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Microalgae as future food: Nutritional composition, safety, and bioprocessing challenges

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Abstract
The integration of nanotechnology into agriculture offers a transformative pathway toward improving crop productivity, resource efficiency, and environmental sustainability. Nanoparticles (NPs), including nano-fertilisers, nanopesticides, nano-herbicides, nano-growth promoters, and nanocarrier delivery systems, are increasingly being developed to provide precision-based solutions for modern farming. These innovations enhance nutrient uptake, improve resistance to pests and pathogens, increase abiotic stress tolerance, and enable soil remediation while minimizing agrochemical overuse and environmental pollution. Their nanoscale properties allow for controlled release and targeted action, thereby reducing input waste and ecological toxicity. However, the rapid growth of agricultural nanotechnology raises critical concerns regarding its long-term ecological safety, environmental footprint, and potential adverse effects on soil microbiota, beneficial insects, and aquatic ecosystems. Furthermore, the lack of standardized synthesis protocols and limited understanding of nanoparticle persistence and transformation in agroecosystems represent major challenges to safe adoption. Green synthesis approaches using biological resources provide a promising alternative to conventional chemical methods, aligning nanotechnology with ecological responsibility. To ensure balanced progress, Life Cycle Assessment (LCA), risk assessment frameworks, and globally harmonized regulations are urgently needed. This review critically examines the applications, mechanisms, and environmental interactions of nanoparticles in agriculture while emphasizing the need for sustainable and safe practices. By bridging nanoscience with agroecology, nanotechnology can play a pivotal role in advancing agricultural innovation that supports both food security and environmental stewardship.

Keywords: Nanotechnology, agriculture, nanoparticles, nano-fertilisers, nanopesticides, crop productivity, sustainable farming

Introduction

Agriculture in the twenty-first century is confronted with unprecedented challenges that threaten global food security and the sustainability of farming systems. Rapid population growth is placing enormous pressure on existing agricultural resources, necessitating higher crop yields to meet rising food demands. At the same time, climate change has introduced unpredictable weather patterns, droughts, floods, and temperature extremes that directly affect crop productivity and soil health. Land degradation caused by intensive farming practices, overgrazing, and deforestation further exacerbates the problem by reducing arable land availability and soil fertility. Adding to these concerns, the growing prevalence of pest and pathogen resistance to conventional agrochemicals underscores the urgent need for alternative solutions that are both effective and environmentally sustainable [1].

Conventional agricultural inputs such as chemical fertilizers, herbicides, and pesticides have undoubtedly supported global food production for decades. However, their excessive and indiscriminate use has led to several adverse consequences. Nutrient run-off contributes to water eutrophication and aquatic ecosystem disruption, while pesticide residues pose risks to human and animal health. Long-term use of synthetic inputs often disrupts soil microbial communities, depletes organic matter, and reduces the natural resilience of soils [2]. Moreover, the reliance on high doses of chemical agents accelerates the development of resistant pest populations, leading to a vicious cycle of increased input requirements and reduced effectiveness. Such practices are unsustainable in the long term and highlight the urgent need for novel approaches that balance productivity with ecological responsibility.

Nanotechnology has emerged as a promising platform to address these challenges by revolutionizing modern agriculture through precision-based interventions. At its core, nanotechnology involves the manipulation of materials at the nanoscale, typically ranging from 1 to 100 nanometers [3]. At this scale, particles exhibit unique physicochemical properties such as increased surface area, reactivity, and bioavailability that are not observed in their bulk counterparts. These properties can be harnessed to design smart agricultural inputs that are more efficient, targeted, and environmentally friendly compared to conventional formulations.

Applications of nanoparticles in agriculture are broad and multifaceted. Nano-fertilisers have shown potential in improving nutrient uptake efficiency by releasing nutrients in a controlled and sustained manner, thereby minimizing leaching losses and reducing input waste. Nanopesticides and nano-herbicides offer precision pest and weed management by delivering active ingredients directly to the target organisms, lowering the amount of chemical needed and reducing collateral damage to non-target species. Similarly, nanocarrier systems enable the encapsulation of agrochemicals, protecting them from premature degradation while ensuring controlled release under specific environmental conditions [4]. Beyond crop management, nanoparticles have also been explored for soil remediation, where they enhance pollutant degradation and support soil health restoration. In addition to productivity enhancement, nanoparticles offer solutions to some of the pressing problems caused by climate change. For instance, nano-enabled plant growth promoters have been shown to improve plants' tolerance to abiotic stresses such as drought, salinity, and temperature fluctuations. By strengthening stress resilience, these innovations could significantly contribute to stabilizing yields in vulnerable regions facing harsh climatic conditions [5]. Furthermore, the integration of nanosensors in agriculture facilitates real-time monitoring of soil nutrients, moisture levels, and pest presence, advancing the concept of precision farming that minimizes resource use while maximizing outputs, the application of nanoparticles in agriculture also raises critical questions and concerns. The fate of nanoparticles in soil, water, and plant systems remains poorly understood, particularly in terms of their long-term interactions with agroecosystems. Potential toxicity to beneficial soil microorganisms, pollinators, and aquatic organisms is a major concern that requires thorough investigation. Moreover, most studies demonstrating the benefits of nanoparticles are limited to laboratory or greenhouse settings, with very few large-scale field trials validating their real-world applicability [6]. The absence of standardized synthesis methods and risk assessment protocols further complicates efforts to regulate and safely implement nanotechnology in farming practices.

Given these opportunities and challenges, there is a clear need for comprehensive evaluation and responsible development of agricultural nanotechnology. Green synthesis approaches using biological systems such as plants, microbes, and agricultural waste have shown promise in producing eco-friendly nanoparticles that minimize environmental hazards associated with chemical synthesis. Life Cycle Assessment (LCA) frameworks, alongside standardized toxicological studies, are also essential to understand the broader ecological and economic implications of nanoparticle use [7]. Policymakers, researchers, and industry stakeholders must collaborate to establish guidelines that balance innovation with safety, ensuring that nanotechnology contributes positively to sustainable food production.

This review article aims to provide a critical overview of the integration of nanotechnology into agriculture. It will discuss the diverse applications of nanoparticles in crop productivity, stress management, pest control, and soil remediation. It will also highlight the mechanisms through which nanoparticles interact with plants and soil systems, evaluate the potential risks associated with their use, and outline future directions for sustainable adoption. By bridging nanoscience and agroecology, this article seeks to demonstrate how nanotechnology can reshape modern farming practices to meet the dual goals of food security and environmental stewardship [8].

Table 1: Applications of Nanotechnology in Agriculture

Application Area	Type of Nanoparticle	Benefits	Examples	References
Nano-fertilisers	ZnO, SiO_2, Fe_2O_3	Controlled nutrient release, reduced leaching, improved uptake	Nano-Zn for flowering, Nano-Si for drought resistance	[Liu *et al*., 2020] [4]
Nanopesticides	AgNPs, CuNPs, polymeric NPs	Targeted pest control, reduced dosage, longer stability	AgNPs against fungal pathogens	[Kah *et al*., 2019] [2]
Nano-herbicides	Encapsulated herbicides	Controlled release, reduced soil accumulation	Nano-paraquat formulations	[Kumar *et al*., 2021] [3]
Nano-plant growth promoters	Carbon nanotubes, SiNPs	Enhanced photosynthesis, enzyme activity, hormone regulation	CNTs promoting root elongation	[Rastogi *et al*., 2019] [5]
Nanocarrier systems	Lipid- or polymer-based NPs	Improved solubility, sustained release, reduced wastage	Nano-encapsulated glyphosate	[Fraceto *et al*., 2016] [1]
Soil bioremediation	Iron oxide, biochar NPs	Heavy metal removal, degradation of pollutants, soil fertility restoration	Fe_3O_4 NPs for Pb removal	[Shen *et al*., 2020] [6]

Table 2: Mechanisms of Plant-Nanoparticle Interactions

Mechanism	Impact on Plants	Potential Concerns
Enhanced nutrient absorption	Improves nutrient efficiency and growth	Possible nanoparticle accumulation in edible tissues
Modulation of antioxidant enzymes	Increases stress tolerance	Overactivation may cause oxidative stress
Regulation of gene expression	Promotes growth and stress signaling pathways	Unintended alterations in metabolic pathways
Interaction with rhizospheric microbiota	Influences nutrient cycling and soil fertility	May disrupt beneficial microbial communities

Table 3: Environmental and Ecological Concerns of Agricultural Nanoparticles

Concern	Description	Research Needs
Persistence in ecosystems	Nanoparticles may accumulate or transform in soil and water	Long-term field studies on stability and degradation
Trophic transfer	Potential movement through food chains	Studies on bioaccumulation and biomagnification
Impacts on non-target organisms	Effects on soil microbes, pollinators, and aquatic life	Comprehensive ecotoxicological assessments
Synthesis methods	Chemical synthesis involves toxic reagents	Advancement of green synthesis approaches

Table 4: Key Challenges and Future Research Priorities

Challenge	Suggested Solutions/Research Directions
Lack of standardized testing protocols	Develop global guidelines for nanoparticle characterization and safety
Limited long-term ecological studies	Multi-year field trials across diverse agroecosystems
High cost of green synthesis	Scale-up bio-based synthesis using agricultural waste and microbes
Integration with agroecological practices	Combine nanotech with crop diversification and soil conservation
Public acceptance and regulations	Transparent communication, participatory policymaking, harmonized standards

2. Applications of Nanotechnology in Agriculture

The integration of nanotechnology into agricultural practices offers innovative strategies to enhance productivity, resource efficiency, and environmental stewardship. Nanoparticles and nanocarrier systems provide opportunities to optimize nutrient delivery, improve pest and weed control, stimulate plant growth, and restore soil health. This section explores the major applications of nanotechnology in agriculture, highlighting their mechanisms, benefits, and potential limitations.

2.1 Nano-Fertilisers

Nano-fertilisers represent one of the most widely studied applications of agricultural nanotechnology. Unlike conventional fertilisers that often release nutrients indiscriminately, nano-fertilisers deliver nutrients directly to plants in a controlled and sustained manner [9]. Due to their nanoscale size and high surface reactivity, these formulations enhance nutrient uptake efficiency while significantly reducing leaching losses into groundwater.

For instance, nano-urea has been developed to release nitrogen gradually, improving assimilation by crops and minimizing volatilization losses. Similarly, nano-phosphates exhibit higher solubility and mobility, addressing the issue of phosphorus fixation in soils. Some advanced nano-fertilisers are designed to respond to specific environmental triggers such as soil pH, temperature, or moisture, ensuring that nutrients are released only when needed. This precision delivery not only boosts crop yields but also contributes to more sustainable nutrient management by reducing excess application.

2.2 Nanopesticides and Nano-Herbicides

Pests and weeds continue to be among the most significant threats to crop productivity. Conventional pesticides and herbicides, while effective, often require large doses and can have detrimental impacts on non-target organisms and ecosystems. Nanopesticides and nano-herbicides offer a solution by enabling precision pest and weed management with reduced dosages [10].

Encapsulation of active ingredients within nanocarriers protects them from degradation caused by sunlight, heat, or microbial activity, thereby extending their shelf life and enhancing stability. Controlled release mechanisms allow pesticides and herbicides to act gradually, maintaining effective concentrations over longer periods and reducing the frequency of applications [11]. Additionally, nanoformulations improve the solubility of poorly soluble active compounds, thereby increasing their bioavailability and efficacy.

Examples include silver nanoparticles with antimicrobial activity against crop pathogens, and nano-encapsulated herbicides that target specific weed species while sparing crop plants. Such innovations minimize off-target toxicity, reduce chemical residues, and lower the risk of resistance development among pests and weeds.

2.3 Nano-Plant Growth Promoters

Beyond nutrient supply and pest management, nanoparticles can directly influence plant growth and development. Nano-plant growth promoters are engineered to modulate physiological and biochemical processes within plants, enhancing productivity and resilience to stress.

For example, nano-silica has been shown to improve drought tolerance by strengthening plant cell walls and reducing water loss. Nano-zinc enhances flowering and fruit set by regulating hormonal pathways and improving enzyme activity involved in carbohydrate metabolism. Similarly, nano-titanium dioxide has been reported to increase photosynthetic efficiency by enhancing light absorption and chlorophyll activity [12].

These growth-promoting nanoparticles provide a unique opportunity to improve crop performance under both optimal and adverse conditions. Importantly, they can help plants withstand abiotic stresses such as salinity, temperature fluctuations, and heavy metal toxicity—factors increasingly relevant under changing climate conditions.

2.4 Nanocarrier Systems for Agrochemicals

Nanocarriers play a pivotal role in enhancing the performance of agrochemicals by offering targeted delivery and controlled release. These nanoscale carriers, which include liposomes, dendrimers, micelles, and polymeric nanoparticles, encapsulate agrochemicals and protect them from premature degradation.

One of the major advantages of nanocarriers is their ability to deliver agrochemicals at specific sites of action. For example, pH-sensitive nanocarriers release their cargo in acidic environments such as pest guts or infected plant tissues. This targeted approach not only enhances efficacy but also reduces the amount of agrochemical needed, thereby lowering environmental contamination.

Nanocarriers also improve the solubility and stability of hydrophobic compounds, which are otherwise difficult to apply in aqueous agricultural systems [13]. Their sustained-release profiles ensure that crops receive a steady supply of agrochemicals over time, reducing the need for frequent applications. Collectively, these features make nanocarrier systems an attractive tool for sustainable and precision farming.

2.5 Soil Bioremediation

Soil health is fundamental to sustainable agriculture, yet it is increasingly threatened by contamination with heavy metals, pesticides, and industrial pollutants. Nanotechnology offers novel strategies for soil bioremediation through the use of reactive nanoparticles that can bind, transform, or degrade contaminants.

Iron oxide nanoparticles, for instance, are widely employed for the immobilization of heavy metals such as lead, cadmium, and arsenic, thereby reducing their bioavailability and toxicity [14]. Carbon-based nanomaterials such as graphene oxide and carbon nanotubes enhance the adsorption of organic pollutants, while photocatalytic nanoparticles like titanium dioxide promote the degradation of persistent pesticides under sunlight.

These nanoscale interventions not only detoxify soils but also restore microbial balance and improve fertility. In addition, certain nanoparticles can stimulate microbial activity, further accelerating the natural processes of pollutant degradation. By integrating nanotechnology into soil remediation strategies, it becomes possible to rehabilitate degraded lands and ensure long-term agricultural sustainability.

Nanotechnology provides a diverse array of tools to address the multifaceted challenges facing agriculture today. From nano-fertilisers that optimize nutrient delivery to nanocarriers that enable targeted agrochemical application, these innovations promise to enhance productivity while minimizing environmental harm. Furthermore, applications such as soil bioremediation and nano-plant growth promotion underscore the potential of nanotechnology not only to sustain but also to transform agricultural systems. Nevertheless, while the benefits are compelling, further research into long-term impacts, safety, and regulatory frameworks remains critical to ensure responsible and sustainable implementation.

3. Mechanisms of Plant-Nanoparticle Interactions

Understanding the mechanisms by which nanoparticles (NPs) interact with plants is essential for evaluating both their potential benefits and possible risks in agricultural systems [15]. At the nanoscale, materials acquire unique surface properties and reactivities that allow them to influence plant physiology in ways that conventional bulk materials cannot. These interactions occur at multiple levels, from the root-soil interface to cellular and molecular processes inside the plant.

3.1 Uptake and Transport of Nanoparticles

Nanoparticles are capable of crossing plant root epidermal barriers more efficiently than bulk particles due to their small size and large surface area. They can penetrate the apoplastic pathway (cell wall spaces) or symplastic pathway (through plasmodesmata) to reach root cortical and vascular tissues. Once inside, they are translocated through the xylem and phloem, enabling distribution to aerial tissues such as leaves, stems, and flowers [16]. The uptake efficiency depends on NP size, surface charge, coating, and the physiological state of the plant. For example, positively charged NPs often bind more effectively to negatively charged root cell walls, enhancing absorption.

3.2 Enhancement of Nutrient Absorption

One of the most significant mechanisms by which NPs benefit plants is by improving nutrient acquisition. Nano-fertilisers, such as nano-iron, nano-zinc, or nano-phosphates, bypass traditional limitations of nutrient solubility and availability. Their small size allows them to diffuse more readily into root tissues, while their controlled-release properties ensure sustained nutrient supply. This leads to improved nutrient use efficiency, reduced leaching losses, and enhanced crop productivity.

3.3 Modulation of Antioxidant Enzyme Activity

Nanoparticles also influence plant responses to abiotic stress by modulating antioxidant enzyme activity. Abiotic stresses such as drought, salinity, and heavy metal toxicity often cause oxidative stress in plants, leading to overproduction of reactive oxygen species (ROS). NPs such as nano-selenium or nano-cerium oxide can activate antioxidant enzymes including superoxide dismutase (SOD), catalase (CAT), and peroxidases (POD) [17]. This modulation reduces oxidative damage, stabilizes cellular structures, and improves tolerance to environmental stressors.

3.4 Influence on Gene Expression

At the molecular level, NPs can trigger changes in the expression of genes involved in growth regulation, stress signaling, and defense responses. For instance, exposure to nano-zinc has been shown to upregulate genes associated with auxin biosynthesis, thereby promoting root elongation and branching. Similarly, nano-silica can activate genes linked to drought and salinity tolerance. While such changes hold potential for boosting plant resilience, they also raise questions about unintended alterations in gene networks that could have long-term effects.

3.5 Interaction with Rhizospheric Microbiota

The rhizosphere, the narrow soil region influenced by plant roots, harbors a diverse community of microorganisms that play vital roles in nutrient cycling, nitrogen fixation, and disease suppression. NPs can influence these microbial communities both directly and indirectly. Some NPs stimulate beneficial microbes, enhancing nutrient solubilization and uptake, while others may exhibit antimicrobial effects that disrupt microbial balance. For example, silver NPs are known for their antimicrobial activity, which could suppress pathogenic microbes but also inadvertently harm beneficial rhizobacteria [18]. Such disruptions may affect soil fertility and plant-microbe symbioses critical for sustainable agriculture.

3.6 Balancing Benefits and Risks

While these mechanisms underscore the potential of NPs to enhance plant productivity and stress resilience, they also highlight possible risks. The long-term ecological consequences of altering gene expression or disrupting rhizosphere microbiota are not fully understood. Thus, a balanced approach is necessary—maximizing benefits while carefully monitoring and mitigating risks through standardized experiments and field trials.

4. Environmental and Ecological Concerns

Despite their promise, nanoparticles in agriculture raise several environmental and ecological concerns. Their unique properties that enhance efficiency in plants also mean they may persist in ecosystems, interact unpredictably with non-target organisms, or accumulate across trophic levels [19]. Understanding these risks is critical for the responsible deployment of nanotechnology in agriculture.

4.1 Persistence and Transformation in Ecosystems

One of the foremost concerns is the persistence and transformation of NPs once introduced into the environment. Unlike conventional agrochemicals, whose degradation pathways are relatively well characterized, the behavior of NPs in soil and water systems is complex [20].

NPs can undergo aggregation, dissolution, oxidation, or reduction depending on environmental conditions such as pH, temperature, ionic strength, and organic matter content. For example, metal oxide NPs such as nano-TiO_2 or nano-ZnO may persist for long periods in soils, while silver NPs can transform into ionic forms with different reactivities. These transformations may alter their toxicity, mobility, and bioavailability. NPs can interact with soil colloids, clay particles, and organic matter, influencing their retention or leaching potential. Over time, accumulation of NPs in soils may alter soil structure, microbial diversity, and nutrient cycling. Trophic transfer through the food chain is another concern—plants that accumulate NPs may pass them to herbivores, with cascading effects on higher trophic levels.

Comprehensive studies assessing the environmental fate of NPs are still limited, and more research is required to understand their long-term impacts on ecosystems.

4.2 Impacts on Non-Target Organisms

The use of NPs in agriculture may also have unintended consequences for non-target organisms.

- **Soil Microorganisms:** Beneficial microbes such as nitrogen-fixing bacteria and mycorrhizal fungi are essential for soil fertility. However, exposure to certain NPs, particularly metallic ones, can inhibit microbial growth or enzymatic activity, thereby disrupting soil microbial balance.
- **Aquatic Life:** Run-off containing NPs may reach aquatic systems, where they can accumulate in sediments and interact with fish, algae, and invertebrates. Studies have shown that high concentrations of silver or zinc oxide NPs can impair photosynthesis in algae and induce oxidative stress in fish.
- **Beneficial Insects:** Pollinators and predators such as bees and ladybirds may also be affected by NPs, either through direct exposure or indirectly via contaminated nectar, pollen, or prey. Since pollinators are critical for global food security, even low-level risks need careful evaluation.

These concerns highlight the urgent need for ecotoxicological studies that go beyond laboratory settings to include realistic field conditions and multi-species interactions.

4.3 Green Synthesis Approaches

A promising way to reduce the environmental footprint of NPs is through green synthesis methods. Conventional NP synthesis often relies on chemical reducing agents, stabilizers, and solvents that are hazardous to the environment and costly to manage. In contrast, green synthesis employs biological resources such as plant extracts, algae, fungi, and bacteria as reducing and stabilizing agents. Plant extracts rich in polyphenols, flavonoids, and alkaloids can efficiently reduce metal ions into NPs under mild conditions, avoiding toxic by-products. Similarly, microbial systems can biosynthesize NPs through enzymatic pathways, producing biocompatible and stable nanostructures [12]. These methods are not only eco-friendly but also cost-effective and scalable. Green-synthesized NPs often exhibit superior biocompatibility and lower toxicity to non-target organisms compared to chemically synthesized counterparts. Additionally, the use of agricultural waste or by-products for NP synthesis supports circular economy principles, reducing waste streams while generating high-value nanomaterials.

4.4 The Way Forward

The environmental and ecological concerns surrounding agricultural nanotechnology cannot be overlooked. While green synthesis provides a safer alternative, challenges remain in scaling up production, standardizing methods, and ensuring consistent quality. Regulatory frameworks must evolve to address the unique properties of NPs, with guidelines for safe synthesis, application, and disposal.

Interdisciplinary research combining nanoscience, ecology, soil science, and toxicology is critical to build a comprehensive understanding of NP behavior in agroecosystems [1]. Field-based Life Cycle Assessment (LCA) and risk assessment models will help determine the net benefits and trade-offs of using nanotechnology in agriculture, the responsible development of agricultural nanotechnology requires balancing innovation with ecological stewardship. If environmental and ecological risks are carefully managed, nanotechnology holds immense potential to transform agriculture into a more sustainable, resilient, and productive system.

5. Life Cycle Assessment and Sustainability

Life Cycle Assessment (LCA) has emerged as a critical framework for evaluating the environmental and socio-economic impacts of new technologies. In the context of agricultural nanotechnology, LCA provides a holistic means of assessing not only the benefits of nanoparticle (NP) applications but also the hidden costs that may arise during production, use, and disposal [13]. This comprehensive approach ensures that technological innovations align with sustainability objectives and do not inadvertently introduce new environmental burdens.

The first stage of an LCA focuses on the production of nanoparticles. Conventional synthesis methods often require high energy inputs, toxic solvents, and hazardous reducing agents, which can contribute to greenhouse gas emissions and chemical waste generation. Green synthesis alternatives—using biological resources such as plant extracts, fungi, or agricultural residues—are increasingly promoted as sustainable options. By integrating renewable feedstocks and low-energy processes, green synthesis aligns more closely with circular economy principles. Evaluating the energy balance and carbon footprint of these methods compared to chemical synthesis is a vital step toward sustainable scaling.

During the usage phase, NPs are applied in various agricultural contexts, such as nano-fertilisers, nanopesticides, and nanocarrier-based agrochemicals. LCA evaluates how these applications influence crop yields, resource efficiency, and environmental outcomes. For instance, the controlled release of nutrients from nano-fertilisers reduces leaching losses, lowers the demand for repeated applications, and minimizes eutrophication risks in water bodies. Similarly, nanopesticides can achieve effective pest control with smaller dosages, reducing chemical residues and non-target toxicity. These benefits represent clear environmental gains compared to conventional agrochemicals [14]. However, LCA also examines trade-offs such as the potential accumulation of nanoparticles in soils or their unintended impacts on microbial diversity and ecosystem functioning.

The disposal and end-of-life phase present some of the greatest uncertainties in agricultural nanotechnology. Unlike conventional fertilisers or pesticides that degrade into well-characterized by-products, nanoparticles may persist, transform, or bioaccumulate in unexpected ways. LCA studies highlight the need to account for long-term ecological interactions, including potential trophic transfer across food chains [19]. Standardized methodologies for quantifying NP residues in soil and water are still lacking, which complicates accurate impact assessments. Developing these protocols is essential for ensuring that disposal pathways are included in sustainability evaluations.

An important feature of LCA is its integration of environmental, economic, and social dimensions. For agricultural nanotechnology, this means assessing not only ecological risks but also farmer adoption rates, cost-benefit ratios, and public acceptance. For example, while nanoparticle-based inputs may reduce input costs and boost yields, their initial production costs may be higher than conventional products. This raises questions about accessibility for smallholder farmers, especially in developing regions where food security challenges are most acute, embedding LCA in the design and implementation of agricultural nanotechnologies ensures that innovations deliver net positive outcomes [6]. By combining life cycle thinking with green chemistry and agroecological principles, nanotechnology can contribute meaningfully to global sustainability goals such as climate resilience, biodiversity conservation, and sustainable food production.

6. Challenges and Future Perspectives

Despite the promising applications of nanotechnology in agriculture, several challenges impede its widespread adoption. Addressing these barriers is crucial for ensuring that nanotechnology evolves into a safe, effective, and sustainable tool for global food systems [12] A primary challenge is the lack of standardized testing protocols for agricultural nanoparticles. Current studies vary widely in experimental design, nanoparticle characterization, and toxicity testing, making it difficult to compare results across studies or establish universal guidelines. Standardization is essential to build reliable datasets that inform regulatory decisions and enable reproducibility in research. Another significant limitation is the paucity of long-term ecological studies. Most research to date has been confined to laboratory or greenhouse conditions, with relatively short observation periods. While these studies demonstrate promising outcomes, they cannot capture the complexity of agroecosystems, where nanoparticles may interact with diverse organisms, soil types, and climatic conditions over extended time frames. Large-scale field trials and multi-year studies are urgently needed to evaluate nanoparticle persistence, transformation, and ecological impacts under realistic agricultural scenarios [12]. The development of scalable and cost-effective green synthesis methods remains another hurdle. Although plant- and microbe-based nanoparticle production has shown eco-friendly potential, challenges in standardizing yields, maintaining particle uniformity, and scaling production for commercial use persist. Advances in bioprocess engineering and nanobiotechnology will be critical to overcoming these barriers. Integration of nanotechnology with agroecological practices and policies is also essential. Nanotechnology should not be viewed in isolation but as part of a broader strategy that includes crop diversification, soil conservation, and climate adaptation. Policies must encourage responsible innovation by promoting research into eco-friendly formulations and incentivizing sustainable farming practices that harmonize with nanotechnology.

Finally, public acceptance and regulatory harmonization present ongoing challenges. Public perceptions of nanotechnology are often shaped by concerns about safety and unknown risks [7]. Transparent communication of scientific evidence, combined with participatory decision-making, can foster trust among stakeholders. At the regulatory level, disparities between countries in defining, testing, and approving nanoparticles create barriers to global adoption. Harmonized international standards will be essential to facilitate trade, the future of agricultural nanotechnology lies in balancing innovation with ecological responsibility. Emerging research directions include the use of systems biology and omics technologies to study nanoparticle-plant-microbe interactions, as well as agroecosystem modeling to predict long-term outcomes. Interdisciplinary collaboration among nanoscientists, agronomists, ecologists, and policymakers will be key to shaping nanotechnology as a cornerstone of sustainable agriculture.

7. Conclusion

Nanotechnology offers transformative opportunities to address the pressing challenges of modern agriculture, from enhancing nutrient efficiency to mitigating environmental pollution and increasing crop resilience. Applications such as nano-fertilisers, nanopesticides, nanocarrier systems, and soil remediation tools highlight the potential of nanoscale innovations to improve productivity while reducing the ecological footprint of farming. Furthermore, advancements in nano-enabled plant growth promoters and stress modulators demonstrate how nanotechnology can enhance resilience against climate-induced stresses. the introduction of nanoparticles into agroecosystems raises legitimate environmental and societal concerns. Issues such as persistence in soils, impacts on non-target organisms, and the lack of long-term ecological data underscore the importance of precautionary approaches. Green synthesis methods, coupled with Life Cycle Assessment, offer pathways to reduce risks and align nanotechnology with global sustainability goals. Future success will depend on addressing key challenges: establishing standardized testing protocols, advancing scalable green synthesis methods, conducting long-term ecological studies, and fostering regulatory harmonization across regions. Public acceptance and farmer adoption will also play pivotal roles in shaping the trajectory of agricultural nanotechnology. the integration of nanotechnology into agriculture represents both a profound opportunity and a responsibility. If guided by principles of sustainability, transparency, and inclusivity, nanotechnology can become a powerful enabler of food security and environmental stewardship. By bridging cutting-edge nanoscience with agroecological values, humanity can chart a path toward resilient farming systems that meet the demands of a growing population while preserving the health of ecosystems for future generations.

References

1. Fraceto LF, Grillo R, de Medeiros GA, Scognamiglio V, Rea G, Bartolucci C. Nanotechnology in agriculture: Which innovation potential does it have? Front Environ Sci. 2016;4:20.
2. Kah M, Kookana RS, Gogos A, Bucheli TD. A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues. Nat Nanotechnol. 2019;13(8):677-84.
3. Kumar S, Nehra M, Dilbaghi N, Marrazza G, Hassan AA, Kim KH. Nano-based smart pesticide formulations: Emerging opportunities for agriculture. J Control Release. 2021;329:123-37.
4. Liu R, Lal R, Zhang G. Nanotechnology for sustainable agriculture: Applications and implications. Sci Total Environ. 2020;728:138918.
5. Rastogi A, Tripathi DK, Yadav S, Chauhan DK, Živčák M, Ghorbanpour M, *et al*. Application of silicon nanoparticles in agriculture. 3 Biotech. 2019;9:90.
6. Shen Z, Hou D, Jin F, O'Connor D, Luo X, Xu D. Lead removal from contaminated soil with biochar-supported nanoscale zero-valent iron. Environ Pollut. 2020;261:114223.
7. Chhipa H. Nanofertilizers and nanopesticides for agriculture. Environ Chem Lett. 2019;17:1-22.
8. Parisi C, Vigani M, Rodríguez-Cerezo E. Agricultural nanotechnologies: What are the current possibilities? Nano Today. 2015;10(2):124-7.
9. Gupta S, Yusuf AA, Sridhar A, Suthar MB, Lakineni PK, Bhor HN. International review of advanced learning and teaching technologies. J e-Sci Lett. 2024;5(2):1-?. doi:10.51470/eSL.2024.5.2.01
10. Rastogi A, Živčák M, Tripathi DK, Yadav S, Kalaji HM, He X, *et al*. Impact of metal and metal oxide nanoparticles on plant physiology: A review. Plant Physiol Biochem. 2017;110:2-12.
11. Yosung L, Swamy GN, Ramesh G, Gupta S, Mohiuddin M. Integrating water management, nutrient inputs, and plant density: A holistic review on optimizing cotton yield under variable agroecosystems. Plant Sci Rev. 2020;1(1):1-?. doi:10.51470/PSR.2020.01.01.01
12. Vidhya CS, Swamy GN, Das A, Noopur K, Vedulla M. Cyclic lipopeptides from *Bacillus amyloliquefaciens* PPL: Antifungal mechanisms and their role in controlling pepper and tomato diseases. Microbiol Arch Int J. 2023;5(2):1-?. doi:10.51470/MA.2023.5.2.1
13. Chawla R, Mondal K, Pankaj MS. Mechanisms of plant stress tolerance: Drought, salinity, and temperature extremes. Plant Sci Arch. 2022;4(8):1-?. doi:10.51470/PSA.2022.7.2.04
14. Sher Sing S, Singh J, Sangma JJD, Chowhan LB, Yashan N. Phubbing: A study to access entrepreneurial drive within apple growers of Kashmir Valley. J Bus IT Soc Sci. 2025;4(1):1-?. doi:10.51470/BITS.2025.04.01.08
15. Sangma JJD. Artificial intelligence in food analysis and nutritional surveillance: Current applications and future potential. J Food Biotechnol. 2024;5(2):13-9. doi:10.51470/FAB.2024.5.2.13
16. Manjulatha G, Rajanikanth E. Emerging strategies in climate change mitigation and adaptation. Environ Rep Int J. 2022;4(2):1-?. doi:10.51470/ER.2022.4.2.06
17. Servin A, Elmer W, Mukherjee A, De la Torre-Roche R, Hamdi H, White JC, *et al*. A review of the use of engineered nanomaterials to suppress plant disease and enhance crop yield. J Nanopart Res. 2015;17:92.
18. Usman M, Farooq M, Wakeel A, Nawaz A, Cheema SA, ur Rahman MA, *et al*. Nanotechnology in agriculture: Current status, challenges, and future opportunities. Sci Total Environ. 2020;721:137778.
19. Sangma JJD. Biofortification as a sustainable strategy to combat malnutrition and hidden hunger. J Food Biotechnol. 2024;5(2):7-12. doi:10.51470/FAB.2024.5.2.07
20. Sangma JJD. Next-generation functional foods: Bridging gut microbiota modulation and personalized nutrition. Microbiol Arch Int J. 2024;6(1):61. doi:10.51470/MA.2024.6.1.61