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THE ROLE OF NANOTECHNOLOGY IN CROP IMPROVEMENT – A REVIEW

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SUMMARY

Nanotechnology is a new and vital scientific transformation used in various fields globally. It has proven its recognition in agricultural sciences with environment-friendly fertilizers produced and applied, which are more efficient than traditional fertilizers. Nano-biotechnological techniques can benefit diverse processes related to plant biology, including seed germination, plant growth enhancement, plant nutrition improvement, secondary metabolites isolation, and protection provision against biotic and abiotic stress factors. Nanotechnology presents significant opportunities for agriculture due to its typical physicochemical traits, such as substantial surface area, heightened reactivity, adjustable pore size, and particle shape. These fertilizers have contributed to addressing the increasing challenges in crop production and food security and can meet the growing food demand of the world's population. Studies have shown that this technology can improve field establishment by increasing seed emergence, plant growth, and yield even under different stresses. Notably, nanotechnology exploration in Iraq, particularly in agriculture production, has focused only on research purposes. Therefore, the current review emphasizes the importance of nanoparticles in the context of plant systems.

Keywords: Nanotechnology, nano-fertilizers, crop production, seed germination, medicinal plants, sustainable agriculture

Key findings: The presented review showed the value of using nanotechnology in crop improvement. Nanotechnology has become one of the prime technologies promising to advance agricultural practices and offer sustainable development by improving management and conservation tactics with reduced agricultural input wastage.

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INTRODUCTION

Nanotechnology is the matter's manipulation of its near-atomic scale to produce new structures, materials, and devices. The technology promises scientific advancement in various sectors, such as agriculture, medicine, consumer products, energy, materials, and manufacturing. Past studies revealed that newly generated materials exhibited distinct physical and chemical characteristics compared with the base material (Afify and El-Nwehy, 2023).

Nanotechnology plays a considerable role in developing novel technologies and instruments that operate on the nanoscale, corresponding to the dimensions of one billionth of a meter. Although some nanoparticles may be of natural origin (e.g., magnetite), most are of synthetic origin. Synthesis techniques can be physical, chemical, and biological (Ansari *et al*., 2020). Nanotechnology is an enabling technology that has facilitated advancements in various sectors. It includes atomic cluster alteration, ranging from five to a thousand atoms, with diameters often falling within 1 to 100 nanometers. These dimensions are far smaller than bacteria and living organisms (Miguel *et al*., 2023).

Consequently, nanoparticles demonstrate distinctive characteristics and encompass a range of elements, including organic, inorganic, and mixed compositions. These compositions' generation emerged through various natural processes, such as chemical reactions, volcanic eruptions, forest fires, and decomposing plants, animals, and microbes (Du *et al*., 2017).

Nanotechnology significantly reduces the number of manufactured materials for fertilizers due to their physical and chemical properties. The size of the material particles, if less than 100 nanometers, allows an increase in surface area and the penetration of that material through the seed membranes and different plant tissues. Their transfer and absorption resulted in a considerable impact despite decreasing their quantity. Given the importance of expanding nanotechnology in various fields, especially crop production, the technology's limited employment is evident in Iraq.

Nanotechnology requires further studies and the construction of specialized factories to produce nanomaterials and fertilizers to meet the local demand. Iraq mainly imports these materials in limited quantities for scientific laboratory research. From the above discussion, the presented study hopes to shed light on the most crucial aspects of nanotechnology in crop production. Approximately 35%–40% of crop output is contingent upon fertilizer use (Afify and El-Nwehy, 2023); however, specific fertilizers directly affect plant development. The global cropping system extensively relies on applying a substantial quantity of fertilizers, pesticides, and herbicides to enhance crop productivity and alleviate environmental pollution (Singh *et al*., 2019). The proliferation of mineral fertilizers raises several issues, including ecological contamination in soil and water and air pollution.

Additionally, using these traditional chemical fertilizers leads to a considerable decline in food material quality, enhancing disease-carrying vectors, soil deterioration, and a significant lack of micronutrients in the cultivated soils. Hence, these promising issues provide critical challenges to supplement nourishment for the bulging global population. However, one of the proposed potential solutions is utilizing nanotechnology as a viable approach, which can quickly address all these issues (Rani *et al*., 2020).

Nanotechnology holds significant potential for transforming the agricultural industry by introducing innovative tools to diagnose and control disease and enhance the nutrient absorption capacity of crop plants. Hence, it offers possible advancements in crop productivity and nutritional values. Moreover, this phenomenon could facilitate the advancement of more effective mechanisms for monitoring and regulating environmental parameters, augmenting plants' ability to assimilate more nutrients and mitigate the impact of pesticides (Singh *et al*., 2019).

Nanofertilizers

Nanofertilizers' primary production starts by wrapping nutrient elements with nanomaterials. Developing primary nanomaterials included physical and chemical procedures. Then, the targeted nutrient elements undergo wrapping inside nanomaterials and formation as nano-sized particles for nutrient elements. These nanofertilizers become distinct by their dimensions, ranging from 1–100 nanometers. However, nanofertilizers behave significantly differently from traditional fertilizers due to two main factors. The first factor is that their surface area to volume ratio is more substantial than in the natural state due to the small size of their molecules, leading to differences in properties, such as hardness, color, strength, chemical activity, thermal properties, and electrical conductivity. Consequently, their surface area increases with an enhanced number of molecules on their external surfaces, increasing reactivity and chemical activities (Agrawal and Rathore, 2014)**.**

The second factor is the quantitative effects of nanomaterials. Given their small diameters, they do not follow classic physics laws but quantum physics ones, making their quantum effect higher. These properties caused these nanofertilizers to possess unique characteristics not existing in the traditional chemical fertilizers and have different impact types on plant growth. It depends on the nanoparticle diameter, chemical composition, concentration, and solubility. Therefore, Nanofertilizers is a suitable mechanism for delivering nutrients to targeted parts of plants, such as roots and other crop plant parts (Mastronardi *et al.,* 2015)**.** The nanofertilizers also provide a broad area for different metabolic reactions in crop plants (Qureshi *et al.,* 2018). Applying nanofertilizers (Nano NPK 1.0 g L^{-1}) maximizes growth characteristics, tubers yield, and nutrient contents of onions (Afify and El-nwehy, 2023).

Why nanofertilizers?

In agriculture, nanofertilizers are essential to improve crop growth, yield, and quality parameters with efficient increased nutrient use, reducing fertilizer wastage and production costs. It is a well-known fact that introducing traditional fertilizers has brought a great revolution in crop management and production, doubling crop yields and improving their quality (Mastronardi *et al.,* 2015). However, the excessive use of these chemical fertilizers in crop production has negatively affected the environment, with their residues also observed in plant parts, which can percolate into groundwater, resulting in health problems for other living organisms, including humans.

In addition, producing these fertilizers consumes a lot of energy, raw materials, and gases, with the wastes also released by factories for some of the manufactured fertilizers, considerably contributing to increasing environmental pollution and global warming. The problems have made researchers earnestly seek alternatives to these fertilizers that reduce pollution by expanding organic fertilizer production using nanotechnology to produce essential plant nutrients (Qureshi *et al.,* 2018).

The global population will reach approximately nine billion individuals by 2050. Adequately sustaining the future expanding population requires imperative augmentation of food production by approximately 60%–100%. The agricultural methodologies incorporate applying substantial fertilizers to enhance soil fecundity and augment crop yield to address the growing need for nourishment. Nevertheless, this phenomenon ultimately results in a significant decline in soil fertility, reduced crop productivity per unit area, and accelerated environmental contamination (Duhana *et al*., 2017).

Nanofertilizers, when applied to seeds, plants, and soil, cause variations in vital structural processes and, eventually, influence plant growth through improved tolerance to abiotic stresses and enhance the grain yield with improved quality (Ismailova and Azizov, 2022; Bakry *et al*., 2024). Essential nutrients are crucial in improving soil fertility and crop productivity. However, fertilizer management is one of the most valuable requirements for crop development. It has also been apparent that one-third of crop productivity refers to using fertilizers, while the rest depends on the efficiency of using other field inputs and operations. The efficient nutrient use for traditional fertilizers, added directly to the soil or sprayed on plant leaves, depends mainly on the final fertilizer concentration that reaches target sites. It will naturally be minimal and much lower than the minimum concentration required in the target site due to chemical loss, drift, surface runoff, leaching, evaporation, photodegradation, and even microbial degradation (Monreal *et al.,* 2016).

Agriculture scientists aimed to enhance specific technologies such as the spraying of zinc sulphate to improve jojoba traits which lead to raise its economic value as a promising tree with multi chemical and pharmaceuticals industries uses to reduce fertilizer consumption without compromising crop productivity and the environment by introducing the concept of 'Control of fertilizer loss in agriculture (Atteya et al., 2018) Developing this type of fertilizer (nanofertilizers) led to lessening such losses. In nanofertilizers, the elements enter the soil through hydrogen bonds and surface tension, with soil filtration simply blocking them. The nutrients also remain stable around the plant roots in the soil, making it easier for plant roots to absorb them to meet their needs throughout the growth period (Das *et al.,* 2016).

Past findings indicated that reducing the size of nanoparticles increases the surface area to mass ratio of the particles, leading to a slow and steady absorption of massive amounts of nutrients over a more extended period, providing balanced nutrition to crop plants during the growing season, ultimately improving the production (Subramanian *et al*., 2015). Singh *et al*. (2019) examined the advancement of nanotechnology-based material to enable the regulated release of plant fertilizers, hence augmenting their efficacy. Suppan (2013) mentioned that nanosizing could boost the accessibility of fertilizer nutrients to plant pores at the nanoscale level, thus resulting in enhanced efficiency in nutrient utilization.

Utilizing nanomaterials in specific quantities may occasionally result in ineffectiveness in obtaining desired goals. However, this phenomenon can point to the fact that the concentration of these substances is notably lower than the minimum effective concentration necessary for the chemicals and has faced numerous hindrances before reaching the intended agricultural regions. The challenges encompass chemical leaching, degradation from photolysis, microbiological activity, and hydrolysis (Nunez *et al*., 2018).

Prioritizing critical features, such as high solubility, stability, and efficacy, is crucial in designing nano-encapsulated agrochemicals to attain an optimal concentration for superior application. Furthermore, these agrochemicals must demonstrate controlled release mechanisms by specified stimuli, heightened efficacy in focused applications, and less ecological toxicity. Moreover, administering these interventions must be safe and convenient, thus reducing the necessity for frequent application (Nair *et al*., 2010). Using slow-release fertilizers is often a highly beneficial alternative to soluble fertilizers, primarily due to their capacity to release nutrients slowly during crop growth and development. The process of progressive release facilitates the efficient absorption of nutrients by crop plants, hence reducing wastage resulting from leaching. The constituents encompass phosphorus, calcium, and numerous minor and trace elements (Navarro *et al*., 2008).

Green nanotechnology revolution

Nanotechnology is a new and essential scientific revolution in industry globally, as it has proven its position in agricultural sciences and related industries as a multi-disciplinary and pioneering technology in solving problems (Rasheed and Al-Anbari, 2023). Therefore, its use has expanded in fertilizer production as it has reduced the losses and yielded better results. Its environmental impact is minimal, while its efficiency is higher than traditional mineral fertilizers. Therefore, the green nanotechnology revolution has significantly changed the global agriculture level. Nano-fertilizers work with a specific goal to regulate the release of nutrients based on crop requirements and minimize losses to the lowest possible level. Subramanian *et al.* (2015) reported that nanofertilizers release nutrients slowly and steadily over an extended period (>30 days), thereby improving their efficiency of use without any adverse effects.

Nanotechnology and medicinal plants

Innovations are capable of removing problems associated with herbal medicines. Novel drug delivery systems, such as nano-drug delivery systems, helped enhance the safety and efficacy of herbal medicines. Al-Taweel and Mohammed's (2023) findings indicated that foliar application of nano-nitrogen fertilizer (3 ml L^{-1}) and nano-potassium (3 g L^{-1}) led to a significant enhancement in total alkaloids content of European black Henbane plant by 270.2% and 248.1%, respectively, compared with the control treatment.

Nanotechnology is a modern technology used to supply medicinal compounds, such as alkaloids, which is achievable by designing novel drug delivery systems (NDDS) for herbal constituents. Therefore, nano-delivery systems with different nanoparticles became applicable, thus allowing them to reduce their limitations, improve their effectiveness, and increase pharmacological potential (Ansari *et al*., 2012). Developing modern extraction methods for medicinal plants is vital to providing high-quality herbal products. Ocsoy *et al.* (2017) conducted a comparative study for extract preparation techniques, extracts for metallic single and hybrid nanoparticle (NP) synthesis, and their antimicrobial properties against pathogenic and plant-based bacteria.

Nanofertilizers role in stimulating seeds

Among different seed priming approaches, such as seed treatment with Ascorbic Acid Al-Taweel *et al.,* 2017), nano-priming methods, such as nano-pesticides, nanofertilizers, and nano-sensors, hold better potential for enhancing germination percentage and the vigor of many crop plants. Previous research indicated that nanoparticle application could improve the seeds' ability to absorb and utilize water and nutrients (Zhang *et al.*, 2016). Navarro *et al.* (2008) reported that nanofertilizers could easily pass through seed coatings, which contributes to improving physiological processes inside the seed, enhancing its germination ability, reducing the germination period, and increasing seedlings potential because of the boosted efficiency of cell membranes to transfer nutrients between seed cells. Singh *et al.* (2015) explained that the activation of seeds with nanofertilizers helped seeds absorb water and initiate the first stages of germination before the emergence of the radicles.

Researchers attributed this to the ease of absorption of nano-nutrients by seed coatings and their supply with elements for a lengthy period, strengthening the seeds and providing a consistent germination rate and uniformity in seedlings. Ezzat and Mohammad's (2016) findings enunciated those soaking seeds in nanofertilizers improved the nutrient contents in seeds, the germination rate, and the resulting seedling characteristics, such as enhanced plant height, chlorophyll content, dry weight, and vigor. Altayy and Cheyed (2021) indicated that nanofertilizers penetrated seed coatings, increased their vitality, and improved their absorption of organic matter, which stimulated hydrolytic enzymes, achieving high germination and better seedling growth. It may be due to the small size of nanofertilizers, which helped water enter the seeds, resulting in enhanced metabolic activities inside the seeds and an increased germination rate.

Nanofertilizers role in enhancing growth and productivity

Nanofertilizers are essential in crop productivity as they are the tools that help solve farmers' challenges in crop management by obtaining high-yielding crops. Consequently, it is possible by balanced nutrition of crop plants, ultimately increasing plant growth and production with good quality (Duhana *et al.,* 2017). Nanofertilizers are distinct in their ability to retain abundant nutrients and release them slowly, facilitating the absorption of nutrients compatible with crop requirements.

With the rapid development in science and technology, including agricultural sciences, it has become necessary to search for modern ways and methods that meet plant requirements for nutrients in the shortest period, with the best quantity and more efficiency. Therefore, researchers have resorted to using nanofertilizers because they target specific sites in plants to encourage growth and increase production under changing climatic conditions while increasing fertilizer use efficiency and positively affecting the quantity and quality of production (Sadiq and Mohammed, 2022).

Applying zinc oxide nanoparticles to maize seeds resulted in notable enhancements in plant growth, leaf area, and dry weight versus the untreated samples (Estrada-Urbina *et al.,* 2018). The findings of Moaveni and Kheiri (2011) showed that the field treated with TiO_2-NPs demonstrated the highest corn production. The fertilization of Nano-SiO_2 has proven to result in an enhancement of leaf fresh and dry weights, chlorophyll content and proline accumulation, free amino acids, nutritional content, and antioxidant enzyme activity in the presence of salinity-induced stress, which boosts the plant capacity to endure abiotic stress. Past studies indicated that Nano-Silica (0.0, 25, 50, and 100 ppm) could reduce the impact of drought on barley growth and improve the nutrient status of plants (Hellal *et al.,* 2020).

Liu and Lal (2015) reported the possibility of enhancing crop production by 35%–40% through balanced fertilizer and irrigation management using high-quality seeds. Abobatta (2017) demonstrated that nanofertilizers stimulated photosynthesis by increasing the chlorophyll content in leaves and enhancing crop tolerance to various stresses, which positively affected seed yield. The study conducted by Benzon *et al.* (2015) revealed that the administration of conventional fertilizer, either alone or in combination with nanofertilizers, substantially influenced the rice's number of reproductive tillers, panicles, and total spikelets. Using nanofertilizers combined with conventional fertilizers can enhance the nutrient uptake by plant cells, hence promoting optimal growth through a synergistic impact. These findings indicate that Nanofertilizers has the potential to serve two chief purposes, i.e., supplying essential nutrients to plants and facilitating the transportation and absorption of existing nutrients, thus enhancing crop development. Hatami *et al.* (2016) highlighted that nanofertilizers could easily penetrate different plant tissues due to their small size and rapid spread, boosting the plants' absorption rate.

Furthermore, Nunez *et al.* (2018) demonstrated that nanofertilizers improved crop seedling growth by increasing the solubility of insoluble nutrients in the soil and reducing nutrient freezing under severe temperature drops, thus maintaining cell viability and enhancing plant stress tolerance. Pacheco and Buzea (2018) observed that nanofertilizers could induce physiological and chemical changes in plant roots and leaves due to their physical and chemical properties, leading to faster plant material transfer and accumulation. Moreover, the use of nanofertilizers in the central region of Iraq has proven to enhance the productivity of wheat, rice, broad bean, and maize crops due to their effectiveness in improving plant growth and development (Burhan and Al-Hassan, 2019; Al-Ziady *et al*., 2021; Mohammed *et al*., 2021; Al-Mafrajee and El-Rubaee, 2022; Sadiq and Mohammed, 2022).

Potential risks of nanotechnology

Nanoparticles have the potential to infiltrate the human body through four primary routes, i.e., inhalation, ingestion, dermal absorption, and intentional injection during medical procedures. Upon entering the human body, these entities exhibit notable mobility due to their small size. In particular instances, the nanoparticles can traverse the blood-brain barrier. Hence, it is imperative to acknowledge the possible hazards posed by nanoparticles to both humans and animals**.** The commercialization of nanotechnology faces several prevalent obstacles. It includes the significant costs associated with processing, difficulties in scaling up research and development efforts for prototype and industrial production, and apprehensions surrounding the public perception of environmental, health, and safety matters. Governments worldwide must establish standardized and stringent regulations and surveillance mechanisms before the nanomaterials' commercialization and widespread utilization.

CONCLUSIONS

The results showed the importance of using nanotechnology, especially in producing plant fertilizers, because of their higher value in developing and enhancing the crop plant's ability to withstand environmental stresses, improving seed germination, augmenting plant growth and yield, and enriching seed quality. Nanotechnology also considerably influences the economy, as it reduces raw material consumption and sources of nanofertilizers production, leading to reduced pollution and waste. Despite the significance of nanotechnology, its utilization in Iraq is low, which requires better attention for an increase in production and a reduced gap between supply and demand for crop products and dependency on imports.

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