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Review Article

Nanotechnology in Agriculture

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ABSTRACT

In recent years, the agricultural sector has witnessed a surge in the development and application of nanotechnologies. This review aims to provide a comprehensive overview of the current state of the field, highlighting the key advancements and challenges that have emerged. We examine the various categories of nanomaterials being used in agriculture, including carbon-based structures, semiconductor nanodevices, and environmentally friendly approaches. Our analysis reveals that these materials have shown great promise in improving crop yields, reducing waste, and enhancing sustainability. We also explore the potential risks and challenges associated with the use of nanoparticles in agriculture, including their impact on soil microbiota and the need for effective regulation. Ultimately, this review aims to provide a nuanced understanding of the role that nanotechnology can play in transforming the agricultural sector, and to identify areas where further research and development are needed.

Keywords: Agri-nanotechnology, precision farming, crop optimization, nanomaterials, sustainable agriculture.

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INTRODUCTION

Nanotechnology, which refers to the manipulation and production of materials and devices on the nanometer scale (where a nanometer equals one billionth of a meter), has become a significant area of research and development across various sectors, including agriculture. In the field of agricultural applications, nanotechnology is an emerging approach for providing innovation that will support advances in crop production, protection, and postharvest handling to make them sustainable and efficient. The most important developments in recent studies under the period 2020-2024 in the field of agricultural nanotechnology are carbon nanomaterials, semiconductor nanodevices, green nanotechnology, and nano-composites (Zhang *et al.*, 2021). These advances are set to herald a new era in material mechanical and optical property enhancements, shows new environmentally friendly methods in nanoparticle synthesis, and clearly exhibit the application of new knowledge in agriculture. Bacteria-assisted nanoparticle synthesis through mechanisms of intracellular biosynthesis, extracellular biosynthesis, and bioaccumulation is green and environmentally friendly. In intracellular biosynthesis, metal ions are reduced to nanoparticles within the bacterial cell, which is then expelled into the environment following cell lysis (Razi Ahmad *et al.*, 2022; Altammar, 2023; Shanmugam *et al.*, 2023). On the other hand, extracellular biosynthesis relies on enzymes secreted by the bacteria, which act on the metal ions outside the cell, so it allows for efficient harvesting and purification of the nanoparticles. In a number of studies, it was determined that this method is important in the production of metallic nanoparticles based on silver and copper using strains like *Bacillus cereus*, *Pseudomonas stutzeri*, or others such as *B. amyloliquefaciens* and *Lactobacillus* sp. This therefore makes it very befitting to describe the role of a reducing enzyme in the conversion of metal ions into metal nanoparticles with an example of biosynthesis of copper, silver, and zinc nanoparticles by using bacterial strain *Streptomyces* sp. and to show the application of bacterial synthesis as an eco-friendly method for the production of nanoparticles. Nanofertilizers are seen to offer several advantages over traditional fertilizers. For example, nano-fertilizers contribute to proper efficiency in using water, nutrients, and other resources in agriculture, thus yielding more crops. Nano-fertilizers increase the nutrient supply and uptake to plants and, thereby enhancing plant growth and development. Nano-fertilizers are used in much lower quantities compared to the common bulk fertilizers. That is, nano-fertilizers can lower the proportion of nutrients lost into the environment through means such as surface runoff, leaching, and volatilization. By preventing this loss, they increase the nutrient supply to the plant. Second, they reduce nutrient losses to the environment, reducing water and soil (Bairwa *et al.*, 2023; Kumari *et al.*, a2023).

Integrating nanotechnology into agriculture offers promising opportunities to boost efficiency and promote sustainable farming methods. Emphasis in research and development needs to continue on green and sustainable nanotechnology, studying a possible impact on the environment and health, and development of an adequate regulatory framework for the safe and effective use of nanotechnology in agriculture.

Advantages of nanofertilizers over conventional fertilizers

Nano fertilizers are claimed to have a number of advantages over the currently available technologies. The most cited reasons are that, with a controlled and targeted mode of releasing nutrients, nano fertilizers will have a reduced effect on leaching. For instance, ZnO, SiO_2, and TiO_2 nanoparticles have been demonstrated to improve plant performance under drought conditions by increasing photosynthetic efficiency, grain yield, and pollen germination. Moreover, with the positive effect of each type of nanoparticle on plants under saline stress, contribution to seed production and plant development with less negative effect of sodium chloride in increased nutrient use efficiency was achieved (Yadav *et al.*, 2023). Nanomaterials for use in nano fertilizer technology can vary from advanced materials like layered double hydroxides (LDHs) to nano capsules, nano gels, and polyurethane-based nano fertilizers. They are built with controlled release and targeted delivery mechanisms, which increase nutrient use efficiency and decrease environmental impacts while at the same time increasing crop yields. The detailed analysis of each component is presented below:

1. LDHs are a class of layered materials with very unique anion exchange ability. LDHs are a group of positively charged layers that intercalate anions and water molecules between their interlayer spaces. Ion release from LDH into the soil is regulated by an ion-exchange reaction whereby anions in the soil replace the intercalated anions within the LDH structure. This release is controlled by factors such as pH and ionic strength of the soil and the presence of competing anions, whereby, in this way, nutrient release could be regulated under different conditions related to soil or crop demands (Ibrahimova, 2022; Pattappan *et al.*, 2023).
2. Nanocapsules are micro-sized particles that carry nutrients and target plants. The base design has been given to the capsules, including restricting the release of nutrients by the gradual degradation of the shell or by reactions responsive to release, such as moisture, acidity, or temperature. This would provide sustainable delivery of nutrients and improved efficiency by plants in taking up these nutrients (Zhang *et al.*, 2021; Vasisht, 2023).
3. Nano-gels are three-dimensional networks that load and deliver nutrients in a targeted way to plants involved in nano-fertilizer technology. The nano gel is an absorbent, wide-channel network responsible for carrying nutrient interaction with the surrounding environment. The nano gel can gradually release the nutrient as the interaction takes place with factors such as soil, moisture, and acidity, hence improving nutrient availability and reducing losses from the soil (Abobatta, 2023; Saraiva *et al.*, 2023).
4. Nutrient carriers based on polyurethane polymers in polyurethane-based nano fertilizers pack the nutrients and release them slowly when the polyurethane reacts with the soil or the environment. Thus, the nutrient availability in the soil increases when the loss decreases through one or another environmental factor. As a whole, nano-fertilizers would ensure better nutrient use efficiency and the sustainability of nutrient supply to plants by reducing leaching effects, and in turn, improve plant performance under drought and saline conditions. However, more assurance of their safety and effectiveness needs to be ensured by investigating their long-term environmental and health effects before they find wide use (Salam *et al.*, 2022).

Effect of nanoparticle properties on plant nutrient interaction

The properties of nanoparticles critically influence nutrient delivery, how these will be released, and uptaken by plants. Some fundamental properties include their size and shape, which influence the eventual interactions between nanoparticles and plant tissues, including the soil environment. For example, nanoparticles are taken up and transported from the soil to other parts of the plant through mechanisms like passive diffusion and endocytosis. It has been shown that metal nanoparticles, metal oxide nanoparticles, carbon-based nano particles, and nanoplastics have their pathways for absorption and distribution in the plant system.

These include direct penetration of plant tissues, involving migration to various plant parts and probably accumulation in edible parts, making it a consideration for human health and environmental safety (Horejs, 2022). Some of the identified pathways are summarized in (Table 1) below:

Table 1: Identified pathways for nanomateriales in agriculture

Type	Study detail
Carbon-based nanoparticulates	Research on carbon nanoparticles found that they were taken up by roots and translocated through the plant's vascular system to the stems and leaves (Sembada and Lenggoro, 2024).
Nanoplastics	Research on nanoplastics has shown that they enter the plant through the root system, mainly accumulating at root zones, and are potentially phytotoxic (Sun *et al.*, 2023).
Metal oxide nanoparticles	Uptake of metal oxide nanoparticles, such as CuO and ZnO, was reported in plant roots, along with their phytotoxic potential on root hair morphology and cell structure (Lv *et al.*, 2019).
Metal nanoparticles	Silver and gold nanoparticles have been absorbed through plant roots and translocated to other parts that may contain edible portions, which can put health at potential risk (Huang *et al.*, 2022).

In conclusion, the effectiveness of nutrient delivery systems based on nanoparticles is dependent on the capability to move across the complex plant structure, which involves overcoming physical obstacles such as the cell wall. Thus, unique nanoparticle designs consider plants and mammalian cells' structural dissimilarities, and as a result, the performance of nutrient delivery systems in agriculture can be enhanced. Consequently, this will enable the tailoring of nanoparticles to improve their functionality and interaction with plant physiology, thus enhancing their safe and efficient use in boosting plant growth and yield (Gao *et al.*, 2023).

Potential of nanofertilizers to mitigate nutrient loss through leaching and volatilization.

The potential of nano fertilizers to reduce nutrient loss through leaching and volatilization resides in these unique characteristics: High surface area, improved solubility, and the capability to target specific parts of the plant more effectively compared to conventional fertilizers. Nano fertilizers, besides enhancing crop yields, reduce nutrient loss. Leaching refers to a process through which soluble nutrients are moved vertically down the soil away from the reach of plant roots. Leaching affects nutrients such as nitrogen and potassium, which are highly mobile (Zahra *et al.*, 2022). Nanofertilizers can minimize leaching through slow and steady nutrient release, which is made possible by their nanoscale size and encapsulation of nutrient particles. For example, polymer-coated urea nanoparticles have been shown to release nitrogen more consistently with crop uptake and have shown to diminish nitrogen leaching by as much as 50% (Yadav *et al.*, 2023).

Volatilization reduction means the loss of nutrients in the gaseous state, which is particularly pronounced for nitrogen in the form of ammonia. It can be cut with nanofertilizers, since they enable nutrients to be rapidly consumed by plants. Thus, using nano-encapsulated urease inhibitors, for example, significantly reduced NH_3 volatilization by temporarily reducing urea hydrolysis, which enabled nitrogen applied to be used more effectively. Based on several findings, it can be safely concluded that nanotechnology-carried out mainly through the use of nano-fertilizers is a very promising area for revolutionizing nutrient delivery systems in agriculture. The study concludes that the use of nanofertilizers can significantly reduce environmental nutrient losses, as consistently reported in studies (Gade *et al.*, 2023; Kumar *et al.*, 2023; Mirbakhsh, 2023; Saraiva *et al.*, 2023; Yadav *et al.*, 2023). Moreover, nanofertilizers have controlled-release systems and high nutrient uptake rates; thus, they represent a sustainable efficient substitute to conventional fertilizers. Nanofertilizers are making progress in crop production by using nanoparticles to gradually deliver nutrients over time rather than causing environmental contamination, runoff or leaching. This leads to the increasing sustainability of agriculture and reduces the ecological risks connected with traditional fertilizers.

Synergistic effects of microorganisms and nanofertilizers:

1- Microbial-nanoparticle interactions in soil: Insights into biological and non-biological processes

Interactions of microorganisms with nanoparticles in soil may be very complex and can exert both positive and negative effects. Plant-associated organisms, such as endophytes, play an important role in the agroecosystem. They can regulate soil fertility and nutrient availability and are involved in the proper health maintenance of plants. Nanoparticle applications in agriculture through nano fertilizers or nano pesticides open new opportunities for enhancing nutrient consumption efficiency and crop protection. The impact of nanoparticles on soil microbiota remains a topic of considerable uncertainty, with conflicting findings emerging from studies on their effects on plant growth, microbial communities, and soil health. While some research has reported positive outcomes, others have identified potential risks and challenges associated with nanoparticle use, underscoring the need for further investigation into this complex issue. Ultimately, understanding microbe-nanoparticle interactions in soils involves deconstructing on how these interactions might impact the fate of carbon and microbial diversity and substrate chemistry (Mgadi *et al.*, 2024). Ultimately, understanding microbe-nanoparticle interactions in soils involves deconstructing how these interactions might impact the fate of carbon and microbial diversity and substrate chemistry. State-of-the-art mass spectrometry techniques have been applied and show the microbial metabolism and resulting products from soil organic matter (SOM) within the lipid fractions of soils. Statistical analysis has used permutational multivariate analysis of variance and principal coordinate analysis to show the effects on microbial communities and chemical composition of dissolved organic matter and lipids exerted by different soil and substrate types. These methodologies can trace complex interactions among microbial diversity, substrate chemistry, and SOM transformation and turnover processes. They provide insights into the possible decomposition products formed and their contribution to stable SOM formation (Raczka *et al.*, 2021).

The soil microbiome is a critical component in biogeochemical cycles, the health of plants, and ecosystem functioning. For example, if relating interactions between plants and their associated microbiomes to plant health, such knowledge on structure, variation, and assembly would be central to root-associated microbiomes. Soil and seed-associated bacterial communities drive both the recruitment and assembly of these microbiomes. It has also been underlined by research that seed-borne plant beneficial endophytes play an essential role in plant growth and resilience against environmental stressors. An interaction such as the one discussed here, together with how nanoparticles impact microbial communities and soil health, underpin the sustainable application of nanotechnology in agriculture. By deconstructing these interactions, researchers seek to harness nanotechnology in improving crop protection and soil management and reducing threat factors over competitive soil microbiomes and ecosystem health (Banerjee and Van Der Heijden, 2023).

2- Microbial-mediated effects on nanoparticle stability and solubilization

Microorganisms have a vital role in stabilizing, dispersing, and increasing the bioavailability of nanoparticles. This field is essential for the future of nanotechnology in medicine and environmental sciences. Recent studies have highlighted several ways to improve the characteristics of nanoparticles by interacting with microorganisms themselves or the bio molecules they produce. These include one such demonstration of cyclic poly ethylene glycol physisorption significantly enhancing the dispersion stability of gold nanoparticles. This forms a protective mechanism that shall protect the AuNPs from aggregation in physiological conditions or the presence of NaCl or electrolytes accountable for aggregation. This is a clear message to the nanoparticles to stay dispersed, which is very idealistic for their stability in biological environments (Wang *et al.*, 2020).

Moreover, nanoencapsulation has been applied to enhance their stability and increase biological activity. In this regard, carotenoids present an excellent example since they show relatively low bioavailability and a relatively high susceptibility to oxidation. For instance, nanoliposomes and polymeric nanoparticles have developed encapsulating carotenoids that accelerate their *in vitro* release and antioxidant capacity. Such nanostructures create more favorable conditions for carotenoids, improving their options in terms of stability, hence increasing their bioavailability and biological activity. It is noted that such studies prove the critical role of microorganisms and biomolecules in improving the physical and biological properties of nanoparticles. More advanced processes, like nanoencapsulation and surface modification or creating hybrid structures to a great extent, make it possible to increase the stability, dispersion, and bioavailability of nanoparticles. This becomes the base for more successful applications in various fields (Sridhar *et al.*, 2021).

3- Case studies demonstrating the synergistic effects of microbe-nanofertilizer combinations on crop productivity and resilience.

Looking into sustainable farming methods is crucial for both ensuring global food security and minimizing the environmental impact of agriculture. One promising method involves blending nanomaterials with plant probiotics, which could enhance crop yields and reduce the negative effects of farming on the environment. This strategy explores how this combination might help mitigate the drawbacks of agrochemicals, making their use safer and more effective. By integrating plant probiotics with nanomaterials, we might also achieve better controlled release and encapsulation, leading to longer shelf life and more eco-friendly farming practices (Upadhayay *et al.*, 2023).

The integration of microbial inoculants and nanofertilizers into precision agriculture and sustainable farming systems will actively and intentionally employ soil microbiomes as a safeguard measure for soil health against changing climates. Using the structural and functional diversities of the plant microbiota for enhancing plant health and performance, this integration will become possible in the foreseeable future. However, the more challenging part is developing precision regular microbiome management that will ensure the full integration of microbial inoculants as a standard agricultural practice. Achieving this goal will imply eliminating the existing variability of these practices and boosting the understanding of the beneficial microbes involved. As a result, precision microbiome management options will be indispensable, focusing on the role of microbial diversity in ecosystem services and ag. sustainability (French *et al.*, 2021).

Integrating microbial inoculants with nano fertilizers in agriculture may improve crop tolerance to drought and phosphorus deficiency, especially under legume-cereal intercropping. Under these stresses, the interaction among the microbial consortia and such cropping systems is complex but has enormous potential to improve plant growth and soil health. The way microbial inoculants act in response to abiotic factors in soils is pretty unpredictable, especially under intercropping conditions. Further research into these interactions is required to develop more effective strategies for managing microbial consortia in agriculture (Benmrid *et al.*, 2023).

Environmental implications and risk assessment:

1- Environmental fate and behavior of nanoparticles in soil and water systems

A combination of chemical, physical, and biological processes controls the destiny and behavior of engineered nanoparticles following their release into the environment. Environmental factors drive dozens of chemical and physical transformations, including homo- or hetero-agglomeration, dissolution/sedimentation, adsorption, oxidation, reduction, sulfidation, as well as photochemically and biologically mediated reactions as shown in Fig. (1). All of these processes cause significant changes in the mobility, bioavailability, and toxicity of engineered nanoparticles (ENPs). The most important environmental factors that determine the rate and outcome of these processes include the physico-chemical properties of the ENPs such as particle size, surface area, as well as zeta potential/surface charge, colloidal stability, and core-shell composition, environmental conditions, and other factors such as pH, ionic strength, presence of organic and inorganic colloids, temperature, etc. Finally, it is worth noting that, in the environment, organisms often confront confronted with transformed ENPs rather than the pristine ENPs material, as these nanomaterials interact with different environmental matrices and co-pollutants. Combining these facts suggest that the research of the behavior of the transformed ENPs is integral to complete the background understanding of the environmental fate, bioavailability, and mode of toxicity of ENPs a complex interplay of chemical, physical, and biological processes governs the destiny and behavior of engineered nanoparticles (ENPs) upon release. Released ENPs are also dynamic and undergo continuous changes due to many environmental factors. These transformations include homo- or hetero-agglomeration, dissolution/sedimentation, adsorption, oxidation, reduction, sulfidation, and photochemically and biologically mediated reactions Fig. (1). Such processes can change the mobility, bioavailability, and toxicity of ENPs quite significantly. The physicochemical characteristics of ENPs-particle size, surface area, zeta potential/surface charge and colloidal stability, core-shell composition-environmental conditions such as pH, ionic strength, presence of organic and inorganic colloids, temperature, etc. come out to be key influencing factors for these transformations as shown in Fig. (2). It is essential to recognize that, more often organisms in the environment are exposed to transformed ENPs rather than pristine materials because of their interaction with various environmental matrices and other pollutants. This makes researching the behavior of transformed ENPs with a view to proper comprehension of ENP ecological fate, bioavailability, and mode of toxicity imperative (Amde *et al.*, 2017; Bundschuh *et al.*, 2018).

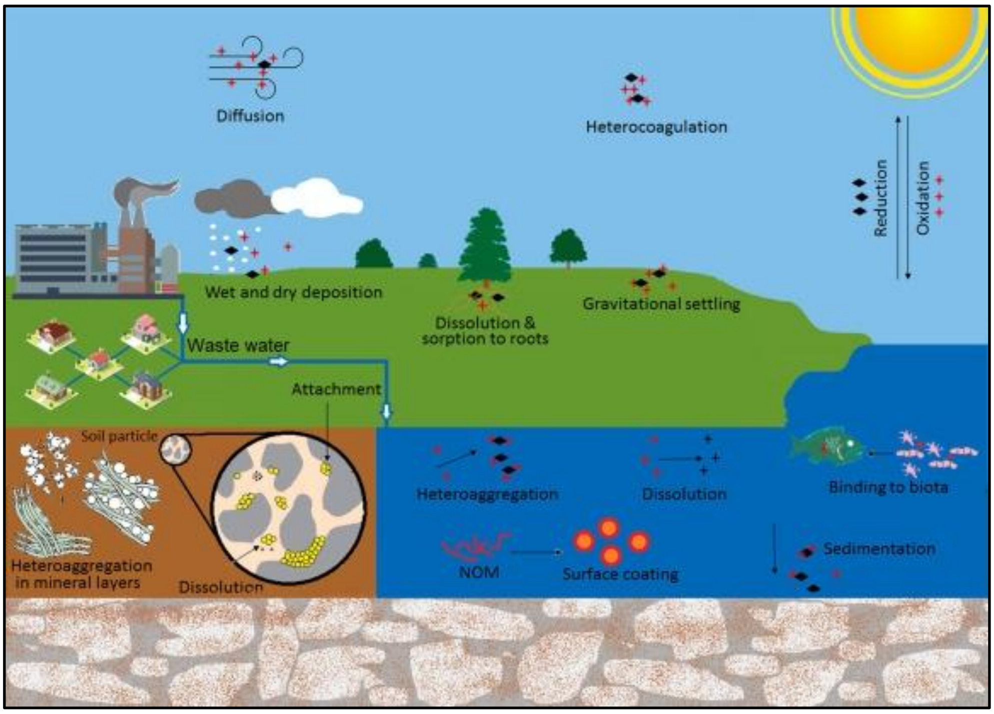

Fig. 1: Pathways and transformations of ENPs in the atmosphere, aquatic and terrestrial environments (Batley *et al.*, 2013).

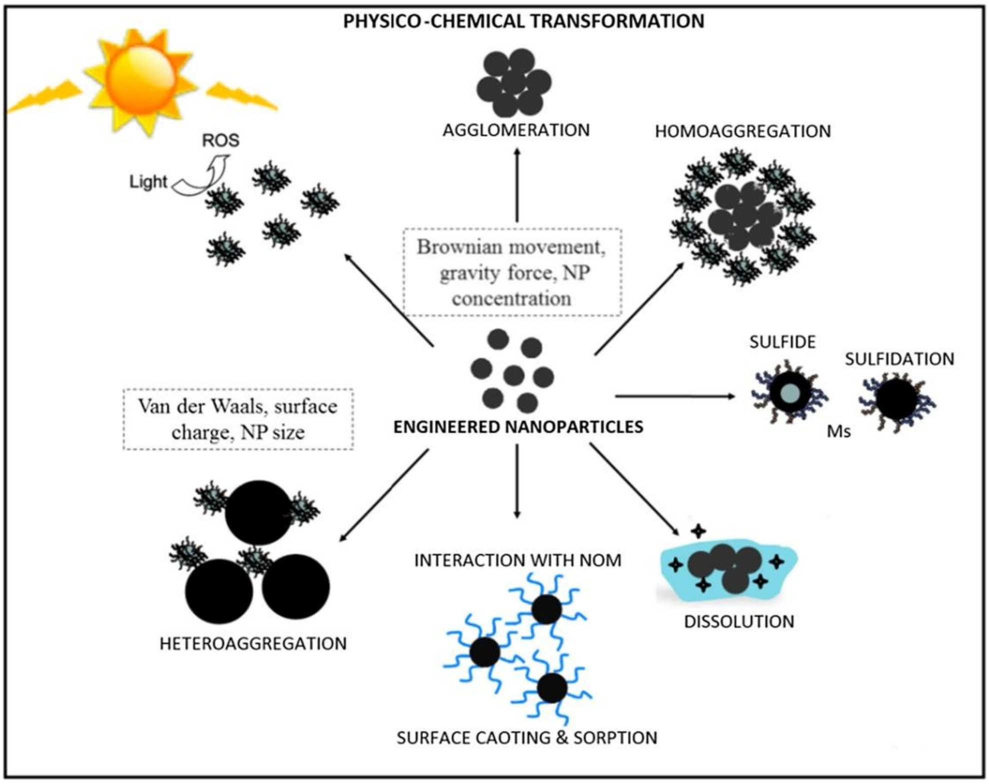

Fig. 2: Physico-chemical and biological transformations of NPs (Pachapur *et al.*, 2016; Abbas *et al.*, 2020).

Engineered nanoparticles typically enter soil, water, and sediments through the discharge of wastewater, sewage sludge, and solid waste Fig. (3). Each year, about 270,000 metric tons of these nanomaterials are produced. Over one year, approximately 270,000 metric tons of widely used ENMs are produced. Landfills and soils are the leading sinks of these ENPs, receiving about 63-91% and 8-28% of the total production volumes, respectively, while the aquatic environment receives around 7%. With the above as the background, to have a better idea about processes related to the fate and transformation of ENPs in both aquatic and terrestrial environments, attention must be given to the current findings and advancements (Abbas *et al.*, 2020).

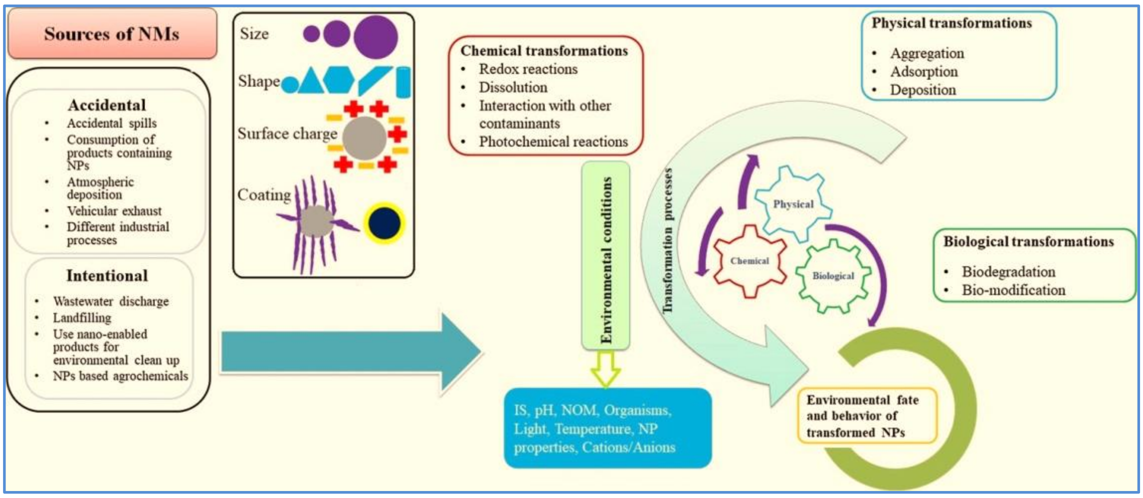

Fig. 3: Schematic diagram showing the release sources and transformations of engineered NPs in the environment (Abbas *et al.*, 2020).

2- Ecotoxicological effects of nanofertilizers on soil microorganisms, insects, and water ecosystems

Nanofertilizers offer significant potential in agriculture by improving crop yields, mitigating various stresses, and enhancing soil fertility. Nonetheless, their environmental impacts, particularly on soil microbiota and beneficial insects, as well as their effects on water bodies and crop quality, require thorough examination (Verma *et al.*, 2022). Nanoparticles have the potential to substantially influence soil microbiota, which plays a crucial role in nutrient cycling, soil health, and plant growth. Developing comprehensive evaluation systems and specialized biotechnologies is essential to mitigate any negative effects and ensure the sustainable use of nanofertilizers (Yadav *et al.*, 2023). The insecticidal properties of some nanoparticles may pose risks to beneficial insects, which are vital for pollination, pest control, and biodiversity, potentially disrupting ecological balance (Hu *et al.*, 2023). Moreover, runoff from nanofertilizers can lead to the accumulation of nanoparticles in aquatic environments, raising concerns about their impact on aquatic plants and animals. The behavior of nanoparticles in these settings can affect their distribution, availability, and toxicity to aquatic life (Nongbet *et al.*, 2022).

Applications of nanotechnology in agriculture

1- Nano-fertilizers: These are designed to slowly release nutrients, thus raising efficiency in the use of nutrients and lowering environmental pollution. Nano-fertilizers help in increasing plant growth, yield, and quality by providing precise nutrition to plants (Khatri and Bhateria, 2023).
2- Nano-pesticides: The nano-formulations of active ingredients in the pesticide witness improvement in solubility, stability, and bioavailability, thereby helping in effective management against pests and diseases. This will result in the overall reduction in the use of chemical inputs and their negative impact on the environment (Kumar et al., 2024).
3- Nanosensors: Nanosensors are used in precision agriculture; they can detect various parameters such as soil nutrients, moisture, among other environmental conditions. This can help increase water and fertilizer use efficiency. It can also be used to monitor plant health and detect diseases in the earliest stages (Yeshe et al., 2022).

4- Nano-biotechnology: Nanotechnology may also help in the delivery of genetic material used in crop improvement, to develop crops that have better features than what are in existence, for example, that are drought-resistant, nutrient-efficient, and resist pests (Javed et al., 2023).
5- Water treatment-nanomaterials can be used in the treatment of water, thus availability of clean water for irrigation can be ensured; irrigation is an important factor in agriculture in both arid and semi-arid areas (Soren *et al.,* 2023).

Addressing knowledge gaps and technical barriers to scaling up microbe-nanofertilizer applications

A thorough understanding of the intricate interactions between microbes and nanoparticles, as well as the environmental factors that impact these interactions, is essential for bridging existing knowledge gaps and overcoming technical challenges. Such insights are vital for advancing the practical application of microbe-nanofertilizers. Nanoparticles biosynthesized by microbes are a capture and enzymatic reduction process of metal capping, which shows the potential of microbial nanofactories. Such microbial processes may lead to nanoparticles with certain beneficial properties for plant growth promotion and stress tolerance (Ghosh *et al.*, 2021).

Mineral-microbe interactions are fundamental as they influence microbial growth, metabolism, and the transformation of minerals. These interactions are pivotal in applications such as bioleaching, mineral fertilizer production, and environmental restoration. Nonetheless, the agricultural potential of these interactions remains significantly underexplored and underutilized. Key challenges include the need for improved mineral-based culture media to enhance microbial resource recovery and to accurately differentiate between biogenic and abiogenic minerals (Dong *et al.,* 2022).

To overcome these challenges, the research specifically targets the following areas:

6- Explore the processes by which microbes synthesize nanoparticles (NPs), focusing on metal reduction and stabilization.
7- Investigate how interactions between minerals and microbes can be utilized to develop more effective nanofertilizer formulations.
8- Improve microbial inoculant formulations to enhance their effectiveness across diverse soil and environmental conditions, with particular attention to intercropping systems experiencing drought and phosphorus deficiency (Benmrid *et al.*, 2023).

This kind of interdisciplinary work among microbiologists, nanotechnologists, agronomists, and soil scientists is needed to adopt such strategies for new developing agricultural practices. The ability to overcome such gaps in knowledge and technological hurdles is very likely to render microbe-nanofertilizer technologies scalable and therefore much more applicable in the systems of sustainable and productive agriculture.

Societal acceptance, adoption, and governance of nanotechnology-driven agricultural innovations.

Societal acceptance, adoption, and governance of nanotechnology-driven agricultural innovations are complex processes that involve numerous considerations. They vary from comprehension of the technological readiness of opportunities provided by nanotechnology to the codification of primary obstacles that inhibit their development for sustainable agriculture. Consumer attitude development to nanotechnology when it is integrated into food production is one of the major aspects as public perceptions are extremely influential to new technology adoption and governance (Hofmann *et al.,* 2020).

Research in this line indicates that nanotechnology revolutionizes agriculture by developing new agrochemicals that minimize negative environmental footprints while maximizing crop production and crop protection, such as in the use of nanofertilizers, nanopesticides, nanobiosensors, and nano-enabled remediation strategies for contaminated soils (Tyagi *et al.*, 2023).

This is an innovation that could be mainstreamed to be used in agriculture under only a comprehensive framework that includes issues like risk assessment, public engagement, and regulation.

Governance of nanotechnology in agriculture requires realizing the economic development and societal benefits that result from the new technologies, while adequately protecting public health and the environment. Nanotechnology governance includes principles and approaches which are used to manage its potential impacts of engineered nanomaterials. It will also have to take a 'One Health' approach toward understanding the possible use and impacts of the developed nanotechnologies in agriculture for environmental sustainability and health-related problems.

Critical in this area, however, is an interdisciplinary research focus on the societal implications of innovations toward sustainable application of nanotechnology in agriculture. It implies an understanding of the ethical, legal, and social issues in the use of nanotechnology in food and agriculture as well as all technological and scientific developments. This only means that it will be a stakeholder-based process to social acceptability and informed policies of governance where benefits and risks related to nanotechnology-driven agricultural innovations are clearly communicated (Hofmann *et al.*, 2020).

Safety and regulatory considerations of nanotechnology in agriculture

The use of nanotechnology in the domain of agricultural practices, and particularly through nanofertilizers and nano-pesticides, is soon going to bring about a change in the management and production of crops. However, the very novelty and complexity of these nanomaterials call for adequate vetting of their safety and regulatory oversight. These concerns emanate from possible risks on human health, environmental sustainability, and the ecological balance. One of the primary concerns associated with the use of nanotechnology in agriculture is its long-term effect on human health. Nanoparticles possess special penetration capabilities which makes it possible for them to cross the biological barriers and accumulate in most tissues of the body hence probably resulting in uncalled for health complications. It is in this respect that this uncertainty calls for a profound study on the toxicological profile of nanomaterials used in agriculture by determining their effects at a cellular and molecular level (Kumari *et al.*, b2023).

There is no understating the environmental footprint of nanotechnology. It may be expected that the persistence of nanoparticles in both soil and water bodies would pose potential disruptive threats in natural ecosystems, hitting both terrestrial and aquatic life forms. The modification of soil microbial communities, key players in nutrient cycling and plant growth, coupled with the bioaccumulation potential in aquatic species, calls for the setting of ecological risk assessment tailor-made for these nanomaterials. The mitigation of these risks calls for setting up broad regulatory frameworks that account for the entire life cycle of nano-agricultural products.

This will involve strict stages in their production, application, and disposal so that minimal amounts are released to the environment and human exposure is assured. The regulatory agencies, such as the FAO and the world health organization (WHO), at the national level, have a strong interest in making the guidelines flexible enough so that it leads to innovation with safety (Peidaei *et al.*, 2021). The laws should focus on the following:

1- Risk assessment: Comprehensive assessment, which should include exposure risks and toxicological profiles of nanomaterials, to allow evidence-based decision-making toward their use in agriculture.
2- Product labeling: Compulsory disclosure of nano-content in agricultural products shall enable informed choice on the part of the consumers.
3- Sustained research efforts: It is an ongoing process of studying the environmental and health effects of nanotechnology to be well understood in the public domain, and the development of safer alternatives.

4- Agreed global standards: International cooperation in standardizing regulations of nanotechnology for assuring safety and fairness of the global agricultural markets (Peidaei *et al.*, 2021) (Kumari *et al.*, 2023b).

Importance of adopting responsible nanotechnology practices to minimize unintended consequences

To summarize, the reasons why responsible nanotechnology practices should be adopted are as follows:

1- Its nature gives rise to serious and complex questions of ethics, safety, environmental, and social justice (Babatunde *et al.*, 2019).
2- Health and safety: Nanoscale materials have unique properties that are not fully understood, and they may cause a health risk. For example, because nanoparticles are more reactive and penetrate biological membranes more easily than their larger counterparts, they may have toxicological effects. To safeguard workers and consumers, responsible practices need rigorous safety testing and guidelines for handling nanomaterials (Buruk *et al.*, 2024).
3- Environmental impact: Nanoparticles can have a surprising environmental effect. The small size and reactivity of nanoparticles will assess all their impact on ecosystems and living organisms very hard to make before trying to reduce them. Applied responsible nanotechnology includes assessing and minimizing environmental risks, developing sustainable nanoproducts, and requiring nanoparticles to not change air, water, and soil quality (Babatunde *et al.*, 2019).
4- Regulatory frameworks-since the harms of nanomaterials is still unknown and not well understood there is probability that the currently existing regulation are inadequate to address them all. Hence, it is crucial to elaborate pertinent rules and norms related to nanomaterials and nano-applications to exclude potential negative effects in the sphere of safety and ecology. This also calls for international collaborations in the deve-lopment of standard guidelines and measures (Buruk *et al.*, 2024).
5- Public trust and engagement: Any societal integration of nanotechnology will rely on public perception and support of the technology, for such wide-ranging integration to be executed to assure consideration of public values in nanotechnologies development, openness and communication of risks versus benefits to society and involvement in deciding are required (Arvidsson *et al.*, 2018).

CONCLUSIONS

Nanotechnology in agriculture is one of the game-changing innovations that will bring enormous outcomes toward both sustainability and efficiency in farming practices. Eco-friendly nanoparticle synthesis methods, coupled with the evolving field of nanofertilizers, hold considerable potential. These innovations are anticipated to boost crop yields, strengthen plant resistance to environmental stresses, and improve the efficiency of nutrient use. These range from layered double hydroxides and nanocapsules/nanogels to polyurethane-based nanofertilizers, providing precision in the delivery of nutrients and thus reducing resource wastage and ecological footprints. The complex interaction of nanoparticles with the soil microbiota holds excellent potential for the sustainable enhancement of soil health toward betterment in agricultural productivity, but associated ecological consequences of nano fertilizers and stringent safety assessments need to be balanced against the benefits about safeguarding humans and the environment. Nanotechnology is thus the new frontier of agricultural development; however, its responsible application will call for careful regulation of potential risks that might be posed against agricultural ecosystems in the process.

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تقنية النانو في الزراعة

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الملخص

شهد القطاع الزراعي تطورًا ملحوظًا في السنوات الأخيرة نتيجة لتطبيق تقنيات النانو، حيث تهدف هذه المراجعة إلى تقديم رؤية شاملة للحالة الراهنة في هذا المجال، مع التركيز على أبرز التطورات والتحديات التي برزت. تتناول المراجعة الفئات المختلفة للمواد النانوية المستخدمة في الزراعة، بما في ذلك الهياكل النانوية القائمة على الكربون، وأجهزة النانو من أشباه الموصلات، والنهج الصديقة للبيئة. يُظهر التحليل أن هذه المواد تمتلك إمكانيات واعدة في تحسين غلة المحاصيل، وتقليل الفاقد الزراعي، وتعزيز ممارسات الزراعة المستدامة. بالإضافة إلى ذلك، تستعرض المراجعة المخاطر والتحديات المحتملة المرتبطة باستخدام الجسيمات النانوية، مثل تأثيرها على التوازن الميكروبي في التربة، وضرورة تطوير أنظمة تنظيمية فعالة. تهدف هذه المراجعة في مجملها إلى تقديم فهم معمق لدور تقنيات النانو في تحويل القطاع الزراعي وتحديد المجالات البحثية التي تتطلب مزيدًا من الاستكشاف والتطوير.

الكلمات الدالة: تكنولوجيا النانو في الزراعة، الزراعة الدقيقة، تعزيز المحاصيل، المواد النانوية، الاستدامة الزراعية.