Application of Nanoparticles on Plants as Fertilizers

Subjects: Plant Sciences

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Soil degradation has led to an imbalance between food and feed production, climate regulation, water retention and carbon storage in the ecosystem. On a larger scale, it has led to soil erosions and nutrient runoffs, leading to soil infertility, thus affecting human beings through malnutrition and other related diseases. To increase productivity and improve soil quality, fertilizers have been used for decades by farmers worldwide on degraded soils affected by human factors. However, their intensive usage has led to the pollution of both water and soil as the crop uses less than half of the applied amount; the other remaining amount is lost through photolysis, hydrolysis, leaching and microbial immobilization and degradation; thus, threatening the soil microorganisms, human health and the ecosystem, and reducing the profit margin of farmers.

agriculture nanoparticles nanofertilizers plant growth

1. Introduction

Integrating cutting-edge nanotechnology into agriculture, including fertiliser creation, is considered one of the greatest feasible methods to significantly increase crop yield and sustain the world's constantly growing population [1]. The application of nanoparticles in agriculture as fertilisers is attributed to their improved characterization, absorption and responsiveness, as well as surface and adhesion effects [2]. Nanofertilizers are macro- or micro-nutrient fertilisers that are used to increase agricultural yields and have a particle size of less than 100 nm. Nanofertilizers are nanomaterials responsible for providing one or more types of nutrients to growing plants, supporting their growth and improving production [3]. They are presented in two different types. On one hand, the nanomaterials supply nutrients to plants to improve their development and yield, on the other, they are the carriers of nutrients and only assist in the transport and release of nutrients without directly being used as a nutrient source [4].

There is a growing need in the agriculture industry to increase food production to reduce hunger. Small-scale crop production has been significantly impacted by the heavy price, limited supply and frequent shortage of inorganic fertilisers, which is partly attributable to the COVID-19 pandemic outbreak, which has led to rising oil and food prices. Over the past years, inorganic fertiliser application has been used to improve plant growth and yields. Nevertheless, crops typically use less inorganic fertiliser than what is administered, and the surpluses are accessible to be leached into rivers, which contributes to water contamination [4]. Repeated application of such fertilisers also makes pollution severe. Therefore, to improve crop yield, it is required to produce fertilisers with targeted, gradual or controlled release. According to [5], nanotechnology, especially material nanotechnology, has gained a reputation in the field of agriculture (**Figure 1**). The publications in this regard have gone from less than 50 in number between 2009 and 2015 to approximately 200 papers in 2021, demonstrating the interest given to this field.

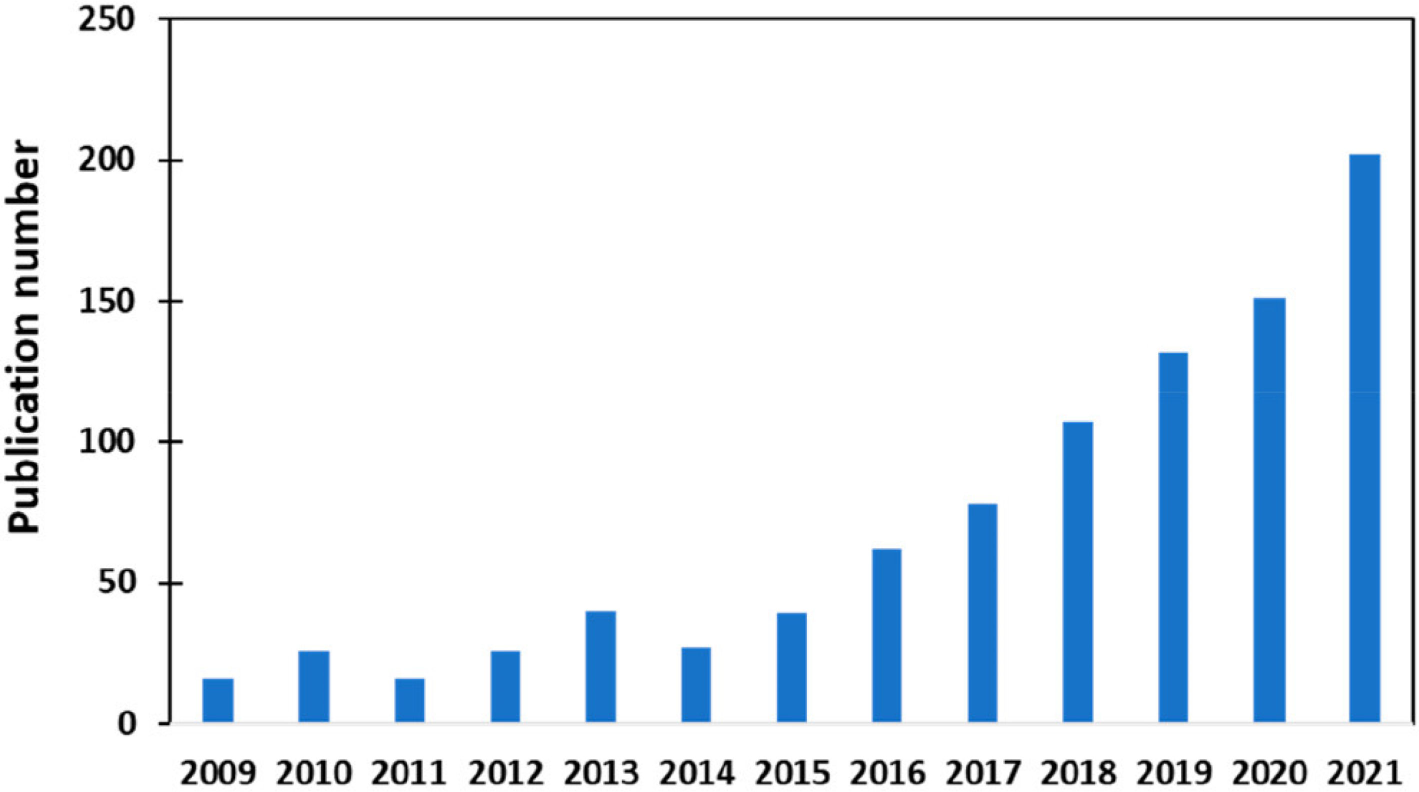

Figure 1. Publication trend of nanotechnology-related articles in the field of agriculture from 2009 to 2021 [5].

Given their distinctive qualities, such as their high surface area to volume ratio, slow or timed-release characteristics and absorption capacities, nanoparticles are thought to be suitable for producing fertilisers for use in agriculture [6]. Nanofertilizers' effectiveness to promote crop productivity is influenced by how they are applied to plants, as well as how they are absorbed and accumulated by plants. To promote plant growth and yield, nanofertilizers can be delivered above or below ground by foliar spray or irrigation. Additionally, biosynthesized nanoparticles can be added to seeds or primed [7][8]. The uptake and accumulation of nanoparticles for enhancing crop growth are dependent on the plant type as well as nanoparticles type, size, concentration, chemical composition, stability and transformation rate after biological interaction [9][10]. Nanofertilizers penetrate the aerial regions of the plant by entering the xylem vessels through the root epidermis and endodermis. Moreover, these nanoparticle nutrients can be delivered to different areas of the plant through the phloem and leaf stomata [10].

2. Application of Silver Nanoparticles

When compared to other nanoparticles, silver nanoparticles are drawing more attention due to their extensive use in a wide range of products, such as antimicrobial agents, shampoo, soap, toothpaste, wastewater treatment, food packaging materials, food storage containers, textiles, air fragrances, detergents and paint [11][12][13]. Silver nanoparticles have recently been linked to improved crop productivity in agriculture. According to numerous studies, the optimal concentration levels of silver nanoparticles are crucial for promoting seed germination [14][15] and plant growth [16]. In addition, chlorophyll concentration and photosynthetic quantum efficiency have been enhanced [17][18], as well as the effectiveness of water and fertiliser utilisation [19]. However, high concentrations of the 25 nm silver nanoparticles were found to tear down the cell wall and harm the vacuoles of *Oryza sativa* root cells, having a toxic effect [20]. According to [21], the silver was unable to infiltrate the root cells of *Oryza sativa* when present in low concentrations of up to 30 g/mL; nevertheless, the larger concentrations were effective in obliterating the cell structure and producing a harmful impact. Several studies reported that various sizes of silver nanoparticles demonstrate a clear relationship between size and nanoparticles toxicity to plants; smaller nanoparticles were consistently found to be more hazardous to plants compared with bigger nanoparticles [22][23][24].

3. Zinc Oxide Nanoparticles

All metallic nanoparticles influence how plants grow and develop; however, ZnO nanoparticles stand out for their exceptional qualities and wide range of applications [25]. Zinc is a regulatory co-factor and structural component of many enzymes and proteins and plays an important role in plant metabolic activity, particularly photosynthesis, phytohormone biosynthesis and antioxidant mechanisms [26]. A correct amount of zinc must be applied and made accessible because both deficiencies and excesses are harmful to plants. Due to their exceptional qualities, ZnO nanoparticles have been determined to be a potential particle for maintaining the necessary concentration of zinc in plants [27].

The study of [28] reported that zinc oxide nanoparticles improved both the fresh and dried weight of *Cicer arietinum* seedlings. Similarly, [29] stated that a high proportion of ZnO nanoparticles had a substantial impact on the viability and growth of tobacco. However, higher concentrations of ZnO nanoparticles at 2000 ppm were found to have toxic effects on the growth and yield of peanuts [30]. On the other hand, no significant impacts of ZnO were found on *Cucurbita pepo* at the investigated concentration [31]. Improved seed germination and root development, as well as plant growth, were observed on Fenugreek (*Trigonella foenum-graecum*) plants [32]. Additionally, similar results were recorded where seed germination was improved on Indian mustard (*Brassica juncea*) [33]. Increased protein content was observed when ZnO nanoparticles were applied, which helps with photosynthesis, promoting the viability and development of maize (*Zea mays* L.) plants [34]. Zinc oxide nanoparticle treatment at a concentration of 1000 ppm was found to enhance seed germination and seedling vigour, which led to initial development in the soil as evidenced by early flowering and increased leaf chlorophyll concentration [30].

4. Iron Oxide Nanoparticles

Iron is a crucial microelement with a variety of physiological and biochemical effects and is the fourth most prevalent element in terms of value; nonetheless, plants require large amounts of iron to grow [35]. Iron plays crucial roles in enzyme reactions and photosynthesis, improving the functionality of the photosynthesis process, DNA translation, RNA synthesis and auxin activities, all of which are necessary for optimal plant development [36]. Due to the limited availability of iron-containing minerals, utilising nanoparticles to address iron shortage is one of the alternative approaches. Nanoparticles can also increase crop production to different environmental stresses [35]. Iron oxide nanoparticles can enhance nutrient intake by interacting with molecules inside plant cells [37].

Several studies have reported that the application of iron oxide nanoparticles on different crops has improved plant growth parameters and dry matter material. According to [38], iron oxide nanoparticles boosted tomato plant development metrics. Similar results were observed by [39], who reported that the plant growth performance, photosynthetic pigments, indole acetic acid, the content of proline, free amino acids and total soluble sugars were significantly enhanced when iron oxide nanoparticles were sprayed on moringa plants.

5. Titanium Dioxide

Titanium dioxide is a well-known nanoparticle that has been used in crop production as well as human consumption. Titanium dioxide nanoparticles have several noteworthy effects on the morphologic, biological and physiological characteristics of the crop [40]. In their study, [41] observed that wheat seedlings treated with titanium dioxide nanoparticles resulted in enhanced growth and production characteristics, including yield. Furthermore, [42], reported that canola plants treated with titanium dioxide nanoparticles had increased germination rates and better radicle and plumule growth.

6. Calcium Carbonate

One of the most prevalent elements in the geosphere is calcium carbonate ($CaCO_3$). Calcium carbonate is an essential element in both basic technology and engineering. It already has a wide range of industrial uses in areas such as polymer, paper, elastomer, paints, fabrics, foodstuff and refreshments. Calcium carbonate is effective in combating pests such as oriental fruit flies and California red scales when sprayed on citrus tankan leaves [43]. Additionally, in research by [44], the combination of calcium carbonate and hydroxyl apatite nanoparticles applied to soybean plants under irrigation showed maximum yield in comparison to other treatments. In addition, [4] found that the application of calcium carbonate nanoparticles with a size of 20–80 nm considerably enhanced the seedling growth and dry biomass in contrast to the control when applied to groundnut seedlings.

7. Magnesium Oxide

Magnesium oxide has received significant attention among nanomaterials because of its simple stoichiometry, high ionic character, crystal structure and surface structural flaws. Peanut seeds responded favourably to MgO nanoparticle dispersion, which promoted germination, growth and photosynthetic pigments [45]. Additionally, the effects of applying magnesium oxide nanoparticles at a dosage of 4 mg/L on mung bean seedling growth revealed rapid germination when compared to other treatments [46]. Furthermore, maximum germination, seedlings, and vigour index were observed on the green gram (*Vigna radiata*) [47].

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