff. Recent studies have reported positive effects on germination, seedling growth, physiological activities like photosynthesis and nitrogen metabolism, mRNA expression and gene expression modulation across various crops, further substantiating their potential for crop improvement (Pramanik and Pramanik, 2016). Nano-carriers offer a means to address nutrient deficiencies in crops, ensuring they receive the essential nutrients for optimal growth (Kumari *et al*., 2025; Goyal *et al*., 2025; Kumar *et al*., 2023).

Table 1: NPs and their attributes in seed science.

Nanomaterial	Plant used on	Attribute	References
Carbon nanotubes (CNTs)	*Solanum lycopersicum*	Enhance the germination of seeds through the better conveyance of moisture. The data shows that acts as a new pore and facilitate the passage of water by penetrating the seed coat and acting as a way to channelize the water from the substrate into the seeds.	Reddy *et al.,* 2016
Ti NPs	*Triticum aestivum*	Increased the ear mass, seed number, biomass, stem elongation, flowering, yield, starch and gluten content	
Carbon nanotubes (CNTs)	*Glycine max, Hordeum vulgare, Zea mays*	Germination percentage of seeds increased	Acharya and Pal, 2020
Nanoparticles (Mg, Mn) and multiwalled carbon nanotubes	*Brassica juncea, Phaseolus mungo*	Increased the germination percentage	
Nano-863	*Vigna unguiculata, Brassica oleracea* and *Cucumis sativus*	Higher Germination rate, bud length, diameter, fresh bud weight, *etc.*	Huang *et al.,* 2014
Zinc nanoparticles	*Pennisetum americanum*	Enhance the productivity	
TiO_2 NMs	*Vigna radiata*	Increases the productivity	Manjunatha *et al.,* 2019
TiO_2 NPs	*Agropyron desertorum*	Enhance seed germination by significantly decreasing the mean time for germination	Azimi *et al.,* 2013
Phosphatic nano-fertilizers	*Glycine max*	Increase the growth rate by (32%) and seed yield by (20%)	McKnight *et al.,* 2020
Carbon nanoparticle nanotubes of Au, SiO_2, ZnO and TiO_2 ameliorate	*Triticum aestivum, Pennisetum glaucum, Solanum lycopersicum Glycine max, Hordeum vulgare, Oryza sativa* and *Zea mays*	Development of plants by enhancing elemental uptake and use of nutrients	Fraceto *et al.,* 2016

Nanotechnology can also be harnessed to identify superior genes for enhancing crop disease resistance and productivity (Kerry *et al.,* 2017). From seed to the digestive process, genome to gluten, nanotechnology plays a pivotal role in enhancing agribusiness control over global food production, akin to the transformative impact of genetically modified agriculture along the food supply chain (Bhau *et al.,* 2016).

Fighting against stress (biotic and abiotic) alleviators

In the realm of combating stressors, both biotic and abiotic, that challenge plant growth and crop production, nanomaterials (NMs) have emerged as potent allies. These stressors can impede plant development and reduce overall crop yields, exacerbating global nutrition challenges. Extensive studies have demonstrated the ability of NMs to assist plants in recovering from stress by enhancing oxidative stress coping mechanisms, regulating metabolic processes and increasing the levels of photosynthetic pigments. Notably, TiO_2 nanoparticles have shown promise in alle*via*ting oxidative stress in plants, as outlined in Table 2.

Various factors, including biotic and abiotic stressors, have the potential to negatively impact plant productivity, thus affecting overall crop production. These pressures can lead to physiological, morphological, genetic and biochemical alterations in plants. In response to these challenges, a range of management techniques, such as plant breeding, genetic engineering, agrochemicals, integrated pest control and various tillage methods, have been employed (Ma *et al.,* 2023).

Among these techniques, nano-priming stands out as a valuable approach in enhancing seed germination,

Table 2: NPs and their attributes in resistance against stress alleviators.

Nanomaterial	Plant used on	Attribute	References
Graphene NPs	*Medicago sativa*	Increase resistance to alkaline circumstances, specifically by enhancing the activity of antioxidant enzymes and boosting seedling root length along with its fresh and dry weight	Chen and Wang, 2021
Silicon NPs	*Calendula officinalis*	Improved antioxidant activity and total flavonoid content under drought stress.	Rhaman *et al.,* 2022
Biogenic Ag NPs	Lentils and *Trigonella foenum*	Improved the growth, length and weight Improved the activity of antioxidant enzymes	Hojjat and Kamyab, 2017
TiO_2 NPs	*Zea mays* *Glycine max* plant	Improved physiological functions and chlorophyll concentration by successfully minimizing Cd toxicity	Singh and Lee, 2016
Silicon dioxide		Improved plant growth parameters by lowering levels of hydrogen peroxide, electrolyte leakage and malondialdehyde. Furthermore, it decreased chlorophyll degradation while increasing stomatal conductance, net photosynthetic rate, transpiration rate and water use efficiency	Hajizadeh *et al.,* 2021
CeO_2 NMs	*Zea mays*	Improved the salt tolerance of maize by maintaining Na+/K+ homeostasis, enhancing photosynthetic efficiency and reducing levels of ROS in salt-stressed leaves [158]	Liu *et al.,* 2022
Nanosilver	*Crocus sativus*	Mitigated the negative effects of flooding stress and increased root development	Rezvani *et al.,* 2012
Al_2O_3 NPs	*Glycine max*	Root length increased while glycolysis-related mitochondrial proteins expression repressed	Mustafa *et al.,* 2016
Ag NPs	*Triticum aestivum*	Protected from heat stress and showed significant improvement in growth	Iqbal *et al.,* 2019
Ag NPs	*Pelargonium zonale*	Petal longevity; mitigate the negative effects of dark-stress-induced oxidative damage	Hatami and Ghorbanpour, 2013
Nanosilver and thidiazuron	*Pelargonium*	Reduced petal abscission in subjected to under dark preservation	Ghorbanpour and Hatami, 2014

seedling growth and crop yield under stressful conditions. Numerous studies have suggested that nano-priming can significantly improve germination percentages, seedling vigour indices and root-shoot lengths, particularly in crops like wheat and tomatoes (Chen and Wang, 2021). Nano-priming has proven highly effective in bolstering seed performance and crop resilience when faced with adverse environmental conditions (Faraji *et al.,* 2019).

In summary, nanotechnology has revolutionized various aspects of seed science and crop production, offering innovative solutions for seed quality preservation, genetic enhancement, nutrient management and stress mitigation. These advancements hold the potential to contribute significantly to addressing global food security challenges and improving agricultural sustainability.

Nanofertilizers

Nanofertilizers represent a significant advancement in agricultural technology, offering multifaceted benefits for soil quality, nutrient delivery and crop productivity. These innovative fertilizers have demonstrated their capability to detoxify soil contaminated with heavy metals, thereby enhancing its suitability for agricultural purposes (Shah and Daverey, 2020). Nano-based approaches designed to boost agricultural productivity encompass various strategies, including the use of nano-porous zeolites for controlled nutrient release, nanocapsules for precise agrochemical delivery, iron nanoparticles for mitigating soil and water pollution caused by heavy metals and nanosensors for pest detection and management. Additionally, nanopesticides have been developed to improve the solubility of active pesticide ingredients and enable targeted and controlled degradation, enhancing their effectiveness in pest control (Ragaei and Sabry, 2014). Nano materials such as thin polymer films and nanoscale emulsions are employed to encapsulate nutrients, facilitating their efficient delivery to crops.

Among essential macronutrients, nitrogen is particularly susceptible to leaching and mobility in soil. Nanofertilizers have emerged as a solution to address this challenge by providing a longer-term, time-dependent release of nitrogen. Various nitrogen-based nanofertilizers, such as urea-coated zeolite, urea-modified hydroxyapatite, urea pine oleoresin and nano chitosan NPK formulations (nitrogen, phosphorus, potassium), have demonstrated their ability to enhance nitrogen bioavailability over an extended period, aligning nutrient delivery with the specific needs of plants (Badran and Savin, 2018). This approach significantly improves nitrogen usage efficiency in agriculture.

Nanofertilizers made from biofertilizers

Nanofertilizers derived from biofertilizers represent a fusion of biological and nanomaterial components, offering high effectiveness for both constituents. These nano biofertilizers are designed for the gradual release of nutrients throughout the crop growth cycle, coupled with enhanced nutrient utilization, ultimately leading to increased agricultural yields and productivity (Piccapietra *et al.,* 2008). Over the past decade, there has been a noticeable shift towards favouring nano- and biofertilizers over their chemical counterparts (Slomberg and Schoenfisch, 2012). Biofertilizers typically consist of beneficial microorganisms that act as catalysts, possessing the unique ability to fix nitrogen and enhance the solubility of complex organic compounds that would otherwise be insoluble. This process simplifies nutrient availability and enhances soil structure by replenishing soil microbial content, improving aeration and promoting natural fertilization (Dan *et al.*, 2015). However, biofertilizers also have limitations, including vulnerability to nanoscale texture retention, poor stability in field conditions, variability in activity under changing environmental conditions, susceptibility to desiccation and high dosage requirements for large agricultural areas (Pérez-de-Luque, 2017). These challenges can hinder effective nutrient delivery to host plants and pose environmental risks.

To address these limitations, nanoencapsulation techniques have been employed to create nano biofertilizers. Nanoencapsulation involves coating nutrient-loaded biofertilizers with nanoscale polymers, providing structural protection to nutrients and microorganisms that promote plant growth. This approach enhances the chemical stability and dispersion of biofertilizers in fertilization formulations, resulting in controlled nutrient release (Wesołowska *et al.,* 2021). Nano biofertilizers offer several key advantages, including improved crop quality, enhanced disease resistance, optimized nitrogen (N), phosphorus (P) and potassium (K) utilization and improved soil ecosystem dynamics (Piccapietra *et al.,* 2008). These compensations contribute to higher crop yields, reduced economic investment through lower costs and reduced application rates and sustainable agricultural practices. Nano biofertilizers represent a promising technology with the potential to revolutionize modern agriculture by addressing nutrient delivery challenges and promoting environmentally friendly farming practices.

Nanopesticides

Nanopesticides represent a promising advancement in the field of agricultural pest management, offering solutions to several challenges associated with conventional pesticide applications. In conventional pesticide use, the leaching of micro pesticides from industrial and agricultural wastewater into water sources following precipitation events can lead to water contamination, posing risks to human health and the environment (Bombo *et al.,* 2019). Nanopesticides are expected to enhance pesticide efficiency, potentially reducing the amount of active ingredients needed for effective pest control. However, this increased efficiency may also raise concerns about potential toxicity to non-target organisms (Kah *et al*., 2013). Implementing nanopesticides can lead to a reduction in food losses due to pest infestations, plant damage and

financial losses (Cosgrove *et al.,* 2019). Additionally, these formulations can minimize the residue of pesticides in the soil, decreasing their impact on the environment. Novel metal or metal oxide nanoparticles are being explored for their ability to treat heavy metal-contaminated soil and water, further highlighting the versatility of nanopesticides (Diyanat *et al.,* 2019).

Nanopesticides, including nanospheres, nanocapsules, nanogels and nanofibers, offer several advantages over traditional pesticide formulations, such as improved dispersion, solubility, stability and bioavailability, enabling reduced application concentrations and minimizing adverse effects on the environment (Huang *et al.,* 2018). These advantages result in modified and, in some cases, reduced impacts on unintended target organisms (Kah and Hofmann, 2014).

Key advantages of nanopesticides over traditional ones include:

1. Higher stability and controlled release of active ingredients.
2. Enhanced effectiveness with smaller required doses.
3. Optimal dispersion and reduced residue buildup.

Nanosensors

Nanosensors play a crucial role in precision farming by enabling the precise delivery of pesticides. These “smart delivery systems” have programmable properties and can operate remotely, offering the potential for region-specific and multifunctional applications (Anjum and Pradhan, 2018). Nanosensors are capable of translating biological responses into electrical signals, making them robust and versatile tools in agriculture. Biosensors, a type of nanosensor, detect biological elements from an analyte, such as antibodies, enzymes and chemical molecules (Saritha *et al.,* 2022).

Nanosensors can monitor various aspects of agriculture, including soil conditions, plant growth hormones, plant diseases and pesticide residues (Saritha *et al.,* 2022). These sensors are particularly valuable in assessing fungicides and residues in the field. Various types of nanosensors, such as optical, calorimetric, electrochemical and piezoelectric biosensors, have been developed based on enzyme inhibition to detect pesticides and residues. Additionally, sensors utilizing materials like graphene and carbon nanotubes have shown promise in detecting heavy metals, agrochemicals, reactive oxygen species (ROS) associated with stress and insects (Gao *et al.,* 2015).

Conventional pesticide detection methods are often time-consuming and require skilled personnel and laboratory equipment, making them unsuitable for field use or rapid optimization. To address these challenges, there is a growing need for faster, more accurate, portable and user-friendly detectors capable of high-throughput detection with sensitivity down to the parts-per-billion (ppb) level. Such detectors would empower farmers to adjust pesticide doses based on soil conditions, optimizing pest control while minimizing environmental impacts.

Conventional fertilizers, though widely used, remain inefficient due to nutrient losses through leaching, volatilization and poor uptake, creating both environmental and economic burdens. Nanomaterials (NMs) have been positioned as a potential remedy by enabling controlled nutrient release, enhancing uptake efficiency and reducing overall fertilizer consumption. While this promise is evident, the debate cannot be confined to yield improvements alone; it must also account for the socio-economic, regulatory and environmental complexities surrounding their use.

One critical gap is the limited understanding of nanopollution-the long-term persistence, accumulation and toxicity of NMs in soil and water systems. Unlike conventional fertilizers, nanoparticles may exhibit unique reactivities that disrupt soil microbiota, bioaccumulate through food chains and pose risks to biodiversity. Despite advances in laboratory studies, real-world data on NM degradation, soil-plant-microbe interactions and life-cycle impacts remain scarce. This knowledge gap restricts the ability to establish comprehensive risk assessments or evidence-based regulations.

Regulatory challenges further hinder adoption. Wealthier nations such as the USA and members of the EU have initiated frameworks for assessing nanofertilizer safety, but developing countries-despite being central to global food production-lag behind in formulating or enforcing such policies. Without harmonized global standards, the large-scale deployment of nanofertilizers risks exacerbating inequities, where wealthier producers benefit first while resource-poor farmers remain exposed to uncertainty.

Socio-economic factors also complicate adoption. High production costs make NMs less accessible to smallholder farmers, who dominate agriculture in developing regions. Additionally, limited farmer awareness, insufficient extension services and consumer skepticism toward nanotechnology-based food products constrain widespread uptake. Thus, the challenge is not merely technological but also social and economic.

Looking forward, the real test lies in balancing agricultural benefits with ecological and human safety. Nano-biofertilizers, which integrate microbial inoculants with nanocarriers, offer an appealing route toward sustainability, yet their field-scale validation is still in its infancy. More interdisciplinary research is needed to (i) quantify nanoparticle concentrations in real farming environments, (ii) evaluate long-term impacts on soil health and microbiota and (iii) develop predictive models of NP fate and transport. Equally important are pilot trials and full-scale demonstrations that bridge laboratory promise with on-ground realities.

Challenges and limitations of nanotechnology adoption

- **High production costs**

  Manufacturing and scaling nanomaterials remain expensive, limiting affordability for farmers, especially in developing regions.

- **Regulatory gaps**

  Inconsistent or underdeveloped policies on labeling, safety standards and approval processes create uncertainty for commercialization.

- **Environmental risks**

  Nanoparticles may persist in soil and water, bioaccumulate in food chains and disrupt non-target organisms and soil microbiota.

- **Knowledge gaps**

  Limited awareness among farmers and lack of training infrastructure hinder effective application in field conditions.

- **Uncertain long-term effects**

  Insufficient understanding of nanoparticle toxicity, persistence and ecological impacts complicates risk assessment.

- **Adoption barriers**

  Concerns about safety, consumer acceptance and return on investment slow down large-scale implementation.

CONCLUSION

In summary, nanotechnology in agriculture is at a crossroads: while it holds potential to reduce dependence on conventional agrochemicals and improve yields, its unchecked use could create new ecological risks. Advancing this field requires not only technological innovation but also stronger regulatory oversight, socio-economic inclusivity and comprehensive environmental risk assessment. Only through such a balanced approach can nanotechnology transition from promise to safe and sustainable practice in global agriculture.

Conflict of interest

The authors declare no conflict of interest.

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