International Journal for Multidisciplinary Research (IJFMR)

E-ISSN: 2582-2160 • Website: www.ijfmr.com • Email: editor@ijfmr.com

Unveiling the Potential Scope of Nanoparticles in the Current Era of Crop Productivity

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ABSTRACT

Nanotechnology, a revolutionary field encompassing the manipulation of matter on an atomic or molecular scale, holds immense potential for upgrading wide areas, including agriculture. Understanding the scope of nanotechnology, researchers have directed their focus towards addressing the challenges in agriculture and enhancing crop productivity. Nanoparticles offer unique properties, including high surface area and reactivity, that can be harnessed to optimize nutrient delivery, mitigate soil toxicity, and enhance plant growth. Various studies have demonstrated the effectiveness of nanoparticles in increasing crop yields, improving nutrient uptake efficiency, and reducing environmental impacts associated with conventional agricultural practices with sustainable agriculture. Nanotechnology overcomes various challenges encountered in traditional agricultural practices including limited availability of nutrients in the soil, inefficient nutrient uptake by plants, soil degradation, and environmental pollution by providing targeted nutrient delivery, improving nutrient absorption, and mitigating environmental impacts. Also, nanoparticle interactions with plants and microbes and strengthening symbiotic relationships by providing active nutrient supplies to microbes. Furthermore, nanoparticles can improve soil structure and fertility by reducing compaction, increasing water retention, and enhancing soil aggregation. These improvements in soil quality not only benefit crop growth but also contribute to sustainable land management practices.This review paper provides an overview of the current research landscape in the application of nanoparticles in agriculture, highlighting key findings, challenges, and future prospects. By leveraging the principles of nanotechnology, agricultural scientists and practitioners aim to revolutionize crop production, meet the needs of farmers, and ensure food security in the face of evolving environmental and socio-economic challenges.

Keywords: Nanoparticles, Sustainable agriculture, Symbiosis, Crop production enhancement.

Highlights

- Reviews potential of nanoparticles in enhancing crop productivity and soil health.
- Discusses improved nutrient delivery, uptake, and reduced environmental impact.
- Highlights potential for nanoparticles to strengthen plant-microbe interactions.

- Emphasizes role of nanotechnology in sustainable agriculture and food security.

Nano-biotechnology presents a promising avenue for advancing sustainable agriculture (Rameshaiahet et al., 2015). Through its controlled application, this technology holds the potential to contribute significantly to sustainability efforts, benefiting both the ecosystem and farmers engaged in agricultural practices. In the context of the increasing global population and the consequent rise in food demand, sustainable agriculture emerges as a crucial component of addressing these challenges (SayedRohollaMousavi*1; Maryam Rezaei2, 2011).

Nanotechnology's applications have been explored across various fields, including medicine, chemistry, pharmaceuticals, diagnostics, and therapeutics (Leso et al., 2019; Stefan &Montagud, 2019; Li et al., 2020). Nanoparticles (NPs), being at the forefront of nanotechnology, offer immense potential compared to their bulk counterparts, leading to their integration into a wide array of consumer products (Jeevanandam et al., 2018). Consequently, the unique and evolving characteristics of these advanced materials have attracted considerable attention in both the food industry and the agricultural sector.

Modern agriculture, driven by advanced materials, is transitioning towards precision agriculture, which aims to maximize production while optimizing resource utilization. Alongside NPs, other nanomaterials like nanoclays, nanotubes, and nanowires offer enhanced sensitivity, faster response times, and improved detection limits due to their distinct surface chemistry, electrical, and optical properties (Yaqoob et al., 2020). Despite the necessity of fertilizers to boost crop yield, their application often disrupts the mineral balance in the soil, leading to a decline in soil fertility, as observed by (Solanki et al. 2015).

In conventional agricultural practices, sprays are commonly employed to distribute insecticides, fertilizers, and antibiotics, often resulting in runoff. However, the high production costs associated with these inputs pose a significant challenge. To address this issue, the integration of nanomaterials (NMs) in agriculture aims to mitigate production expenses while maximizing output. By leveraging NMs, there is a concerted effort to reduce the quantity of products utilized for plant protection, minimize nutrient losses, and ultimately enhance crop yields. This approach is geared towards optimizing agricultural efficiency and sustainability (Usman et al., 2020).

In this review, we advocate for the utilization of nanomaterials (NMs) to enhance food systems and agriculture, supported by compelling data. However, it is crucial to emphasize the necessity of conducting comprehensive toxicity tests on NM-based products before their market introduction. Ongoing developments in nanotechnology have led to the creation of innovative agrochemical delivery systems utilizing NMs to transport active chemicals efficiently.

Furthermore, agricultural waste materials like wheat straw and soy hulls can be transformed into advanced bio-nanocomposites possessing superior mechanical and physical properties suitable for industrial applications. Despite the potential benefits of nanotechnology in agriculture, certain advancements are still required. These include refining process design, conducting thorough risk assessments for nanopesticides and nanofertilizers, and establishing robust regulatory frameworks to govern the commercialization of nano-agro-products (Kaushal, M., 2018).

An additional challenging aspect that requires attention is the development of farming systems capable of effectively managing the unpredictability associated with climate variability. This involves the creation of new crop varieties resilient to factors such as heat, drought, and other environmental stressors, encompassing a broad spectrum of modern farming practices utilized worldwide (Mittal, D., et al., 2020). We strongly believe that realizing the goal of bolstering global agriculture necessitates a thorough comprehension of nanotechnology.

2. Drastic changes overcomes by the aid of Nanoenzymes

2.1.Non-nanoenzymes (Fe, TiO2 ,SiO 2, ZnO).

Non-nanoenzymes are larger enzymes with strong stability. They're tough, easy to handle, and great for big-scale work. Unlikely tiny nanoenzymes, they resist harsh conditions like heat and chemicals. Plus, they're good at specific tasks and can handle complex reactions. Researchers can tweak them for different jobs, from making drugs to cleaning up the environment. While nanoenzymes also get a lot of attention, non-nanoenzymes are still super useful and have lots of potential.

2.2. Nanoenzymes

2.2.1. Carbon-based Nanoparticles

(NPs) are tiny particles composed primarily of carbon atoms, typically ranging in size from 1-00 nanometers. They have garnered significant interest due to their unique properties and wide-ranging applications across various fields, including medicine, electronics, energy storage, and environmental remediation. These nanoparticles can be synthesized using various methods, such as laser ablation, chemical vapor deposition, and pyrolysis. Some common types of carbon-based NPs include fullerenes, carbon nanotubes (CNTs), graphene, and carbon dots. Their high surface area, excellent mechanical strength, and unique electronic, optical, and chemical properties make them attractive for use in drug delivery, biosensing, catalysis, and as additives in materials for enhancing conductivity and strength. Additionally, carbon-based NPs exhibit low toxicity, biocompatibility, and biodegradability, making them promising candidates for biomedical applications. In a study by Wang et al. (2016), the antifungal properties of six nanomaterials made of carbon were investigated at concentrations of 62.5, 125, 250, and 500 mg/L. These nanomaterials included reduced graphene and graphene oxide (GO), among others. Despite their numerous advantages, challenges remain in the large-scale production, functionalization, and precise characterization of carbon-based NPs, which researchers continue to address to unlock their full potential in various applications.

2.2.2. Titanium-based Nanoparticles

(NPs) have emerged as promising materials with diverse applications across various fields. Due to their unique properties, such as high surface area, biocompatibility, and corrosion resistance, Ti-based NPs find applications in biomedicine, catalysis, environmental remediation, and electronics. In biomedicine, titanium dioxide (TiO2) NPs are utilized in drug delivery systems, imaging agents, and tissue engineering scaffolds. In catalysis, Ti-based NPs exhibit excellent activity and selectivity in various reactions, including hydrogenation and oxidation processes. Additionally, Ti-based NPs are employed in environmental applications for wastewater treatment and pollutant removal due to their photocatalytic properties. High photocatalytic activity and antibacterial potential of photocatalytic TiO2 NPs against X. perforans, the pathogen causing spot disease in tomato plants, were reported by Paret et al. (2013). Continued research in synthesis methods and understanding their behavior will further expand the applications of Ti-based NPs.

2.2.3. Silver-based Nanoparticles (NPs)

According to Zhang et al. (2016), there was an investigation into the toxicity of AgNPs at the physiological and molecular levels. Additionally, silver-based nanoparticles (Ag-based NPs) are nanoparticles primarily composed of silver atoms, typically ranging in size from 1 to 100 nanometers.

They have garnered significant attention due to their unique physical, chemical, and biological properties, making them versatile materials with numerous applications. Ag-based NPs exhibit remarkable antibacterial, antifungal, and antiviral properties, which have led to their widespread use in biomedical applications, such as wound dressings, coatings for medical devices, and drug delivery systems. Their ability to inhibit the growth of microorganisms is attributed to their high surface area-to-volume ratio, which enhances interaction with microbial cells, and the release of silver ions, which disrupt cellular processes. In addition to their antimicrobial properties, Ag-based NPs also find applications in catalysis, sensing, electronics, and environmental remediation. They are employed as catalysts in various chemical reactions due to their high surface reactivity and catalytic efficiency. Furthermore, Ag-based NPs are utilized in sensors for detecting gases, biomolecules, and environmental pollutants. DNA-directed AgNPs were created by Ocsoy et al. (2013), demonstrating a novel method of synthesis that offers precise control over the size and shape of the nanoparticles. Additionally, DNA-directed silver nanoparticles (Ag) grown on graphene oxide were discovered, enhancing their stability and functionality. Despite their wide range of applications, concerns have been raised about the potential toxicity of Ag-based NPs to human health and the environment. Research continues to focus on understanding their interactions with biological systems and developing strategies to mitigate any adverse effects while maximizing their benefits. Overall, Ag-based NPs represent a promising class of nanomaterials with diverse applications and ongoing research aimed at unlocking their full potential while addressing safety concerns.

2.2.4. Copper-based Nanoparticles (NPs)

have emerged as promising materials with diverse applications, including agriculture, electronics, catalysis, and biomedicine. Recently, Borgatta et al. (2018) compared the capacity of CuONPs and Cu3(PO4)2·3H2O nanosheets to inhibit root fungal disease in watermelon (Citrulluslanatus) caused by Fusariumoxysporum f. sp. niveum, shedding light on their potential as agricultural fungicides. Additionally, Cumplido-Najera´ (2019) studied the effects of CuNPs and K2SiO3NPs on tomato plants grown hydroponically and subjected to the disease Clavibactermichiganensis, highlighting the role of Cu-based NPs in plant disease management. Cu-based NPs exhibit antimicrobial properties due to their ability to release copper ions, making them effective agents against various pathogens. Furthermore, their unique electronic and catalytic properties render them useful in electronic devices and catalytic converters. Continued research on Cu-based NPs aims to optimize their properties and explore novel applications while ensuring their environmental safety.

2.2.5. Cerium-based Nanoparticles (Ce-based NPs)

have emerged as promising materials with diverse applications across various fields. These nanoparticles, primarily composed of cerium atoms, exhibit unique physical and chemical properties that make them versatile for use in catalysis, energy storage, environmental remediation, and biomedical applications. (Adisa et al. 2018) recently conducted a greenhouse study to evaluate CeO2NP-mediated control of tomato Fusarium wilt, highlighting the potential of Ce-based NPs in agriculture for disease management. In addition to their agricultural applications, Ce-based NPs are utilized in catalysis due to their high surface area and redox properties, making them effective catalysts for various chemical reactions. Furthermore, Ce-based NPs have shown promise in fuel cells and batteries for energy storage and in environmental remediation for removing pollutants from air and water. Despite their wide-ranging applications, ongoing research is needed to further understand the behavior and potential risks associated with the use of Ce-based NPs, ensuring their safe and effective implementation across different fields.

2.2.6. Iron-based Nanoparticles

have garnered significant attention for their diverse applications in agriculture, environmental remediation, biomedical fields, and beyond. Studies conducted by (Liu et al. 2016) investigated the impact of varying doses of FeOXNPs on the growth of Lactucasativa seedlings, shedding light on their potential as growth-promoting agents in hydroponic systems. Similarly, (Ghafariyan et al. 2013) demonstrated that Fe2O3NPs at concentrations of 30–60 mg/L significantly increased the chlorophyll content in hydroponically grown soybean plants, highlighting their role in enhancing plant vitality. (Li et al. 2016) showed that γ-Fe2O3NPs at 20 mg/L substantially improved maize seedling germination rates and root length, leading to a notable increase in overall plant growth. Furthermore, (Palchoudhury et al. 2016) found that α-Fe2O3NPs at extremely low concentrations significantly stimulated the growth of legume embryonic roots. Recently, (Rui et al. 2016) assessed Fe2O3NPs as a potential substitute for conventional Fe-based fertilizers, indicating their promising role in sustainable agriculture. Additionally, the effects of nano-Fe2O3 on soybean seedlings were examined by (Alidoust and Isoda 2013) using two distinct exposure scenarios (root and leaves), further expanding our understanding of their impact on plant growth and development. These findings collectively underscore the multifaceted benefits of Fe-based NPs in enhancing plant growth, nutrient uptake, and overall agricultural productivity while promoting environmental sustainability.

2.2.7. Magnesium-based Nanoparticles

have emerged as promising materials with diverse applications across various fields. These nanoparticles, primarily composed of magnesium atoms, exhibit unique physical, chemical, and biological properties that make them versatile for use in biomedical, energy, environmental, and industrial applications. After applying foliar-sprayed MgNPs to black-eyed pea, (Delfani et al. 2014) discovered that a dose of 0.5 g/L greatly boosted photosynthesis and plant biomass, underscoring their potential as agricultural growth enhancers. Mg-based NPs have been explored for drug delivery systems, biosensing, and medical imaging due to their biocompatibility and biodegradability. Additionally, they hold promise in hydrogen storage and fuel cell technologies due to their high hydrogen storage capacity and catalytic activity. In environmental applications, Mg-based NPs are utilized for water purification and pollutant removal. Furthermore, they find applications in the aerospace industry for lightweight structural materials and in electronics for magnesium-based batteries and sensors. Despite their numerous advantages, challenges remain in the synthesis, functionalization, and scale-up production of Mg-based NPs. Ongoing research aims to address these challenges and unlock the full potential of Mg-based NPs for various applications, contributing to advancements in science and technology.

2.2.8. Zinc-based Nanoparticles

have gained attention for their diverse applications and potential impact on plant growth and development. (Dhoke et al. 2013) investigated the effects of ZnONPs on the development of mung bean (Vignaradiata) seedlings cultivated hydroponically, providing insights into their role as growth enhancers in agriculture. Additionally, (Dimkpa et al. 2017) conducted a pot experiment to examine the effects of ZnONPs or Zn salt amendment on the development of sorghum, a significant yet understudied grain crop. These studies highlight the importance of understanding the interactions between Zn-based NPs and plants, as well as their potential as novel tools for sustainable agricultural practices. Further research is needed to explore the mechanisms underlying the effects of Zn-based NPs on plant growth, optimize their application methods, and ensure their safety for both plants and the environment. Overall, Zn-based NPs hold promise for improving crop productivity and contributing to food security in a rapidly changing world.

2.2.9. Manganese-based Nanoparticles

have drawn attention for their potential applications in agriculture and biomedicine.(Pradhan et al. 2013) conducted one of the few investigations examining the effects of NPs on plants at cellular and whole-plant levels, focusing on mung bean growth. They evaluated the effects of MnNPs at a concentration of 0.05 mg/L, comparing them with commercially available manganese salt, $MnSO4$. This study aimed to understand the impact of Mn-based NPs on plant growth and development, shedding light on their potential as novel plant growth regulators or micronutrient supplements. Manganese plays a crucial role in various physiological processes in plants, including photosynthesis, enzyme activation, and hormone synthesis. By utilizing Mn-based NPs, researchers seek to enhance plant productivity, improve nutrient uptake efficiency, and mitigate environmental stressors. Further research is needed to elucidate the mechanisms underlying the effects of Mn-based NPs on plants and optimize their application methods for sustainable agriculture practices. Mn-based NPs hold promise for addressing challenges in crop production and contributing to global food security.

3. Crop Improvement by adapting Nanoparticles practices

Nanoparticles offer promising avenues for enhancing crop production and achieving higher yields. Engineered nanomaterials possess unique properties that can modify agronomic characteristics, including plant growth, biomass production, and physiological aspects, ultimately impacting produce quality and yield (Gardea-Torresdey et al., 2014;Salama et al., 2012).Nanofertilizers, as highlighted by (Subramanian et al. 2015), serve as nutrient carriers with nano dimensions, enabling the gradual and steady release of nutrients in accordance with crop demand due to their large surface area. This controlled release mechanism enhances nutrient absorption and photosynthesis, ultimately leading to improved crop productivity.

Research studies by (Kumar, Y et al., 2021) underscore the significant impact of nanofertilizers on crop production. Nanofertilizers not only increase nutrient use efficiency but also mitigate toxicity resulting from excessive fertilizer application and split fertilizer application (Naderi and Danesh-Shahraki, 2013). Recent advancements have shown that nanofertilizers or nano-encapsulated nutrients possess properties that effectively release nutrients and chemical fertilizers on demand, regulating plant growth and enhancing target activity (Nair et al., 2010).

Overall, the use of nanoparticles as nanoagrochemicals in recent agriculture holds great promise for optimizing crop production and achieving higher yields. By improving nutrient absorption, enhancing photosynthesis, and regulating nutrient release, nanofertilizers contribute to increased crop productivity while minimizing environmental impacts associated with conventional fertilization practices. Continued research and development in this field will further unlock the potential of nanoparticles to revolutionize modern agriculture and address global food security challenges as represented in Figure 1.

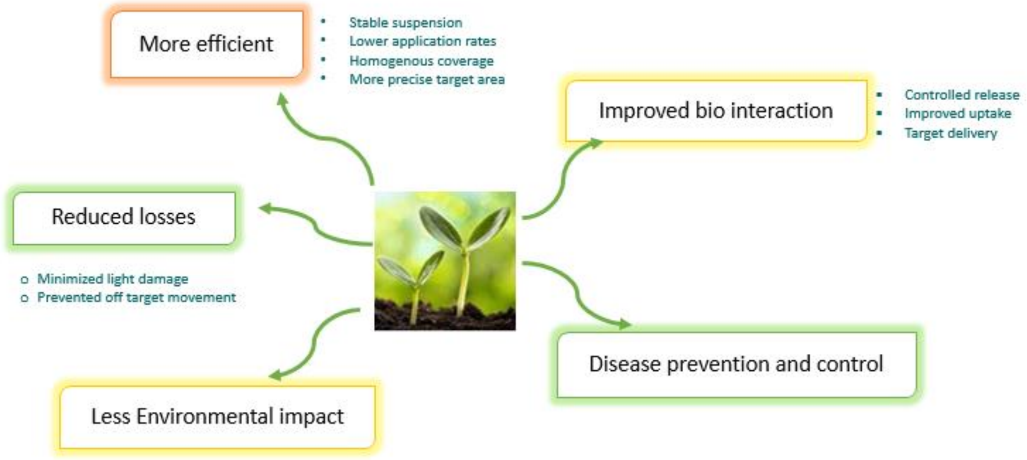

Figure 1:The new era of nanoagrochemicals and its multidimesional applications in crops growth enhancement and productivity.

Nanoparticles also hold tremendous potential in revolutionizing crop production and addressing global food security challenges. Engineered nanomaterials can effectively modify agronomic characteristics, enhance plant growth, and improve biomass production, ultimately leading to higher crop yields (Gardea-Torresdey et al., 2014; Salama et al., 2012). Nanofertilizers, with their nano dimensions and large surface area, enable the slow and controlled release of nutrients, enhancing nutrient absorption and photosynthesis while reducing environmental impact (Subramanian et al., 2015). Additionally, nanotechnology presents a promising alternative for transforming agriculture, with the potential to improve food quality, increase global food production, protect plants, detect diseases, monitor plant growth, and reduce waste (Prasad et al., 2014). The unique properties of nanoparticles, including high reactivity, better bioavailability, bioactivity, and surface effects, further contribute to their immense potential in agriculture (Gutiérrez et al., 2011). Nanofertilizers and nano-encapsulated nutrients offer the advantage of releasing nutrients on demand, effectively regulating plant growth and enhancing target activity (Rosa et al., 2010; Nair et al., 2010). For instance, urea-modified hydroxyapatite nanoparticle-encapsulated Gliricidiasepiumnanocomposites demonstrate a slow and sustained release of nitrogen, offering a promising solution for nutrient management in crop production (Kottegoda et al., 2011). Overall, nanotechnology holds the key to unlocking new possibilities in agriculture, paving the way for sustainable and efficient crop production systems.

Nanoparticles offer significant potential for enhancing crop production and achieving higher yields. Studies have demonstrated that soil amended with metallic Cu NPs can significantly increase lettuce seedling growth by 40% and 91%, respectively (Shah and Belozerova, 2009). Furthermore, research focusing on the characteristics of nanoparticles has revealed their ability to enter plant cells and transport DNA and chemicals inside the cell (Ambrogio et al., 2013; Ghafariyan et al., 2013; Torney et al., 2007).Moreover, nanofertilizers have a profound impact on soil health by reducing soil toxicity and decreasing the frequency of fertilizer application (Naderi and Danesh-Shahraki, 2013). DeRosa et al. (2010) reported that nanofertilizers offer various delivery mechanisms, such as encapsulation by nanomaterials (NMs), coating with a thin protective film, or delivery as emulsions or nanoparticles

(NPs). Nano and subnano composites enable controlled release of nutrients from the fertilizer capsule (Liu et al., 2006).

Nanoscale science and nanotechnology have the potential to transform agriculture and food systems (Norman and Hongda, 2013). Previous studies have utilized materials such as urea-loaded zeolite chips and nanocomposites containing nitrogen to induce a slow nitrogen release and increase plant nitrogen uptake (Kumar, Y et al.,2020)Other materials employed for similar purposes include nutrient sources coated with thin polymer films and nutrients encapsulated inside nanoporous materials (Rai et al., 2012).

Nanofertilizer formulation represents an innovative approach in agricultural science, aiming to enhance nutrient delivery and uptake efficiency while minimizing environmental impacts. Nanoemulsions, nanogels, and dendrimers are among the key nanomaterials utilized in these formulations. Nanoemulsions, consisting of fine droplets of oil dispersed in water, offer a promising avenue for delivering nutrients to plants effectively. Their small droplet size and high surface area facilitate rapid nutrient absorption, promoting plant growth and development. Nanogels, three-dimensional networks of crosslinked polymer chains, provide a versatile platform for encapsulating and releasing nutrients gradually. These nanocarriers offer controlled release properties, ensuring a sustained supply of nutrients to plants over an extended period, thus optimizing fertilizer efficiency and reducing nutrient leaching. Dendrimers, highly branched macromolecules with well-defined structures, exhibit unique properties ideal for targeted nutrient delivery. By functionalizing dendrimers with specific nutrient molecules, precise targeting and controlled release can be achieved, allowing for efficient nutrient uptake by plants while minimizing wastage. Incorporating nanoemulsions, nanogels, and dendrimers into nanofertilizer formulations holds immense potential for revolutionizing nutrient management in agriculture. These advanced formulations offer advantages such as improved nutrient absorption, reduced environmental impact, and enhanced crop yields, contributing to sustainable agricultural practices and global food security as shown in Figure 2.

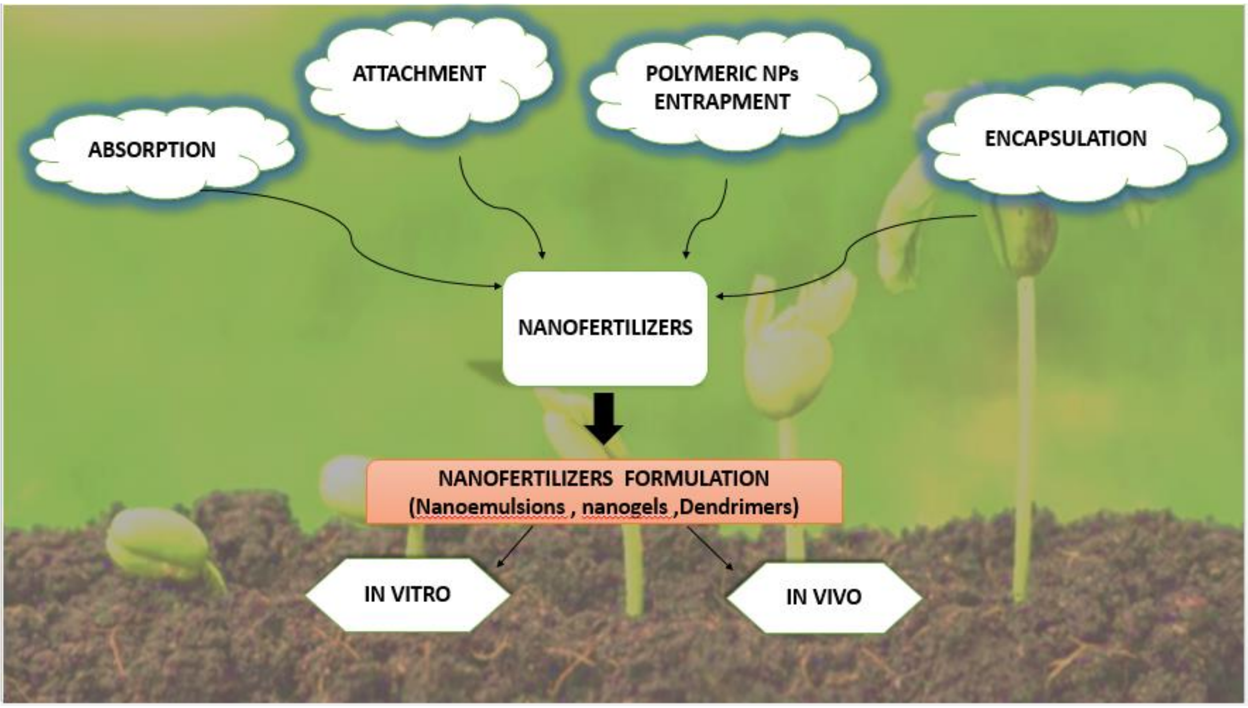

Figure 2 (In vitro and In vivo) applications of nanofertilizershighlight the transformative potential of nanoparticles in optimizing crop production and fostering sustainable agriculture practices.

4. Smart Delivery System

Smart delivery systems in crop productivity involve the use of advanced technologies to precisely deliver nutrients, water, pesticides, and other agrochemicals to plants, optimizing their growth while minimizing resource wastage and environmental impact. These systems often utilize sensors, actuators, and control algorithms to monitor plant needs and adjust delivery parameters accordingly. By providing tailored inputs to plants based on real-time data, smart delivery systems can enhance crop yields, improve resource efficiency, and reduce labor requirements. (Mishra et al. 2015).

One example of a smart delivery system is the use of precision agriculture techniques coupled with automated irrigation systems. These systems incorporate soil moisture sensors, weather data, and crop water requirements to precisely control irrigation schedules and amounts. By delivering the right amount of water directly to the root zone when and where it's needed, these systems prevent overwatering, reduce water loss through evaporation, and ensure optimal plant growth.

Another example is the development of nanotechnology-based delivery systems for agrochemicals. Nanoparticle carriers can encapsulate pesticides, fertilizers, or growth regulators, allowing for controlled release and targeted delivery to plants. These systems can improve the efficacy of agrochemicals, reduce environmental contamination, and minimize off-target effects.

4.1. Nanobiosensors

Nanobiosensors are playing an increasingly important role in improving crop productivity by providing real-time monitoring of various parameters crucial for plant health and growth. These sensors offer advantages such as high sensitivity, specificity, and portability, making them ideal for on-field applications. One area where nanobiosensors have been particularly useful is in monitoring soil nutrients, which are vital for optimizing crop growth. By providing accurate and timely data on nutrient levels, nanobiosensors enable farmers to adjust fertilizer application more precisely, thereby reducing waste and enhancing crop yield.

One example of a nanobiosensor used in agriculture is a graphene-based sensor for nitrate detection. This sensor, developed by (Liu et al. 2012), utilizes graphene oxide as a sensing platform coupled with enzyme-functionalized gold nanoparticles for specific nitrate detection. The sensor offers high sensitivity and selectivity, enabling real-time monitoring of nitrate levels in soil. This information can help farmers optimize nitrogen fertilization, leading to improved crop productivity while minimizing environmental impact.

4.2. Safety concerns

The use of nanomaterials in various applications has raised concerns about their safety and potential toxic effects. Nanomaterials have unique physicochemical properties that can lead to interactions with biological systems, which may result in unintended consequences. Some of the safety concerns associated with nanomaterials including Potential for Cellular Damage where Nanomaterials can penetrate cells and tissues, leading to cellular damage. They can also induce oxidative stress, inflammation, and DNA damage, which can have long-term health effects. Bioaccumulation of nanomaterials can accumulate in organs and tissues over time, raising concerns about their long-term effects on health. Environmental Impact of use of Nanomaterials released into the environment can have detrimental effects on ecosystems and wildlife. Unknown Toxicity can impact due to their unique properties, the toxicity of nanomaterials is not well understood, and more research is needed to assess their safety. Studies on soil Microbial Communities have shown that nanomaterials like silver nanoparticles (AgNPs) can adversely affect soil microbial communities, leading to changes in microbial diversity and function (Kah et al. 2013). However with advancement in technologies new risks also emerge in environment but withfurtherresearch can open new essential solutions and altrenative prevention measures to establish comprehensive safety protocols for the responsible development and application of nanomaterials in agriculture.

5. Effects of Nanoparticles on Plant-Microbe Interactions

The effects of nanoparticles on mycorrhizal and rhizobial symbioses represent a critical area of research with significant implications for plant-microbe interactions and overall ecosystem health. Mycorrhizal associations, particularly arbuscularmycorrhizal fungi (AMF) and rhizobial interactions, play crucial roles in nutrient uptake, plant growth, and ecosystem functioning. However, the introduction of nanoparticles into the soil environment poses potential challenges to these symbiotic relationships.Studies exploring the impact of nanoparticles on mycorrhizal symbioses have revealed complex and context-dependent effects. Nanoparticles can influence the growth and functionality of mycorrhizal fungi, affecting nutrient cycling and plant nutrition. Researches on the use of nanoparticles highlighting CeO nanoparticles at certain concentrations had contrasting effects on soyabean crops. However, CeO NP concentration (10-100g /1Kg) soil nitrogen fixing was inhibited reporting sensitivity of specific symbiotic processes against nanoparticle exposure (Tian, H., Kah, M. Et al 2019).

Several factors influence the outcomes of nanoparticle interactions with mycorrhizal and rhizobial associations. These include nanoparticle composition, size, concentration, and exposure duration, as well as soil properties and microbial community composition. The complexity of these interactions underscores the need for a nuanced understanding to predict the environmental impact of nanoparticles accurately. The findings emphasize the importance of considering concentration thresholds and the potential dual effects of nanoparticles on different facets of symbiotic relationships. While some concentrations may not hinder nodulation, they may disrupt nitrogen fixation, which is critical for plant growth. This highlights the delicate balance in nanoparticle-soil-plant-microbe interactions and emphasizes the need for tailored approaches to mitigate potential adverse effects. As research in this field progresses, a deeper understanding of the intricate dynamics between nanoparticles and mycorrhizal/rhizobial symbioses will contribute to sustainable agricultural practices and environmental stewardship. This knowledge will inform strategies to harness the benefits of nanotechnology while minimizing unintended consequences on essential plant-microbe interactions crucial for ecosystem health.

The effects of nanoparticles (NPs) on plant-microbe interactions has garnered significant attention due to the potential implications for agriculture and ecosystem health. NPs, defined as particles with at least one dimension less than 100 nanometers, possess unique physicochemical properties that can influence their interactions with plants and microbes. Understanding these interactions is crucial for predicting the ecological consequences of NP exposure in the environment. One significant aspect of NP-plant-microbe interactions is their impact on soil microbial communities. Studies have shown that NPs can alter the composition and function of soil microbial communities, potentially affecting nutrient cycling, soil fertility, and plant health. For instance, research by (Zhang et al. 2021) demonstrated that silver nanoparticles (AgNPs) can disrupt the structure of soil microbial communities, leading to changes in microbial diversity and activity. Moreover, NPs can directly influence plant growth and physiology by affecting nutrient uptake, photosynthesis, and stress responses. For example, titanium dioxide nanoparticles (TiO2 NPs) have been shown to enhance plant growth and photosynthesis under certain conditions (Raliya et al., 2023).

However, the mechanisms underlying these effects are complex and may vary depending on NP properties and plant species. Additionally, NP-mediated changes in plant-microbe interactions can have cascading effects on ecosystem processes such as carbon sequestration and nutrient cycling. For instance, NPs may alter the symbiotic associations between plants and beneficial microbes, such as mycorrhizal fungi or nitrogen-fixing bacteria, thereby impacting plant nutrient acquisition and soil fertility. Furthermore, the fate and transport of NPs in the environment play a critical role in determining their overall impact on plant-microbe interactions. Studies have shown that NPs can undergo transformations in soil and water systems, influencing their bioavailability and toxicity to plants and microbes (Sun et al., 2024). Understanding the factors governing NP fate and transport is essential for assessing their environmental risks and developing strategies to mitigate their adverse effects.

6. CONCLUSION

In conclusion, the utilization of nanoparticles in enhancing crop productivity holds immense promise for revolutionizing agriculture and ensuring food security in the face of escalating global challenges. Through their unique properties, nanoparticles offer unprecedented opportunities to address critical issues such as nutrient availability, pest management, and environmental sustainability in agricultural practices.Firstly, nanoparticles have shown remarkable efficacy in improving nutrient uptake and utilization by plants. Their small size and high surface area enable efficient delivery of essential nutrients to plant roots, thereby enhancing growth and development. Moreover, nanoparticles can serve as carriers for micronutrients, enabling targeted and controlled release, which minimizes nutrient losses and maximizes their utilization by crops. This targeted nutrient delivery system has the potential to mitigate nutrient deficiencies, particularly in soils with poor fertility, thus enhancing crop productivity and yield. Secondly, nanoparticles exhibit potent antimicrobial properties, offering a sustainable solution to combat plant pathogens and pests. By incorporating nanoparticles into crop protection formulations, farmers can effectively manage diseases and pests while reducing reliance on conventional chemical pesticides. This approach not only safeguards crop health but also minimizes environmental pollution and mitigates the development of pesticide resistance. Additionally, nanoparticles can enhance the efficacy of biocontrol agents, further augmenting their potential for integrated pest management strategies.

Acknowledgements:I would like to acknowledge the Head, Dept. of Tech Biosciences, Digianalix for guidance in this review work.

Authors Contribution

PriyankaKumari, SurbhiTiwari, TanviRisha, PhoolBalaBhagat, PrabhaKumari contributed in literature search and manuscript writing; Priyangulta Beck, HarsimranKaurHora, MukeshNitin manuscript writing, literature searching and proof reading; Swati Shalika, Pinki Raj Sahu helped with proof reading; MukeshNitin helped with experimental design, proof reading, guiding, manuscript and proof reading of the review article.

Source: No external funding. Digianalix internal funding.

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