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Review Article: Nanoparticle Applications in Plant Nutrition: A Comprehensive Review and Future Perspectives

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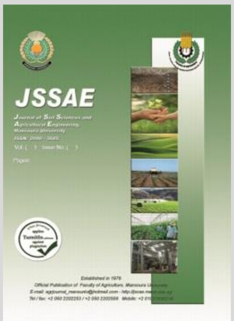

ABSTRACT

This review offers a comprehensive examination of the current state of knowledge regarding nanoparticle applications in plant nutrition. By synthesizing existing literature, it aims to analyze significant discoveries, emerging trends, and research gaps. The study focuses on several key topics, including nanotechnology applications, nanotechnology in agriculture, nano-fertilizers, and the superiority of the nanotechnology approach over chelated methods. The review explores the effects of nano-fertilizers on plant growth, yield, and nutrient uptake, emphasizing their potential to address challenges such as low nutrient use efficiency and environmental contamination. Studies demonstrate the effectiveness of nano-fertilizers in enhancing plant growth and productivity, particularly under stress conditions, with significant improvements observed in various crop parameters. Furthermore, the review highlights the advantages of nanotechnology over traditional methods, showcasing its potential to revolutionize agricultural practices. Nano-fertilizers exhibit superior performance compared to conventional fertilizers, offering precise and controlled nutrient delivery, leading to enhanced plant growth and environmental sustainability. Generally, nanotechnology holds immense promise for sustainable agriculture, offering innovative solutions to improve crop productivity, environmental sustainability, and food security. Harnessing the potential of nano-fertilizers could lead to significant advancements in agricultural practices, benefiting both farmers and the environment. However, further research is needed to fully understand the long-term effects and implications of nano-fertilizers on crop production and ecosystem health.

Keywords: Nano-fertilizers, nanotechnology, plant nutrition

INTRODUCTION

This review aims to provide a comprehensive overview of the current state of knowledge on the nanoparticle application in plant nutrition. Examining the existing literature aims to amalgamate and scrutinize the significant discoveries, emerging patterns, and research deficiencies up to this point. In order to fulfill the objectives of this study, a comprehensive examination of the relevant literature has been conducted, focusing on the following main topics:

1. **Nanotechnology application**
2. **Nanotechnology applications in agriculture**
3. **Nano-fertilizers**
   Effect of micronutrients Nano-fertilizers on plants
   Effect of macronutrients Nano-fertilizers on plants
3. **The superiority of the nanotechnology-approach over the chelated approach**

1. Nanotechnology application

Nanotechnology entails the manipulation or spontaneous arrangement of individual atoms, molecules, or molecular clusters to create novel structures, resulting in the production of materials and devices with greatly modified properties. The rise of this field, coupled with the development of inventive nanodevices and nanomaterials, offers exciting prospects in the agricultural domain (Neme *et al.* 2021).

Nanotechnology is essentially the mastery of matter on a scale ranging from approximately 1 to 100 nanometers, enabling the realization of novel applications due to the distinctive characteristics exhibited at this scale (Sangeetha *et al.* 2021).

Nanoscale materials and devices can be created through two primary fabrication approaches: "bottom-up" and "top-down" methods. In bottom-up techniques, nanomaterials or structures are constructed by gradually assembling atoms or molecules in a controlled manner, guided by thermodynamic principles, such as self-assembly (Zhang *et al.* 2022).

Alternatively, advances in microfabrication technologies can be harnessed to produce nanoscale structures and devices. These methods fall under the category of top-down nanofabrication technologies, which encompass processes like photolithography, nanomolding, dip-pen lithography, and Nano fluidics (Guleria *et al.* 2022).

2. Nanotechnology applications in agriculture

Nanotechnology holds the potential to trigger a groundbreaking revolution in the management of natural resources in agriculture. It has emerged as a new interdisciplinary field that combines scientific and engineering principles with agriculture and food systems, representing a fusion of knowledge and expertise that has the capacity to bring about significant advancements in this domain (Davari *et al.* 2017).

Nanotechnology is positioned to revolutionize the agricultural and food sector by introducing groundbreaking tools for molecular disease treatment, enabling rapid disease detection, and improving plants' ability to absorb

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nutrients. Furthermore, it holds the potential for smart sensors and delivery systems, empowering the agricultural industry to efficiently combat viruses and other crop pathogens. In the near future, we can expect nanostructured catalysts to greatly enhance the effectiveness of pesticides and herbicides, leading to reduced dosage requirement (Mali *et al.* 2020).

Moreover, nanotechnology is expected to contribute to environmental protection indirectly by facilitating the adoption of alternative, renewable energy sources. It will also play a role in pollution mitigation and cleanup through the deployment of filters and catalysts designed to reduce pollution levels and address existing pollutants, further advancing sustainable practices in agriculture and environmental stewardship (Sadati-Valojai *et al.* 2021).

The exploration of potential nanotechnology applications in developing countries has emphasized the enhancement of agricultural productivity as the second most critical area for achieving the millennium development goals. Energy conversion and storage have been identified as the top priority, while water treatment has been recognized as the third area requiring focused attention. This highlights the importance of utilizing nanotechnology to tackle pressing challenges in these regions, including sustainable energy solutions, agricultural advancement, and access to clean water. These efforts are essential for enhancing overall well-being and socio-economic conditions in developing countries (Sivarethinamohan and Sujatha, 2021).

3. Nano-fertilizers

Nano fertilizer technology presents a profoundly innovative approach, and there exists a sparse body of literature on this topic in scientific journals. Conventional fertilizers have demonstrated restricted effectiveness, with nutrient utilization efficiencies seldom exceeding 30-35% for nitrogen (N), 18-20% for phosphorus (P), and 35-40% for potassium (K). Despite research endeavors, these percentages have remained relatively stagnant for numerous decades (Preetha and Balakrishnan, 2017).

Nano-fertilizers, on the other hand, are designed to carry nutrients by utilizing substrates with nanoscale dimensions ranging from 1.0 to 100 nanometers. Nano-particles offer a significant surface area, allowing them to hold a substantial amount of nutrients and release them gradually and consistently. This controlled release aligns with the crop's nutrient requirements, minimizing any adverse effects associated with conventional fertilizer applications (Adisa *et al*. 2019).

Nano fertilizers lead to improved nutrient utilization efficiency, reduced soil toxicity, alleviation of adverse effects associated with excessive application, and a decrease in the need for frequent fertilizer application. Consequently, nanotechnology offers substantial potential for promoting sustainable agriculture, especially in developing countries (Rossi *et al.* 2019).

1. Effect of macronutrients Nano-fertilizers on plants

Nano fertilizers have emerged as a modern agricultural innovation that has the potential to transform how plants receive crucial macronutrients such as nitrogen, phosphorus and potassium. Engineered at the nanoscale, typically ranging from 1.0 to 100 nanometers, these tiny particles offer precise and controlled nutrient delivery to plants. The integration of nanotechnology in agriculture aims to tackle issues associated with traditional macronutrient fertilization, including low nutrient use efficiency, environmental contamination, and limitations in nutrient uptake by crops. This cutting-edge technology holds the promise of improving plant growth, increasing crop yields, and mitigating the environmental impact of fertilization (Singh, 2017).

This introduction sets the stage for an exploration of the impact of macronutrient Nano fertilizers on plants, revealing the potential advantages and challenges linked to their adoption in contemporary agriculture.

In a study conducted by Merghany *et al.* (2019), the effects of liquid Nano NPK at various concentrations (3.0, 4.0, 5.0, 6.0, and 9.0 ml) on cucumber growth and fruit yield were examined, with a mineral fertilizer serving as the control. The results indicated that the Nano fertilizer treatments had a significantly positive influence on both the growth and yield of cucumber compared to the control treatment. Across all concentrations of Nano fertilizer, there was an observed increase in plant height, number of leaves per plant, chlorophyll content, fruit yield, and the percentage of NPK in both leaves and fruits. Particularly noteworthy was the 6.0 ml NPK treatment, which resulted in a 4.84% increase in yield during the first season and an impressive 53.42% increase in the second season. Additionally, the 6.0 ml NPK treatment exhibited the lowest weight loss percentage and the highest overall appearance quality after 21 days of storage at 5°C. In contrast, the control NPK treatment showed the highest firmness and total soluble solids (TSS) value.

In a study conducted by AL-Gym and Al-Asady (2020), the effects of NPK (20:20:20) nanoparticles and conventional mineral fertilizers, along with different application methods and fertilizer levels, on corn growth and productivity were evaluated. The results revealed that when NPK nanoparticles were incorporated into the soil, they exhibited a substantial superiority over traditional NPK fertilizers in stimulating vegetative growth and increasing crop yield.

Mahmoud and Swaefy (2020) examined the impact of applying Nano nitrogen (N), phosphorus (P), and potassium (K) elements to sage plants subjected to water stress, in comparison to traditional commercial NPK fertilizers. The results demonstrated that the Nano fertilizers exhibited superior effects across various parameters, including plant height, fresh and dry herb weight, leaf area, plant pigments, oil yield, total flavonoids, total carbohydrates, total phenolic content, tannin levels, oil constituents, as well as macro and microelement concentrations.

Helaly *et al.* (2021) conducted a study examining the effects of soil application of Nano NPK at varying rates (0%, 12.5%, 25%, 50% of the RD of conventional NPK chemical fertilizers) on the growth, yield, and quality of lettuce heads. The results demonstrated that the application of Nano nitrogen at a high rate (50%) led to a notable enhancement in performance, as evidenced by increased head fresh weight, head size, total yield, and marketable yield. Moreover, employing 50% Nano potassium resulted in a significant rise in ascorbic acid, total sugar content, and total soluble solids (TSS). The total chlorophyll, carotenoids, and dry matter content showed significant increases with the 50% Nano nitrogen treatment, while head phosphorus and potassium content peaked with 50% Nano phosphorus and 50% Nano potassium, respectively. Conversely, head nitrate content exhibited a significant increase with the control NPK conventional treatment compared to all Nano treatments.

Mohammed and Mijwel (2021) investigated the impact of Nano fertilization on the growth and yield of cabbage. They utilized Nano fertilizer at three distinct concentrations (0.0, 1.0, and 2.0 g L-1). Remarkably, the application of Nano fertilizer at a concentration of 2.0 g L-1 demonstrated superior performance across various aspects, including the chlorophyll content of non-wrapped leaves, total head weight, total yield, marketable yield, weight of marketable head, and total soluble solids.

Sharaf-Eldin *et al.* (2022) examined the influence of nitrogen on the growth characteristics and essential nutrient absorption by lettuce plants, using various combinations of bulk and Nano nitrogen forms. The findings indicated that the application of 75% Nano-nitrogen had a significant impact on growth and biochemical parameters, including plant biomass, β-carotene, crude protein, and yield, when compared to the use of 100% bulk-sized nitrogen.

Abdel-Hakim *et al.* (2023) assessed the impact of incorporating small quantities of Nano NPK fertilizers alongside conventional NPK fertilizers on the performance of lettuce plants. They tested five different treatments: T_1: 100% conventional NPK, T_2: 75% conventional NPK + 25% Nano NPK, T_3: 50% conventional NPK + 50% Nano NPK, T_4: 25% conventional NPK + 75% Nano NPK, and T_5: 100% Nano NPK. The results indicated that treatments T_2 (75% conventional NPK + 25% Nano NPK) and T_3 (50% conventional NPK + 50% Nano NPK) exhibited the highest values for various plant growth parameters.

Al-Jubouri *et al.* (2023) investigated the effects of Nano-fertilizer NPK at concentrations of 0.0, 20.0, and 30.0 gL-1 on the vegetative growth attributes of cabbage plants. The results revealed that applying Nano-fertilizer at a concentration of 30 gL-1 led to an augmentation in plant height, the number of outer and inner leaves of the head, as well as the length and width of the longest leaf.

2.Effect of micronutrients Nano-fertilizers on plants

The utilization of nanotechnology in agriculture has not only transformed the way plants receive macronutrients but has also ushered in a new era for the application of micronutrient fertilizers. These engineered nanoparticles, typically ranging from 1 to 100 nanometers, have opened up exciting possibilities for optimizing the delivery of essential micronutrients to plants. Micronutrients, though required in smaller quantities, play a critical role in plant health and productivity. The integration of Nano fertilizers at the micronutrient level offers the potential to address longstanding challenges, such as micronutrient deficiencies in soil, irregular nutrient distribution, and limitations in nutrient uptake by plants (Sturikova *et al.* (2018).

This introduction sets the stage for an exploration of the impact of micronutrient Nano fertilizers on plants, delving into the potential benefits and considerations surrounding their application in modern agriculture.

Javadimoghadam *et al.* (2015) investigated the impact of different concentrations of iron and zinc chelate nano fertilizers on the growth and performance of cucumber plant. Nano-iron and zinc fertilizers were applied as foliar sprays at concentrations of 1.5, 2, and 2.5 ppm. The results of the experiment revealed that the application of iron and zinc chelate Nano fertilizers at a concentration of 2.0 ppm significantly increased the number of fruits, chlorophyll content, superoxide dismutase activity, and the concentration of essential microelements in the cucumber plants.

Hussein and Abou-Baker (2018) investigated the influence of Nano-zinc fertilizer at various rates (0.0, 100, and 200 ppm) on cotton plants exposed to salt stress. The findings revealed that with increasing concentrations of Nano-zinc, the measured growth parameters of the cotton plants demonstrated enhancement. This implies that Nano-zinc positively impacted the growth of cotton plants, particularly under conditions of salt stress.

Konate *et al.* (2018) examined the effects of Nano and bulk iron oxide (Fe_3O_4) at various concentrations (50, 500, and 2000 mg L^{-1}) on cucumber plants. At the lowest concentration, the application of nano-Fe_3O_4 resulted in a decrease in enzyme activities and plant biomass compared to the control. However, at higher doses of Nano-Fe3O4, there was a notable increase in the activity of antioxidant enzymes and biomass. In contrast, the utilization of high concentrations of bulk-Fe_3O_4 induced phytotoxic effects, leading to diminished enzyme activities and biomass.

Xu *et al.* (2018) investigated the effects of different doses of zinc oxide nanoparticles (ZnO NPs) and bulk zinc oxide (0, 1, 10, 100 mg ZnO/kg) on the growth of lettuce plants. The study revealed that at a dose of 10 mg/kg, both ZnO NPs and bulk ZnO positively influenced lettuce biomass and the net photosynthetic rate. Moreover, the zinc content in plant tissue was notably higher in the NPs treatment compared to the bulk counterpart at doses of 10 mg/kg or higher. These findings suggest that both ZnO NPs and bulk ZnO can enhance lettuce growth and influence zinc uptake by plants, with nanoparticles demonstrating a more pronounced effect at specific concentrations.

Gil-Díaz *et al.* (2022) conducted a study investigating the response of spinach plants to different doses of two commercially available Nano fertilizers. Their findings indicated that foliar application of these Nano fertilizers caused noticeable changes in the surface composition and nutrient content of the leaves. This application introduced new elements and raised the levels of certain nutrients, especially at the highest doses tested.

Meanwhile, Turan *et al.* (2022) concluded that the application of Nano iron (Fe) resulted in a significant increase in various growth and physiological parameters in spinach plants. These parameters included plant fresh and dry weights, root fresh and dry weights, root dry matter, leaf area, as well as the concentrations of chlorophyll, carotenoids, and leaf mineral elements.

3.The superiority of the nanotechnology-approach over the chelated approach

Roosta *et al.* (2015) examined the effects of various iron (Fe) sources, including Nano iron, Fe-EDDHA, and iron sulfate (FeSO4), on lettuce. Their study revealed that the application of Nano iron notably enhanced leaf Fe content and overall plant growth. Among the treatments, plants treated with Nano iron displayed the highest values of leaf Fe content, plant pigments, and vegetative growth. In contrast, the FeSO4 treatment resulted in the lowest levels of Fe, chlorophyll, carotenoids, and soluble sugars in the leaves. Remarkably, there were no significant differences in the soluble sugar content of plants between the Nano iron and Fe-EDDHA treatments.

Mahdieh *et al.* (2018) investigated the influence of zinc oxide (ZnO) nanoparticles and other zinc (Zn) fertilizers (sulfate and chelate) on the bean plants. The results demonstrated that, when compared to the control treatment, the application of zinc Nano fertilizers led to noticeable improvements in various vegetative characteristics, including plant height, root and shoot dry and fresh weight, the number of pods, seed weight, and zinc content in the seeds. Among the various zinc fertilizer treatments, it was observed that the use of 0.10% and 0.15% ZnO nanoparticles proved to be the most effective, yielding superior results in promoting plant growth and zinc accumulation in the seeds.

Dhaliwal *et al.* (2021) examined the potential of foliar applications of different fertilizer forms (mineral, chelated, and Nano) to augment zinc (Zn) and iron (Fe) content in chickpea plants. Among these applications, the foliar application of a combination of 0.5% zinc oxide nanoparticles (ZnO NPs) and 0.5% iron oxide nanoparticles (Fe2O3 NPs) during the pre-flowering stage demonstrated the highest efficacy in increasing grain yield, as well as Zn and Fe content and uptake. Notably, a single foliar application of the Nano-fertilizers yielded comparable results to two separate foliar applications of the mineral and chelated forms. This suggests that the Nano-fertilizer approach shows significant promise in enhancing Zn and Fe levels in chickpea crops.

El-Desouky *et al.* (2021) found that the application of Nano-Fe significantly increased several plant growth parameters, including plant height and leaf area, as well as the fresh and dry weights of both shoot and root. Notably, when Nano-Fe was applied at a rate of 100 mg/kg, it led to a substantial increase in total yield, and its various components of tomatoes, surpassing the effects of other Fe rates.

CONCLUSION

In conclusion, this review highlights the transformative potential of nanoparticle applications in plant nutrition. Nanotechnology offers innovative solutions to enhance nutrient delivery, improve crop productivity, and mitigate environmental impacts in agriculture. Nano-fertilizers, with their controlled release mechanisms and precise nutrient delivery, demonstrate superior performance compared to traditional fertilizers, particularly under stress conditions. The integration of nanotechnology in agriculture holds promise for addressing key challenges such as low nutrient use efficiency and environmental contamination. However, further research is needed to fully understand the long-term effects and implications of nano-fertilizers on crop production and ecosystem health. Overall, nanotechnology presents exciting opportunities to revolutionize agricultural practices and contribute to sustainable food production and environmental stewardship.

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تطبيقات الجسيمات النانوية في تغذية النباتات: استعراض شامل وآفاق مستقبلية

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الملخص

تقدم هذه المراجعة فحصًا شاملاً للحالة الحالية للمعرفة بشأن تطبيقات الجسيمات النانوية في تغذية النباتات. من خلال تجميع الاعمال البحثية القائمة، يهدف إلى تحليل الاكتشافات الهامة، والاتجاهات الناشئة، والثغرات البحثية. تركز الدراسة على عدة مواضيع رئيسية، بما في ذلك تطبيقات التكنولوجيا النانوية، والتكنولوجيا النانوية في الزراعة، والأسمدة النانوية، وتفوق نهج التكنولوجيا النانوية على الطرق التقليدية. تستكشف المراجعة تأثير الأسمدة النانوية على نمو النباتات، وإنتاجيتها، وامتصاص المغذيات، مؤكدًا إمكانية التصدي للتحديات مثل الكفاءة المنخفضة في استخدام المغذيات والتلوث البيئي. تظهر الدراسات فعالية الأسمدة النانوية في تعزيز نمو النبات وإنتاجيته، خاصة في ظل ظروف الإجهاد، مع ملاحظة تحسينات كبيرة في مختلف معايير المحاصيل. علاوة على ذلك، تسلط المراجعة الضوء على مزايا تكنولوجيا النانو مقارنة بالطرق التقليدية، وتعرض قدرتها على إحداث ثورة في الممارسات الزراعية. تتميز الأسمدة النانوية بأداء فائق مقارنة بالأسمدة التقليدية، حيث توفر توصيلًا دقيقًا ومنضبطًا للمغذيات، مما يؤدي إلى تعزيز نمو النبات والاستدامة البيئية. بشكل عام، تحمل تكنولوجيا النانو وعودًا هائلة للزراعة المستدامة، حيث تقدم حلولاً مبتكرة لتحسين إنتاجية المحاصيل، والاستدامة البيئية، والأمن الغذائي. إن تسخير إمكانات الأسمدة النانوية يمكن أن يؤدي إلى تقدم كبير في الممارسات الزراعية، مما يعود بالنفع على المزارعين والبيئة. ومع ذلك، هناك حاجة إلى مزيد من البحث لفهم التأثيرات والآثار طويلة المدى للأسمدة النانوية بشكل كامل على إنتاج المحاصيل وصحة النظام البيئي.