**Biogenic metallic nanoparticles as biofertilizer: an emerging paradigm for sustainable agricultural practices**

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**Abstract**

Nanotechnology has revolutionized many facets of human lives, the economy, health and the environment with their multifaceted and multifarious benefits. One of the most notable contributions to the wellbeing of the population is the agricultural sector. However, negative impacts from uncontrolled agrochemical applications adversely affect a sustainable environment. Nanotechnology engenders eco-friendly technology for agricultural upliftment and environmental management. Agriculture production systems have relied on chemical fertilizers indiscriminately to support the growing world population, which has created an environmental burden. This had a detrimental impact on ecosystems, food and environmental quality. It is therefore necessary to develop an alternative mechanism that enhances farm production and the sustainability of the environment in order to overcome the negative impacts of traditional chemical fertilizers. Nanofertilizers (NFs) are an excellent alternative to traditional chemical fertilizers because they provide smart-controllable and target-specific nutrient delivery to plants and are eco-friendly. Plants are better able to tolerate biotic and abiotic stress when NFs are applied through the foliage or roots. Due to their nanoranged structures, they are excellent for sustainable agriculture, climate mitigation, and environmental rebirth in comparison to bulky fertilizers. Although the use of NFs is not without challenges, their extensive use may create another set of emerging pollutants that may be difficult to remediate. In this chapter, the synthesis, type, advantages and demerits of NF application are reviewed for better understanding and comparison.

**Introduction**

Environmental sustainability, food security and economic viability are tripod factors that define human health. Due to the ever-increasing world population and industrial advancements, traditional agriculture was threatened with extinction, encouraging the use of chemical fertilizers to boost production. As such, getting the required daily nutritional dose is becoming more challenging and immediate scientific and policy interventions must be put in place (Aguilar-P´erez *et al*., 2020; Bilal *et al*., 2021). The global food demand can only be achieved by increasing resource utilization efficiency without compromising agricultural production through the advancement of modern science and technologies (Adhikari and Ramana, 2019). Hence, the current food production must be raised by 60–70% to meet the calories demand of the galloping populace (van Dijk *et al.,* 2021). Overcoming these daunting challenges of eradicating worldwide hunger calls for an urgent improvement in the nutrient used by improving the nature of fertilizers or by improving their application method, to enhance efficiency as well as decrease total nutrient use (Ruan et al, 2016, Bhardwaj *et al.,* 2020, Bhardwaj *et al*., 2021). Sustainable agriculture can be best achieved through policy directives and scientific contributions. Some of the challenges faced by farmers in traditional agriculture include chemical toxicity owing to the excessive use of chemical inorganic fertilizer and sometimes their high cost, which is beyond the reach of marginal farmers, particularly in developing countries (Wang *et al*., 2016).

Chemical inorganic fertilizers account for ~50–55% crop yield increment in developing countries (Adhikari and Ramana, 2019). However, Out of the total amount of chemical inorganic fertilizers applied, more than 50% has been estimated to remain unused as they accumulate in the soil and water bodies through leaching and mineralization (Adhikari and Ramana, 2019). This usually triggers excess soil nutrient mining, leading to a net negative soil nutrient balance, thus deteriorated the soil health (Chugh *et al.,* 2021). The overuse of chemical inorganic fertilizers is in vogue to attain the desirable yield, which causes soil and water pollution including soil quality deterioration, ground water and air pollution (Chhipa, 2017; Ye *et al.,* 2020).

Additionally, the indiscriminate use of chemical inorganic fertilizers raises the production cost and reduces farmer’s profit (Diatta *et al.,* 2020). Hence, systematic initiatives to restore natural resources are required to make intensive agriculture productive while reducing adverse environmental impacts (Babu *et al.,* 2020).

Nanotechnology has a great potential for its application in agriculture, such as crop management, fertilizers, plant nutrition, crop growth, plant pathology, genetics, plague control, and even nanosensors (Ndaba *et al.,* 2022). It can be utilized to modulate the nutrient requirements of the plants for healthy growth, enhance productivity, agricultural water quality management, product processing, storage, and quality control.

Nanotechnology provides eco-friendly methods for increasing crop production using nano-fertilizers, which promote the plant’s efficiency in absorbing nutrients and controlling targeted delivery (Khan *et al*., 2019, Shang *et al*., 2019, Azeez *et al*., 2020).

Nano-fertilizers provide some nutrients in a nano form, enhancing plant growth and production (Dimkpa and Bindraban, 2016). Based on the nutrient needs of plants, nano fertilizers are classified into three categories: macro nano-fertilizers, micro nano-fertilizers, and nano-particulate fertilizers (Chhipa and Joshi, 2016). Nano-fertilizers can be spread like a powder or a liquid with a diameter of < 100 nm (Josef and Katarina, 2015). Because of the rising need and demand for environmentally and non-toxic nano-material synthesis, biofabrication of nanoparticles using biological methods has got great attention (Abd- El-Hack *et al*., 2021; Saad *et al.,* 2021; El-Saadony *et al.* 2018; Akl *et al.* 2020; El-Saadony *et al.* 2021c; El-Saadony *et al.* 2021d; Sheiha *et al*. 2020). Proteins, enzymes, alkaloids, phenolic compounds, pigments (Abdelnour *et al.,* 2020), and amines are the molecules responsible for NPs’ synthesis in plants (Shah *et al*., 2015; Hassanin *et al.,* 2020; El-Saadony *et al*., 2021e). On the other hand, the physical methods are expensive while, chemical methods use toxic solvents which adversely affect the environment. Hence, the synthesis, type, advantages and demerits of nanofertilizers application are reviewed for better understanding and comparison.

**Nanotechnology**

Nanotechnology is a multidisciplinary field of research that has shown promise in biotechnology, medical sciences, environmental science and engineering, food technology as well as agriculture (Thakur *et al.* 2018). It involves the manipulation of matter, on a molecular scale, whereby structures termed ‘nanoparticles’ (NPs) that are less than 100 nm in size in at least one dimension are formed (Qureshi *et al*. 2018; Sharma *et al.* 2019). Their minute size and large surface area to volume ratio convey special properties that are distinct from those of the bulk material (Thakur *et al*. 2018).

**Nanoparticles**

Nanoparticles (NPs) are tiny molecules with a small size range of 1–100 nm with different physiochemical properties than bulk materials (El-Saadony *et al.* 2021a; Reda *et al.* 2020; Reda *et al.* 2021). Some properties that contribute to NPs application in agriculture include their enhanced bioactivity, bioavailability, and reactivity, as well as their surface and adherence effects. (El-Saadony *et al.,* 2021).

NPs improved physical, chemical, and biological properties and functions due to their expanded surface area to volume ratio. Nanoparticles are excellent adsorbents for many pollutants due to their sizes, shapes, magnetic properties, modifiable surfaces, reactivity and high sorption capacities (Azeez *et al*., 2020). These properties help to immobilize heavy metals and boost the synthesis of phytochemicals in plants against environmental stress and infection of pathogenic organisms (Ben-Moshe *et al.,* 2013).

**Fabrication of Nanoparticles**

**Production of nanoparticles by the top-down method**:

Materials are prepared mainly by breaking the bulk into smaller particles using physical processes such as crushing, milling, and grinding methods. Generally, this NPs production method is not appropriate for formulating evenly shaped nanomaterials, and it is complicated to get tiny nanoparticles even with high energy usages (Khan, 2020).

**Production of nanoparticles by the bottom-up method:**

Materials are prepared atom-by-atom or molecule-by-molecule. This method is more frequently used for producing most nanomaterials. This method can produce a uniform size, shape, and well-distributed nanomaterials. It controls the chemical synthesis process precisely to prevent undesirable particle growth (Khan, 2020).

**Production of nanoparticles by physical Methods:**

Several physical methods for the synthesis of metallic nanoparticles exist which include laser ablation, pyrolysis, lithography and sputtering. Due to its fast-processing times which provides better control over the size and shape of the nanoparticle’s particles, high yields and longterm stability of the generated nanoparticles, laser ablation is often considered an alternative to chemical synthesis methods. In this case, a solid surface is irradiated with a laser beam leading to a low flux plume which is evaporated or sublimated to form nanoparticles. Sputtering on the other hand involves the deposition of a thin film of nanoparticles generated by the collision of ions over a substrate followed by annealing. It is commonly referred to as physical vapor deposition and its efficiency is dependent on substrate type, duration of annealing, temperature used during deposition which all directly affect the size and shape of the nanoparticles (Khashan *et al.,* 2015a). Although the physical route for synthesis of metallic and metal oxide nanoparticles with uniformly-sized particles is employed, it is expensive because it involves energy intensive processes which make the whole process very costly (Almatroudi, 2020; Wu *et al.,* 2019).

**Biosynthesis**

Because of the rising need and demand for environmentally, effective, and non-toxic nanomaterial synthesis, biofabrication of NPs using biological methods has got great attention (Abd- El-Hack *et al*., 2021; Saad *et al.,* 2021; El-Saadony *et al.* 2018; Akl *et al.* 2020; El-Saadony *et al.* 2021c; El-Saadony *et al.* 2021d; Sheiha *et al*. 2020). Proteins, enzymes, alkaloids, phenolic compounds, pigments (Abdelnour *et al.,* 2020), and amines are the molecules responsible for NPs’ synthesis in plants and microorganisms (Shah *et al*., 2015; Hassanin *et al.,* 2020; El-Saadony *et al*., 2021e). On the other hand, the physical methods are expensive while, chemical methods use toxic solvents and adversely affect the environment.

**Fertilizers**

**Inorganic fertilizer**

Inorganic fertilizers provide nutrients needed by the plants for optimal productivity. Farmers typically apply inorganic fertilizers through the soil, either by surface broadcasting, sub-surface placement or mixing with irrigation water. However, a large portion of fertilizers applied using these methods is lost to the atmosphere or surface water bodies, thereby polluting ecosystems. For example, excess nitrogen is lost through volatilization as NH3 or emission as N2O or NO, or through NO3 leaching or runoff to water bodies. In contrast, excess phosphorus becomes “fixed” in soil, where it forms chemical bonds with other elements such as Ca-P, Mg-P, Al-P, Fe-P and Zn-P, and become unavailable for uptake by the plants. Eventually, rain washes the nitrogen and phosphorus compounds into waterways such as rivers, lakes and the sea, where they can cause serious pollution problems.

**Nanofertilizer**

Chemical fertilizers are being used to increase crop productivity, but they negatively affect soil fertility and disturb the mineral quality. Their prolonged use damages soil structure, mineral cycle, microbes, and plants. Nanotechnology is an expanding field, and it has applications in agriculture and plant science as nanofertilizers. Nanofertilizers are required to limit the adverse effect of inorganic fertilizers on the environment. They are highly reactive and can penetrate the epidermis (Chhipa and Joshi, 2016). Nanofertilizers are efficient as they slowly release nutrients throughout the plant’s life cycle. They reduce the risks of adsorption, decomposition, leaching, and surface runoff (Joshi *et al*., 2019).

**Types of nanofertilizers (NFs)**

Based on the type of nutrients content, nano-fertilizers can be generally categorized into three groups: Macronutrient-based, micronutrient-based, and biofertilizer-based NFs.

**Macronutrient-based NFs:**

The product in which nano-sized macronutrients are encapsulated or coated is called macronutrient-based NFs. These are quite effective in enhancing crop growth and yield. Globally, NFs are reported to have 18–29% higher NUE than those of conventional chemical fertilizers (Kah *et al.,* 2018). Macronutrients like N, P, and K are used in very high quantities to get higher crop yields.

**Nitrogen-based nanofertilizers (N-NFs):**

For optimum plant growth and development, nitrogen is indispensable. However, excess nitrogen application has serious environmental implications. Nano carriers like zeolites, chitosan, or clay can synchronize with plant demand and release of nitrogen in a gradual fashion, resulting in improved plant absorption (Aziz *et al.,* 2016). Nano zeolites and their blends have been widely used in the development of N-NFs because of their large surface area and the ability to synchronize nitrogen release.

**Potassium nanofertilizers (K-NFs):**

Potassium regulates water transport, photosynthetic capacity enhancement, cell tissue strengthening, nitrate absorption, triggering blooming stimulation, and carbohydrate and enzyme production in plant systems. Better crop response due to K-NFs over chemical inorganic potassium fertilizers has been reported across the world (Nido et al., 2019; Hussein et al., 2019). Similarly, increased leaf number, improved product quality, pest resistance, and drought tolerance have also been reported in foliar nano-K fertilizer treated summer squash (Gerdini *et al*., 2016).

**Calcium nanofertilizers (Ca-NFs):**

Calcium is an important element for cell wall stabilization, mineral retention in soil and transportation, hazardous chemical neutralization, and seed development. A small quantity of Ca-NFs increases pomegranate yield and quality as compared to higher concentrations of calcium chloride (CaCl2) (Davarpanah *et al.,* 2018). Similarly, spraying of Ca-NFs on apple fruit at the pre-harvest stage improves quantitative and qualitative features over CaCl2 (Ranjbar *et al.,* 2020).

**Magnesium nanofertilizers (Mg-NFs):**

Magnesium is essential for plant growth because it makes up the core of the chlorophyll molecule essential for photosynthesis. Owing to its leaching and high mobility, Magnesium is frequently lost from the soil. Application of magnesium hydroxide NPs (500 ppm) produced 100% seed germination and improved plant growth of maize (Shinde *et al.,* 2018).

**Sulfur nanofertilizers (S-NFs):**

Sulfur aids in chlorophyll production, improves nitrogen use efficiency and strengthens plant defenses. Elemental sulphur is not directly available to crop plants. It can only be absorbed after biological oxidation. Biological oxidation is chiefly regulated by fertilizer particle size (Valle *et al.,* 2019). Excess sulphur application aggravates leaching into the soil and causes negative environmental consequences.

**Micronutrient-based NFs:** Plants rely on micronutrients for a variety of physiological processes. These are needed in trace amounts (< 100 ppm) yet they play a key function in a variety of plant metabolic processes. Iron, boron, manganese, zinc, copper, molybdenum, nickel, and chlorine are the examples of these elements. Micronutrient NFs often supply adequate nutrition without posing environmental hazards.

**Fe nanofertilizers** (Fe-NFs):

Iron is an essential cofactor for enzymes involved in diverse biological processes in plants. Plants do not have access to an enormous amount of Fe because it is present in insoluble forms in soil. Using very stable and slow-release NFs is a promising strategy to make Fe available to plants. Additionally, Fe-NFs are free from ethylene-based chemicals which cause premature senescence in plants (Armin *et al.,* 2014). In a wide pH range, iron chelated NFs are highly stable and provide a gradual Fe release. The use of hematite NFs (α-Fe2O3-NFs) and ferrihydrite (5Fe2O3⋅9H2O) NFs in hydroponically grown maize and soybean were found to increase the chlorophyll content in seedlings (Ghafariyan *et al.,* 2013; Pariona *et al*., 2017).

**Zn nanofertilizers (Zn-NFs):**

Zinc is essential for the catalytic activity of various enzymes in the plant system. Zn adsorption on soil clay complex is a major challenge for low Zn efficiency. Zn-NFs reduce the Zn fixation in soil and enable smart delivery to the plants (Wang *et al.,* 2016). The beneficial effect of ZnO-NPs on some crops over to common Zn amendments, indicating their potential use in crop plants (Wang *et al.,* 2013; Sabir *et al*., 2014). ZnO-NFs enhance antioxidant content in tomatoes and growth parameters in cotton (Venkatachalam *et al.,* 2017; Faizan *et al.,* 2018).

**Cu nanofertilizers (Cu-NFs):**

Copper is an essential mineral for several physiological functions in plants, including mitochondrial respiration, cellular transport, antioxidative action, protein trafficking, and hormone signaling. Cu-NFs are an important source of Cu for plants (Rawat *et al.,* 2018). Even very low concentration of Cu ions stimulated plant growth (Rajput *et al.,* 2018).

**Mn nanofertilizers (Mn-NFs):**

Manganese plays a crucial role in photosynthesis-anabolic process, respiration-catabolic process, and N metabolism in plants. Mn NFs have been proven as a better micronutrient source for Mn as compared to commercially available MnSO4 salt (Elmer and White, 2016). The growth and photosynthesis in mungbean have been reported to significantly increase with Mn-NFs. Shoot and root growth of mungbean increased by 38% and 52%, respectively, over control (Pradhan *et al.,* 2013). Dimpka *et al.* (2018) reported that foliar application of Mn-NFs increased Mn translocation efficiency (22%) in wheat crops.

**B nanofertilizers (B-NFs):**

Boron is required by plants in modest amounts and plays a crucial role in the construction of cellular walls and the movement and transmission of photosynthates. The flowering stage of legumes requires continual boron supply for proper nodulation and nitrogen fixation. Nanotechnology provides a viable alternative strategy for the efficient use of boron (Shireen et al., 2018). Boron metal and its NPs had a greater effect on raising plant height, pod number, and seed yield of mungbean when sprayed at 90 mg Liter− 1 (Ibrahim et al., 2019). B-NFs under calcareous conditions produced good alfalfa yield with adequate feed quality (Taherian *et al.,* 2019). Genaidy *et al.* (2020) sprayed olive trees with 20 ppm nano-boron and 200 ppm nano-Zn, and the plants produced the greatest number of fruits with the highest seed oil content. The use of B-NFs (34 mg B plant− 1) enhanced the fruit yield of pomegranate (Davarpanah *et al.,* 2016).

**Foliar application of Nanofertilizer**

The traditional nutrients’ application to the soil has several drawbacks in terms of nutrient availability to plants. Therefore, foliar application is the most efficient method of correcting nutrient deficiencies and increasing crop yield and quality (Semida *et al*., 2021). In addition, it also reduces environmental contamination and increases nutrient use efficacy via decreasing the amount of fertilizer applied to the soil (Schwab *et al*. 2015). Nano-fertilizers have a large surface area, a high sorption capability, and regulated release kinetics to specific sites, making them a smart delivery system (Rameshaiah *et al.* 2015; Solanki *et al.* 2015). Nano-carriers often deliver nutrients at the right time and in the right place.

**Effect of nanofertilizer on plant growth and nutrition**

Nanoparticles as the building block of nanotechnology influence a variety of biological processes in plants such as plant growth, yield, health, and other physiological processes (Jaskulski *et al.,* 2022). Physicochemical features of nanoparticles most importantly their large surface to volume ratio and chemical compositions make them very veritable for agricultural practices (Salem *et al.,* 2022). The plant growth-promoting ability of nanoparticles have been well documented (Table 1) and are ascribed to their abilities to penetrate, translocate, facilitate electron exchange and develop favourable interactions with varieties of plants which enhance photosynthetic process, water utilization, nitrogen metabolism, seed germination, cell division and elongation to consequently increase their growth, promote their physiological activities and diseases control (Gupta *et al.,* 2018; Siddiqi and Husen, 2021). Nanoparticles as fertilizers are more efficient in supplying nutrients to plants as they maintain gradual and continuous release of nutrient to plants thereby reducing the risk of nutrient run-off into water and also protect environmental degradation induced by the excessive use of chemical fertilizer (Tombuloglu *et al.,* 2019). Biosynthesized nanofertilizers are most preferred unlike chemically synthesized nanopfertilizer owing to their simplicity in production, less toxicity, eco-friendliness and biocompatibility nature (Adelere and Lateef, 2021; Sharma *et al*., 2023). Nanofertilizers provide great surface area that enhance photosynthesis rate, improves the crop biomass and also help the crop to combat environment stress (Singh, 2017). They are very efficient for nutrient delivery systems owing to their wide interfacial area, sorption capacity, and controlled-release dynamics to specific sites (Achari and Kowshik, 2018). The effectiveness of nanofertilizers to enhance crop productivity depends on their distribution to crops, uptake and accumulation by crops, including the factors like particle size, surface area to volume ratio, as well as their interactions with soil and plant system (Ndaba *et al.,* 2022).

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**Table 1: Effects of nanofertilizer on plant growth**

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| --- | --- | --- | --- |
| **Nanoparticles** | **Mode of synthesis** | **Effects on plants** | **References** |
| Silver nanoparticles | Chemical | Improved the height, leaf sizes, plant fresh and dry weight of *Chrysanthemum morifolium* | Tung *et al.* (2018) |
| Silver nanoparticles | Biological | elongated the shoot and root length of *Corchorus olitorius* | Azeez *et al.* (2019) |
| Silver nanoparticles | Biological | Enhanced the seed germination percentage and seedling growth of watermelon, corn and zucchini plant | Almutairi and Alharbi (2015) |
| Silver nanoparticles | Biological | Protect wheat plants against heat stress and improve plant growth parameters | Iqbal *et al*. (2019) |
| Silver nanoparticles | Biological | Demonstrated 1-1.58-fold improvement in seed germination, shoot height, root length, leaf size, chlorophyll contents and other growth parameters of *Corchorus olitorius*, *Amaranthus caudatus* and *Celosea argentea* | Lateef *et al.,* (2023) |
| Silver nanoparticles | Chemical | Promoted the growth and root nodulation of cowpea (*Vigna sinensis*, var. Pusa Komal) | Pallavi *et al.* (2016) |
| Zinc oxide nanoparticles | Chemical | Increased the yield of *Sorghum bicolor* (L.) under drought stress | Dimkpa *et al.,* 2019 |
| Combined zinc oxide nanoparticles (ZnO-NPs) and biofertilizer | Chemical | Protect safflower plants (Carthamus tinctorius L.) under salinity stress and significantly enhanced agronomic parameters | Yasmin *et al.* (2021) |
| Zinc oxide nanoparticles | Biological | Stimulated the germination of mung bean seeds and promoted the seedling growth | Javed *et* *al*. (2022) |
| Zinc oxide nanoparticles | Biological | Improved physiological growth with elevated protein and chlorophyll contents of pulses plant (Bengal gram, Turkish gram, and green grams) | Ukidave and Ingale (2022) |
| Zinc oxide nanoparticles | Chemical | Significant enhancement of root morphology of the rice plant (*Oryza* *sativa* L.) grown under salt stress conditions | Singh *et* *al*. (2022) |
| Combined zinc oxide nanoparticles and plant growth-promoting rhizobacteria | Biological | Protected wheat plants against heat and drought stress as the biomass and growth parameters were considerably improved compared | Azmat *et al*. (2022) |
| Iron nanoparticles | Chemical | Promoted the growth of *Capsicum annuum,* increase the chloroplast number*,* and regulated the development of vascular bundles | Yuan *et al.* (2018) |
| Combined iron oxide nanoparticles and plant growth-promoting bacteria | Chemical | Attenuated the toxic effect of arsenic andpromoted the growth and photosynthetic parameters of Ajwain (*Trachyspermum ammi* L.) seedlings | Sun *et al*. (2022) |
| Iron oxide nanoparticles | Biological | Alleviate abiotic stress on Setaria italica cultivated under drought condition and enhanced the photosynthetic, nutrients and growth parameters of the plant | Sreelakshmi *et al.* (2021) |
| Iron oxide nanoparticles | Biological | Enhanced the growth parameters, chlorophyll and sugar content of mulberry (*Morus alba* L*.*) | Haydar *et al.* (2021) |
| Selenium nanoparticles | Biological | Improved the morphological and physiological features of lettuce plant | Mohammadi *et al.* (2022) |
| selenium nanoparticle | Chemical | Improved the growth of eggplant, tomato, and cucumber plant | Gudkov *et al.* (2020) |
| selenium nanoparticle | Biological | Improved seed microstructure, seed germination, growth traits, physiochemical attributes, minerals uptake by two rapeseed cultivars and seedlings biomass | El-Badri *et al.* (2022) |
| selenium nanoparticle | Biological | Enhanced the growth parameters of sunflower (*Helianthus annuus* L.) as well as chlorophylls, carbohydrates, proteins, phenolic compounds, and free proline contents of the plant | Amin *et al.* (2021) |
| [Hydroxyapatite](https://www.sciencedirect.com/topics/earth-and-planetary-sciences/hydroxylapatite) [nanoparticles](https://www.sciencedirect.com/topics/earth-and-planetary-sciences/nanoparticle) | Chemical | Demonstrated positive effect on soybean, sorghum, pea and pakchoi plants growth | Maghsoodi *et al*. (2020) |
| [Hydroxyapatite](https://www.sciencedirect.com/topics/earth-and-planetary-sciences/hydroxylapatite) [nanoparticles](https://www.sciencedirect.com/topics/earth-and-planetary-sciences/nanoparticle) |  | Increased the agronomic parameters and essential oil production in rosemary (*[Rosmarinus officinalis](https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/rosmarinus-officinalis" \o "Learn more about Rosmarinus officinalis from ScienceDirect's AI-generated Topic Pages)* L.) plant cultivation | Elsayed *et al.* (2022) |
| chitosan nanoparticles combined with mineral nitrogen fertilizer | Biological | Significantly enhanced the growth, grain yield, total chlorophyll contents as well as nitrogen and potassium concentrations of wheat plant | Saad *et al.* (2022) |
| chitosan nanoparticles combined with NPK fertilizer | Chemical | Significantly improved the growth, yield parameters, photosynthetic contents, chemical constituents, and macronutrients in potato leaves and tubers | Elshamy *et al.* (2019) |