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Nanoparticle Innovations in Plant Systems: Enhancing Photosynthesis and Nutrient Dynamics

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Plant nanobionics is an innovative interdisciplinary approach which integrates engineered nanoparticles into plant systems to enhance their natural functionalities and enable novel capabilities. This paper explores the potential of nanoparticles to improve photosynthetic efficiency, nutrient uptake, and increase plant resilience against environmental stressors. Enhancing carbon fixation with functionalized silica nanoparticles, reducing photoinhibition with cerium oxide nanoparticles, and broadening the light absorption spectrum with nanomaterials such as carbon nanotubes (CNTs) and quantum dots are some of the main uses of plant nanobionics. These

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advancements offer solutions to fundamental limitations in photosynthesis, including suboptimal light ustilization, restricted carbon dioxide availability, and oxidative stress.
Nanoparticles also revolutionize nutrient management through innovations such as nanofertilizers and chelated metal nanoparticles. These technologies enhance nutrient bioavailability, minimize environmental impacts, and improve plant growth in nutrient-deficient soils. For example, zinc oxide and iron oxide nanoparticles encourage the effective delivery and uptake of nutrients, while titanium dioxide and carbon-based nanomaterials contribute to soil remediation by immobilizing heavy metals and improving soil health.
Nanotechnology in agriculture offers transformative benefits such as increased crop yields, sustainable resources management, and climate change mitigation. However, challenges such as environmental safety, scalability, and regulatory considerations must be addressed to ensure responsible application. This study highlights the role of plant nanobionics in advancing agricultural productivity and sustainability, emphasizing its potential to address global challenges such as food security and environmental conservation.

Keywords: Plant nanobionics; nanoparticles; photosynthesis; nutrient uptake; sustainable agriculture.

1. INTRODUCTION

Plant nanobionics is an emerging interdisciplinary field that integrate the principles of nanotechnology with plant biology to enhance and expand plant functionalities far beyond their innate capabilities. This cutting-edge field focuses on the integration of engineered nanoparticles into plant tissues or cells, enabling plants to perform tasks that they cannot achieve naturally (Sharma & Kar, 2019). By introducing nanoparticles, scientists aim to enhance the efficiency of photosynthesis, optimize nutrient uptake, and strengthen plants against environmental stressors such as drought, salinity, and pathogens (Francis et al., 2024). These advancements are pivotal in addressing pressing global challenges like food security, resource efficiency, and climate change adaptation. For instance, augmenting photosynthesis with nanomaterials such as carbon nanotubes and quantum dots can significantly improve light absorption and energy conversion efficiency, directly boosting plant productivity (Giraldo et al., 2014; Li et al., 2021). Similarly, nanoparticles like zinc oxide or chelated iron improve nutrient bioavailability and uptake, mitigating deficiencies in poor soils and reducing dependency on conventional fertilizers, which often contribute to environmental degradation (Prasad et al., 2017). Furthermore, nanoparticles with antioxidant properties, such as cerium oxide, help plants to combat oxidative stress caused by extreme environmental conditions, (Sun et al., 2019). This innovative field not only holds promise for sustainable agricultural practices but also opens avenues for creating "smart plants" capable of environmental monitoring or pollutant removal. However, despite its potential, plant nanobionics must address challenges such as environmental safety, scalability, and regulatory frameworks to ensure its responsible application (Usman et al., 2020; Rico et al., 2011).

2. THE CONCEPT OF PLANT NANOBIONICS

Plant nanobionics involves the integration of nanomaterials—particles typically ranging in size from 1 to 100 nanometers scale—into plant tissues to improve or extend their natural capabilities. These nanomaterials interact with plant biological processes at the molecular and cellular levels, offering opportunities to enhance physiological functions or introduce entirely novel ones (Butnariu & Butu, 2019). Due to their unique properties such as high surface area, small particles size and greater reactivity, nanoparticles easily penetrate in plant cells, bind to specific biomolecules, and directly influence key biochemical pathways (Mu et al., 2014).

The applications of plant nanobionics span a wide spectrum, but two primary focuses stand out; improving photosynthesis efficiency and enhancing nutrient acquisition (Guirguis et al., 2023). By introducing nanomaterials like carbon nanotubes and quantum dots into chloroplasts, researchers have successfully extended the light absorption range of photosynthetic pigments and allowing plants to utilize a broader spectrum of light for energy conversion (Elhefnawy & Elsheery, 2023). Additionally, nanoparticles functionalized with enzymes or other bioactive molecules have shown promise in boosting carbon fixation and reducing energy losses in the Calvin cycle (Swift et al., 2019).

In terms of nutrient acquisition, nanomaterials such as zinc oxide and iron chelated nanoparticles improve the bioavailability of essential nutrients in soils, particularly in environments where nutrients are scarce or immobilized (Ahmad & Ahmad, 2024). These nanoparticles are designed to release nutrients in a controlled manner, ensuring optimal absorption by plant roots and reducing nutrient losses to leaching or volatilization (Hyder et al., 2023). This dual capability to enhance photosynthesis and nutrient uptake highlights the transformative potential of plant nanobionics in advancing sustainable agriculture and meeting the global demand for food production (Mony et al., 2022).

3. ENHANCING PHOTOSYNTHESIS WITH NANOPARTICLES

Photosynthesis, the process by which plants convert light energy into chemical energy, driving energy flow in ecosystems and sustaining food production. Despite its importance, photosynthesis is inherently inefficient with limitations in light capture, carbon fixation, and vulnerability to photoinhibition (Moore & Brudvig, 2011). Nanotechnology provides innovative solutions to these challenges, using engineered nanoparticles to enhance photosynthetic efficiency and improve overall plant productivity (Wilhelm & Selmar, 2011).

3.1 Improved Light Absorption

Nanoparticles such as carbon nanotubes (CNTs) and quantum dots are gaining significant attention for their exceptional optical properties, which allow them to absorb and convert light much more efficiently than natural pigments like chlorophyll. These nanoparticles can be engineered to interact with plant cells and enhance their photosynthetic processes by extending the range of light absorbed (Peng et al., 2024). For instance, CNTs and quantum dots can capture light in wavelengths that are typically underutilized by plants, such as ultraviolet (UV) and infrared (IR) light. By incorporating these nanoparticles into chloroplasts, plants can better harness the full spectrum of sunlight resulting improve the overall photosynthetic efficiency (Jafir et al., 2024).

Studies have demonstrated that embedding single-walled CNTs into chloroplasts of *Arabidopsis thaliana* significantly enhances photosynthetic activity, with increases of up to 30% in photosynthesis. This improvement is largely attributed to the enhanced light harvesting capabilities and increased electron transport efficiency facilitated by the CNTs (Velikova et al., 2021). CNTs are particularly effective in reducing energy losses during the absorption process, thereby maximizing energy utilization for growth (Giraldo et al., 2014). Similarly, quantum dots have shown promise in improving energy capture and transfer, as they possess unique optical and electronic properties, such as size-tunable light absorption and fluorescence. Research has indicated that quantum dots can improve energy conversion rates by directly transferring excitation energy to photosystems, which results in more efficient light-to-energy conversion (Tan et al., 2021).

Moreover, the integration of nanoparticles like CNTs and quantum dots into chloroplast can lead to enhanced electron flow within the photosynthetic apparatus. This not only improves light absorption but also increases electron transport, which is crucial for the efficient conversion of light energy into chemical energy (Guirguis et al., 2023). Recent advancements in nanomaterials are focused on optimizing these nanoparticles for specific wavelengths of light, allowing for targeted improvements in photosynthesis under varying environmental conditions. This level of precision could be pivotal in boosting plant productivity, especially in regions where light conditions are less than ideal for traditional photosynthesis (Swift et al., 2019).

3.2 Enhanced Carbon Dioxide Capture

Carbon fixation in the Calvin cycle is a crucial yet often limiting step in photosynthesis. The availability of carbon dioxide (CO_2) is one of the major bottlenecks in this process, especially under conditions of low atmospheric CO_2 or in plants with limited access to this essential resource (Ducat & Silver, 2012). To address this challenge, recent advancements in plant nanobionics have focused on enhancing the conversion of CO_2 into bicarbonate ions, which are more readily utilized by the Calvin cycle. One promising approach involves the use of functionalized silica nanoparticles with carbonic anhydrase (CA) mimicking enzymes facilitate the rapid conversion of atmospheric CO_2 into bicarbonate ions, thus increasing the bioavailability of CO_2 within chloroplasts and enhancing the overall efficiency of carbon fixation (Shekhawat et al., 2021).

The incorporation of carbonic anhydrase-mimicking silica nanoparticles into plant systems has shown significant promise in improving the rate of carbon fixation. These nanoparticles mimic the natural role of carbonic anhydrase, an enzyme found in plants that accelerates the interconversion between CO_2 and bicarbonate (Bose & Satyanarayana, 2021). Increased availability of bicarbonate ions in the chloroplasts not only accelerates the Calvin cycle but also improves the plant's overall photosynthetic efficiency (Zolotareva et al., 2023).

Recent studies have demonstrated that functionalized silica nanoparticles can significantly enhance the rate of photosynthesis in plants (Yoon et al., 2019). Application of these nanoparticles to *Arabidopsis thaliana* resulted in a 25% increase in carbon fixation rates (Lu et al., 2020). This improvement was attributed to the enhanced ability of the plant to concentrate CO_2 around RuBisCO, thus alleviating one of the primary limitations in photosynthesis. Furthermore, the ability to fine-tune the properties of these nanoparticles, such as their size, surface charge, and functionalization, allows for greater control over their interaction with plant cells, optimizing their effect on the Calvin cycle (Montes et al., 2017).

In addition to enhancing carbon fixation, the use of these nanoparticles could potentially mitigate the effects of elevated CO_2 levels in the atmosphere, contributing to climate change mitigation by improving the efficiency of photosynthesis in crops (Hussain et al., 2021). This approach aligns with broader goals to increase agricultural productivity while reducing the environmental impact of farming. By optimizing one of the most critical steps in photosynthesis, nanoparticles functionalized with CA-mimicking enzymes hold great promise for improving plant productivity and addressing food security challenges in a changing climate (Prasad et al., 2017).

3.3 Reduction of Photoinhibition

Photoinhibition is a phenomenon that occurs when plants absorb excessive light, particularly during periods of high solar radiation, which can overwhelm the photosynthetic apparatus. This excess energy is not efficiently processed by the plant's photosystems, leading to damage and the generation of harmful reactive oxygen species (ROS). ROS are highly reactive molecules that can cause oxidative stress, damaging cellular components such as lipids, proteins, and DNA, ultimately impairing plant growth and productivity (Rico et al., 2013). To combat photoinhibition, researchers have turned to cerium oxide nanoparticles (nanoceria), which are known for their powerful antioxidant properties. These nanoparticles can effectively scavenge ROS, protecting plant cells from oxidative damage and preserving the integrity of the photosynthetic apparatus (Djanaguiraman et al., 2018).

Nanoceria's has unique properties, including its ability to catalytically neutralize ROS, make them a great option for safeguarding plants in high light levels (Reed et al., 2014). Studies have shown that when cerium oxide nanoparticles are applied to plants, they act as potent antioxidants, minimizing oxidative stress and reducing photodamage of the chloroplasts. This enables plants to maintain optimal photosynthetic efficiency, even under stressful conditions such as intense sunlight, drought, or heat. For instance, a study found that the application of nanoceria to *Arabidopsis thaliana* under high light intensity conditions significantly reduced ROS levels and protected the plant's photosystems from degradation. This resulted in an increase in overall photosynthetic efficiency, even during periods of photoinhibition (Zhou et al., 2021).

In addition to their ROS-scavenging capabilities, cerium oxide nanoparticles also possess regenerative properties that allow them to sustain their antioxidant function over extended periods (Gao et al., 2014). This regenerative ability makes nanoceria particularly effective in providing long-term protection against oxidative stress, ensuring that plants can continue to produce energy via photosynthesis, even under prolonged high light exposure (Rajeshkumar & Naik, 2018). The stability and longevity of nanoceria's antioxidant activity make it a promising tool for improving plant resilience to environmental stressors that would otherwise impede photosynthesis (Nelson et al., 2016).

Furthermore, the use of nanoceria in plant systems could also contribute to increased crop yield and improved stress tolerance, which is particularly important in the context of climate change, where extreme weather conditions are becoming more common. By mitigating photoinhibition and protecting photosynthetic systems, nanoceria can help plants adapt to fluctuating environmental conditions, ensuring stable and sustained agricultural production (Nelson et al., 2016).

4. ENHANCING NUTRIENT UPTAKE WITH NANOPARTICLES

Nutrient uptake is a critical factor in plant growth and productivity, yet it is frequently hampered by poor soil quality, nutrient immobilization, and limited bioavailability of essential elements such as nitrogen (N), phosphorus (P), and potassium (K) (Nelson et al., 2016). These challenges are compounded by imbalance use of traditional fertilizers, which are prone to leaching, volatilization, and runoff, leading to environmental pollution and economic losses. Nanotechnology offers innovative solutions to enhance nutrient delivery and uptake, revolutionizing agricultural practices (Nelson et al., 2016).

4.1 Nanofertilizers

A revolutionary method of managing nutrients, nanofertilizers address number of the drawbacks of traditional fertilizers such as nutrient leaching, low bioavailability, and environmental contamination, leading to significant nutrient losses and environmental degradation (Chhipa, 2017). By utilizing nanotechnology, Nanofertilizers encapsulate essential nutrients in nanoscale carriers, allowing for their controlled and sustained release. This targeted delivery not only ensures that nutrients remain available to plants over longer periods but also minimizes the amount of fertilizer needed, reducing both economic costs, increase nutrient use efficiency and environmental impacts. This level of precision is particularly important in nutrient-deficient soils or in regions where efficient use of resources is critical (Geranian et al., 2019).

The small size and high surface area of nanoparticles enable them to interact more effectively with plant roots and soil particles (Geranian et al., 2019). This increased interaction facilitates the movement of nutrients into plant tissues, improving their bioavailability. For example, zinc oxide nanoparticles have been shown to enhance zinc bioavailability in plants, promoting vital enzymatic activities that are crucial for plant growth and development. This is particularly important in regions where zinc deficiency is prevalent, as it can lead to stunted growth, reduced yields, and poor crop quality. Additionally, the controlled release of nutrients from nanofertilizers ensures that the nutrients are available to the plants for extended periods, reducing the need for frequent applications and minimizing nutrient loss to the environment through runoff or leaching (Guo et al., 2018).

Nanofertilizers are also being explored for their potential to improve the efficiency of other essential nutrients such as nitrogen and phosphorus. For instance, nitrogen-based nanofertilizers have been shown to increase nitrogen uptake by plants, promoting better growth and reducing the environmental impact of excess nitrogen, which can otherwise lead to water contamination through nitrate leaching (Fatima et al., 2021). Similarly, phosphorus nanofertilizers, often in the form of phosphate nanoparticles, have been shown to enhance phosphorus uptake by plants and reduce the need for phosphatic fertilizers, which can be both costly and environmentally harmful (Zulfiqar et al., 2019). By improving the availability of nitrogen and phosphorus, nanofertilizers not only boost crop yields but also contribute to more sustainable agricultural practices by decreasing reliance on bulk fertilizers (El-Saadony et al., 2021).

4.2 Chelated Nanoparticles

The availability of micronutrients, particularly iron, is often limited in soils with high pH, such as calcareous or alkaline soils, where metal ions tend to form insoluble compounds that plants cannot access. This problem significantly impedes plant growth and crop yield, especially in regions where these soil types are prevalent. To address this issue, metal nanoparticles functionalized with chelating agents offer a novel solution by preventing nutrient precipitation and ensuring a steady supply of essential micronutrients to plants (DeAlba-Montero et al., 2017). Chelating agents such as ethylenediaminetetraacetic acid (EDTA) or other organic ligands can bind to metal ions, creating stable complexes that remain soluble in soil, making them more accessible to plant roots. Iron oxide nanoparticles, when chelated with EDTA, effectively maintain iron in a bioavailable form, enhancing plant iron uptake and preventing the formation of insoluble iron compounds that would otherwise be unavailable to plants (Jung et al., 2022).

Chelated metal nanoparticles, such as iron oxide and copper oxide nanoparticles, are particularly beneficial in soils with nutrient immobilization issues. In such soils, metal ions often react with minerals to form insoluble compounds which making it difficult for plants to absorb. By functionalizing nanoparticles with chelating agents, these particles can maintain metal ions in solution, significantly improving nutrient availability (Huhtinen et al., 2005). Studies have shown that the use of iron oxide nanoparticles functionalized with EDTA in calcareous soils increases the bioavailability of iron and improves overall plant health and growth. This approach not only enhances the nutrient uptake of plants but also reduces the need for frequent applications of traditional fertilizers, leading to cost savings and more sustainable farming practices (Tofighi Alikhani et al., 2021).

Moreover, the use of chelated nanoparticles extends beyond iron. For instance, chelated copper oxide nanoparticles have been shown to improve copper bioavailability in soil, which is critical for enzyme activation in plants. The enhanced solubility and targeted delivery of these nanoparticles enable more efficient nutrient uptake, reducing the environmental risks associated with traditional fertilizers, such as nutrient leaching and contamination of water systems. Furthermore, these nanoparticles can be customized to target specific plant requirements, providing a more efficient and environmentally friendly alternative to conventional fertilizers (Xu et al., 2022).

In addition to improving nutrient availability and reducing fertilizer use, chelated metal nanoparticles can enhance the overall health and resilience of plants. By ensuring a continuous supply of essential micronutrients, these nanoparticles support plant physiological processes such as photosynthesis, enzyme activity, and stress tolerance. As a result, plants exhibit improved growth, yield, and quality, even in nutrient-deficient soils. In this way, chelated metal nanoparticles represent a promising way for improving soil fertility, enhancing crop productivity, and promoting sustainable agriculture, particularly in areas where soil quality is poor and traditional fertilization methods are less effective (Berchmans et al., 2002).

4.3 Soil Remediation

In addition to enhancing nutrient delivery, certain nanoparticles are increasingly recognized for their potential to play a dual role in improving nutrient uptake and remediation of contaminated soils. Heavy metal contamination, often due to industrial activities, mining, or excessive use of agrochemical, poses a significant challenge to soil quality and plant growth. Heavy metals such as cadmium, lead, arsenic, and mercury can accumulate in the soil, negatively affecting plant growth and posing risks to the food chain and human health. Fortunately, nanoparticles such as titanium dioxide (TiO_2) and carbon-based nanomaterials (e.g., graphene oxide, activated carbon) have shown promise in mitigating these risks by adsorbing and immobilizing these toxic metals, thereby reducing their bioavailability and toxicity in the soil (Sarkar et al., 2019).

Titanium dioxide nanoparticles are particularly effective at adsorbing heavy metals like arsenic and lead in contaminated soils. The high surface area and reactive sites of TiO_2 allow it to bind with metal ions, preventing their leaching and reducing their availability for plant uptake. This is crucial for protecting plants from the harmful effects of heavy metals, which can inhibit root growth, reduce nutrient uptake, and disrupt cellular processes (Zhao et al., 2016). Moreover, titanium dioxide's photocatalytic properties allow it to break down organic contaminants, further improving soil quality and creating a healthier environment for plant growth. As a result, plants are better able to access essential nutrients like nitrogen, phosphorus, and potassium, which might otherwise be hindered by the toxic presence of heavy metals (New et al., 2023).

Similarly, carbon-based nanomaterials, such as activated carbon and graphene oxide, have shown significant potential in adsorbing heavy metals in contaminated soils. These nanomaterials possess a high surface area and functional groups that can form stable complexes with metal ions, reducing their mobility and preventing them from entering plant tissues. A study demonstrated that graphene oxide nanoparticles could effectively remove lead and cadmium from soil, improving the overall nutrient uptake efficiency in plants. This dual function—remediating soil contaminants while facilitating nutrient acquisition—makes carbon-based nanomaterials a valuable tool in agricultural practices, especially in areas with high levels of industrial pollution or pesticide contamination (Li et al., 2021).

The use of nanoparticles in soil remediation is particularly in regions where soil quality has been severely degraded due to excessive use of chemical fertilizers, pesticides, or industrial waste. By immobilizing heavy metals, nanoparticles reduce the risks of heavy metal toxicity and enhance plant health and productivity. This is crucial not only for improving crop yields but also for ensuring food safety and sustainability in polluted environments (Shipley et al., 2011). Furthermore, this approach contributes to the circular economy by allowing polluted lands to be restored for agricultural use, promoting long-term soil fertility and environmental health. Various roles of nanoparticles are shown in Fig. 1.

5. ADVANTAGES OF NANOPARTICLES IN PLANT SYSTEMS

Nanoparticles possess unique physicochemical properties, such as high surface area-to-volume ratios, quantum effects, and tunable optical and electronic characteristics, making them uniquely suited for applications in plant systems (Fig. 2). These features enable nanoparticles to interact with plant cells and tissues at the molecular and subcellular levels, offering unparalleled precision and efficiency in agricultural applications (Parveen et al., 2016). Their versatility allows for innovations that are unattainable with conventional agricultural materials.

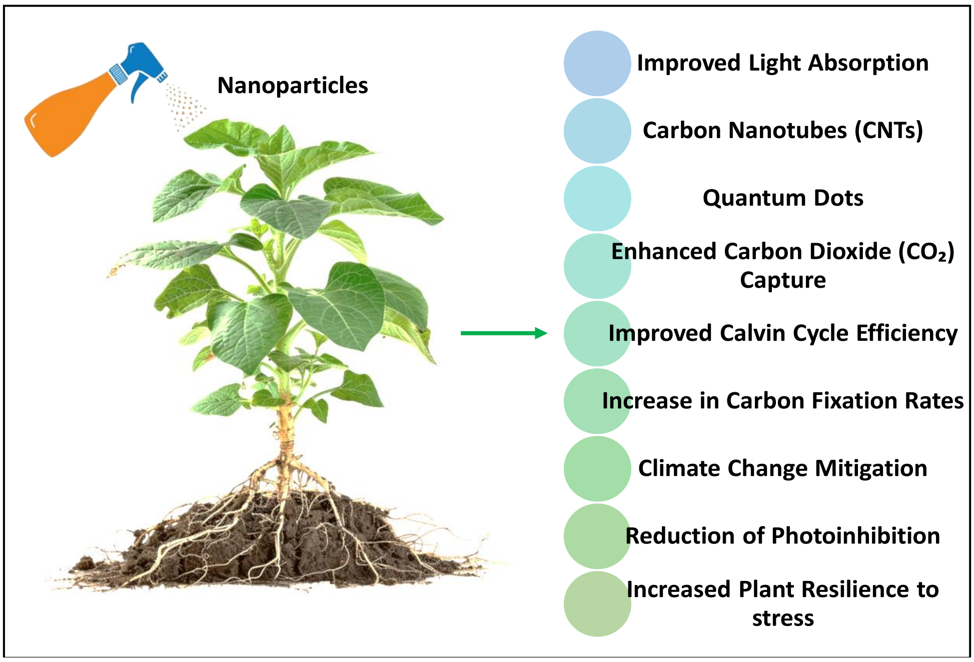

Fig. 1. Beneficial role of Nanoparticles in plant system

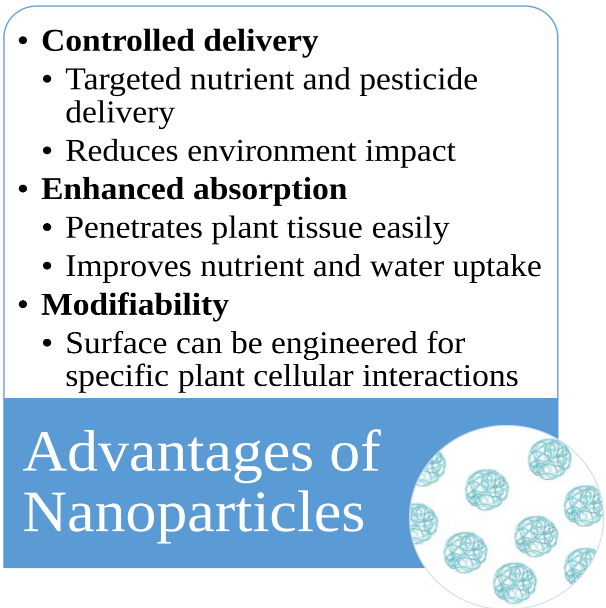

Fig. 2. Advantages of nanoparticles in agriculture

Nanoparticles offer significantly controlled delivery of nutrients. It is encapsulate nutrients, pesticides, or other biomolecules and release them in a targeted and sustained manner (Parveen et al., 2016). This reduces the loss of active compounds to leaching, evaporation, or degradation, ensuring that nutrients and bioactive molecules reach specific sites within the plants. For instance, polymer-based nanocarriers have been shown to improve the delivery efficiency of fertilizers, minimizing environmental impact while boosting crop productivity (Geranian et al., 2019).

Nanoparticles enhanced absorption of nutrients by the plants. Due to their nanoscale size, nanoparticles penetrate plant tissues more effectively than bulk materials, allowing them to bypass natural barriers like the cuticle or cell walls. This improved absorption facilitates more efficient uptake of nutrients and water, even under suboptimal conditions, such as poor soil quality or drought stress. Research has demonstrated that metal oxide nanoparticles, like zinc oxide and titanium dioxide, improve the availability and assimilation of essential nutrients by altering their bioavailability in the rhizosphere (Hu & Xianyu, 2021).

Moreover, nanoparticles offer modifiability. Their surfaces can be engineered to interact specifically with plant cellular components, such as enzymes, chloroplasts, or transport proteins. This property is particularly useful for enhancing photosynthetic efficiency or targeting stress-responsive pathways (Singh et al., 2016). For example, carbon nanotubes functionalized with specific biomolecules can localize within chloroplasts to enhance light capture and energy transfer, significantly boosting photosynthetic rates (Patil et al., 2021).

The integration of these advantages enables nanoparticles to improve agricultural efficiency while reducing resource waste and environmental impact. These innovations hold tremendous promise for sustainable farming, particularly in addressing challenges like nutrient depletion, climate change, and the need for increased crop yields to feed a growing population (Arruda et al., 2015).

6. CHALLENGES IN NANOPARTICLE RESEARCH

While the use of nanoparticles in agriculture offers promising solutions for enhancing plant productivity and sustainability, their adoption is accompanied by several challenges and concerns that need to be addressed. These challenges span environmental safety, economic feasibility, and regulatory frameworks, highlighting the need for a balanced approach to their implementation (Lv et al., 2019).

The potential environmental impacts of nanoparticles, particularly their long-term effects on soil health, water systems, and non-target organisms, remain poorly understood. Nanoparticles can accumulate in the soil, altering its chemical and biological properties, and potentially disrupting microbial communities critical for nutrient cycling and plant growth. For example, studies have shown that certain metal oxide nanoparticles, like zinc oxide and silver nanoparticles, can inhibit the activity of beneficial soil microbes, impacting soil fertility (Tripathi et al., 2016). Similarly, the leaching of nanoparticles into water systems raises concerns about bioaccumulation in aquatic organisms and the potential for trophic transfer through the food chain (Silva et al., 2015). These risks underscore the importance of thorough ecotoxicological assessments to ensure that the benefits of nanotechnology do not come at the expense of environmental health.

Scaling up the production and application of nanoparticles for agricultural use poses significant challenges. Current manufacturing processes for nanoparticles, such as chemical vapor deposition or sol-gel techniques, are often expensive and energy-intensive, making large-scale production economically unfeasible for many farmers (Mishra et al., 2017). Additionally, ensuring the uniform distribution of nanoparticles in fields without causing environmental contamination requires innovative delivery systems, which further complicate scalability. Cost-effectiveness must be achieved without compromising environmental safety, necessitating advancements in green nanotechnology approaches, such as using plant-derived nanomaterials or biodegradable carrier (Berchmans et al., 2002).

The absence of comprehensive guidelines and regulations for the use of nanomaterials in agriculture significantly hinders their widespread adoption. Existing regulations often fail to address the unique properties and potential risks of nanoparticles, leading to uncertainty among stakeholders regarding their safe use. For instance, while traditional agrochemicals are subject to rigorous testing and approval processes, similar frameworks are lacking for nanoparticles, leaving a regulatory gap. Furthermore, inconsistencies in regulatory policies across countries complicate international trade and the global implementation of nanoparticle-based agricultural products. The development of standardized testing protocols and international guidelines is crucial to ensure the responsible use of nanotechnology in agriculture (Kumari et al., 2023).

7. FUTURE DIRECTIONS IN PLANT NANOBIONICS

The potential of plant nanobionics extends far beyond its current applications, promising transformative advancements in agriculture and environmental sustainability. One of the primary focuses for the future in the development of biocompatible and biodegradable nanoparticles. Unlike traditional nanoparticles that may pose risks of accumulation and toxicity, these next-generation materials would degrade into harmless byproducts, reducing environmental and ecological risks while maintaining functionality. Recent research highlights the use of plant-derived nanomaterials, which offer a renewable and eco-friendly alternative, aligning with global sustainability goals (Jadoun et al., 2021).

Advancements in synthetic biology and nanotechnology are expected to converge, enabling the design of multifunctional nanoparticles tailored to address specific plant needs. For example, researchers are exploring the development of "smart nanoparticles" capable of simultaneously delivering nutrients, protecting against pathogens, and responding to environmental stimuli. These nanoparticles could include sensors to monitor plant health in real time, releasing nutrients only when required. Such innovations could significantly enhance resource efficiency and crop productivity while minimizing environmental impact (Marchiol, 2012).

Integrating plant nanobionics with precision agriculture technologies represents another promising direction. Precision agriculture leverages data-driven approaches, such as remote sensing and geographic information systems, to optimize farming practices. The incorporation of plant nanobionics into this framework could enable highly targeted interventions (Makarov et al., 2014). For instance, drone-based delivery systems equipped with imaging and navigation tools could precisely distribute nanoparticles to areas of the field requiring attention, reducing waste and ensuring uniform application. Combined with internet-of-things (IoT) technologies, these systems could provide real-time feedback on crop health, nutrient levels, and environmental conditions, enabling farmers to make informed decisions with unparalleled accuracy.

Moreover, the role of plant nanobionics in mitigating climate change could be pivotal. Researchers are investigating nanoparticles that enhance carbon fixation or reduce greenhouse gas emissions from agricultural activities. For instance, integrating silica-based nanoparticles that mimic carbonic anhydrase enzymes could improve carbon sequestration in plants, contributing to climate mitigation efforts (Landa, 2021).

8. CONCLUSION

Plant nanobionics represents a groundbreaking fusion of nanotechnology and plant biology, offering innovative solutions to enhance photosynthesis, improve nutrient uptake, and bolster plant resilience. This emerging field holds immense potential to address critical global challenges, including food security, environmental sustainability, and climate change. By leveraging nanoparticles' unique properties, researchers can design highly efficient systems for targeted nutrient delivery, enhanced carbon fixation, and real-time health monitoring in plants.

However, the widespread adoption of plant nanobionics requires overcoming challenges such as environmental risks, production scalability, and the absence of robust regulatory frameworks. Continued advancements in biocompatible and biodegradable nanomaterials, coupled with their integration into precision agriculture technologies, could revolutionize farming practices and pave the way for sustainable agriculture.

Collaboration with scientists, policymakers, and industry stakeholders will be essential to address safety concerns, establish standardized guidelines, and ensure equitable access of this technology. By balancing innovation with sustainability, plant nanobionics has the potential to transform agriculture, enabling a futurewhere productivity meets environmental stewardship.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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