

Prospects and Constraints of Nano Fertilizer Technology in Agriculture

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ABSTRACT

The global population is rapidly expanding and is expected to reach 9.1 billion by 2050 and 10.4 billion by 2100. To ensure food and environmental security of huge population, the pressure on agricultural system is tremendously increasing. Conventional fertilizers are widely utilized to supplement essential nutrients in the soil. However, conventional fertilizers suffer from low nutrient utilization efficiency due to leaching, volatilization, fixation, immobilization etc., leading to substantial economic losses and decreased soil fertility. Nanotechnology is one of the rapidly developing technologies that have the potential to support sustainable agricultural growth. One of the key applications of nanotechnology in agriculture is nano fertilizer. Nano fertilizers designed to enhance nutrient uptake efficiency, minimize nutrient losses and reduce environmental contamination. These fertilizers operate on controlled and targeted release mechanisms, ensuring that nutrients are available to plants in a more efficient manner. Compared to conventional fertilizers, nano fertilizers offer advantages such as increased nutrient use efficiency, reduced soil and water pollution, improved crop yield and quality. Additionally, nano fertilizers have the potential to mitigate nutrient runoff and reduce the overall application frequency, leading to cost savings and environmental benefits. Despite these

promising benefits, the widespread adoption of nano fertilizers is constrained by several challenges. High production costs, potential environmental and health risks, uncertainties regarding long-term effectiveness and challenges in scalability hinder their large-scale application. The limited awareness among farmers, coupled with the absence of comprehensive safety guidelines, further restricts their adoption.

INTRODUCTION

Agriculture serves as a cornerstone for sustaining the growing global population and bolstering economic growth. Fertilizers play a crucial role in this endeavour by enhancing crop yields and maintaining soil health. Commonly used conventional fertilizers, such as urea, nitrogen, phosphorus, potassium, monoammonium phosphate, and diammonium phosphate, are essential for replenishing vital soil nutrients. However, these fertilizers have relatively low nutrient utilization efficiency, which leads to significant leaching and, consequently, economic losses and diminished soil fertility. Specifically, the nutrient utilization efficiency of conventional fertilizers is approximately 30–35% for nitrogen, 18–20% for phosphorus, and 35–40% for potassium, underscoring the challenges of nutrient loss and its impact on soil quality. Therefore, it is crucial to adopt alternative methods and techniques for fertilizer application to sustain adequate plant nutrition while safeguarding the ecosystem from pollution.

Nanotechnology in agriculture

Nanotechnology, first introduced by Norio Taniguchi in 1974, involves studying and manipulating atoms or structures within the range of 1 to 100 nano meters, each with unique properties. At this nanoscale, controlling matter enables a deeper understanding of physical, chemical, and biological processes, along with the development of innovative materials or structures that offer significant advantages.

Changes in properties at the nanoscale result from atomic-level alterations. Moreover, smaller nanomaterials generally exhibit a larger surface area, increasing their activity (Pokropivny *et al.* 2007). This transformative field is now extending its influence into agriculture, promising groundbreaking advancements. Nanotechnology, as a new enabling technology, has the potential to revolutionize agriculture and food systems. Agricultural and food systems security, disease treatment delivery systems, new tools for molecular and cellular biology, new materials for pathogen detection and protection of the environment are examples of the important links of nanotechnology to the science and engineering of agriculture and food systems.

Nano fertilizers:

Nanotechnology has emerged as a transformative tool in agriculture, with one of its key applications being the development of nano fertilizers. Nano fertilizers are advanced formulations developed by altering traditional fertilizers, bulk fertilizer materials, or extracts from plant, microbial, or animal sources. These materials are engineered using chemical, physical, mechanical, or biological techniques, often incorporating nanotechnology. In some cases, nanoparticles are also produced directly from conventional fertilizers. At the nanoscale, these fertilizers exhibit unique physical and chemical behaviours that differ significantly from their larger counterparts (Kumar *et al.* 2021).

Properties of nano fertilizers

- a) **Nano scale size:** The nanoscale size of nano-fertilizers typically ranges from 1 to 100 nano meters (nm). Within this size range, materials exhibit unique physicochemical properties—such as increased surface area, reactivity, and bioavailability—which make nano-fertilizers more efficient than conventional ones.
- b) **Controlled and targeted release:** Controlled and targeted release of nano-fertilizers refers to the ability of these fertilizers to deliver nutrients to plants in a precise, efficient, and sustained manner, minimizing losses and maximizing effectiveness.
- c) **Enhanced solubility and dispersion:** Enhanced solubility means that nutrients in nano-fertilizers dissolve more easily in water, making them quickly available for plant uptake. Improved dispersion refers to the uniform spreading of these tiny particles in soil or water, ensuring even nutrient distribution. These properties are due to the small size and large surface area of nanoparticles, which boost nutrient efficiency and reduce waste.
- d) **Precise composition:** The precise composition of nano fertilizers can be tailored to meet the exact nutritional demand of the crops.

Advantages of nano fertilizers

a) From plant's perspective:

1. **Enhanced nutrient uptake:** Nano fertilizers result in enhanced nutrient uptake due to their increased surface area and improved solubility.
2. **Controlled release and targeted delivery:** Controlled release ensures that nutrients are

released gradually over time, matching the plant's growth needs. This reduces nutrient loss and prevents over fertilization, leading to better efficiency and healthier plants. Targeted delivery directs nutrients specifically to the plant's root zone or other key areas, maximizing nutrient absorption and minimizing wastage. This ensures that nutrients are available where and when the plant needs them most, promoting faster growth and higher yields.

3. **Abiotic stress tolerance:** Nano fertilizers enhance stress resilience by improving nutrient availability and uptake, boosting antioxidant activity and stimulating natural defence mechanisms. By supplying essential nutrients in a controlled and efficient manner, they help plants maintain cellular function and growth even under challenging conditions. This leads to better survival rates, reduced crop loss and improved productivity under stressful environmental conditions.

b) From farmer's perspective:

1. **Cost effectiveness:** Nano fertilizers are cost effective due to their reduced application frequency (nano fertilizers provide nutrients to plants over an extended period of 40-50 days compared to conventional fertilizers having period of 4-10 days. This reduces the frequency of application, saving time and labor costs).
2. **Increased yield:** Using nano fertilizers helps farmers increase crop yield by improving nutrient efficiency and reducing losses. These fertilizers release nutrients in a controlled, targeted manner ensuring plants get the right nutrients at the right time.
3. **Increased quality:** Nano fertilizers are not just helping in increasing the crop yield but they also result in improved crop quality

which offers farmers a range of benefits that goes beyond quantity.

4. **Ease of application:** Nano fertilizers are simpler to apply and often needing in smaller quantities.

c) **From environmental perspective:**

1. **Reduced pollution:** Nano-fertilizers release nutrients slowly and in a targeted manner, preventing excessive application. This reduces nutrient runoff into water bodies, which can cause eutrophication (excessive algae growth) and pollution. Nano fertilizers are more efficient, they reduce the need for repeated applications, minimizing the carbon footprint and the release of harmful gases associated with fertilizer use.
2. **Soil health:** Nano-fertilizers are more efficient in nutrient delivery, reducing the need for excessive fertilization, which can lead to soil degradation and contamination. This helps maintain the soil's natural balance and prevents nutrient buildup.
3. **Sustainable agriculture:** By reducing nutrient runoff, leaching, and emissions, nano fertilizers help protect water quality, soil health, and air quality, contributing to an eco-friendlier farming approach. Also, Nano-fertilizers support higher crop yields with less input, promoting agricultural sustainability by meeting food demands without overburdening the environment.

Modes of nano fertilizer application:

Nano fertilizers can be applied through various methods. They can be applied through foliar sprays, soil application and nano priming. Nano priming is just like seed treatment in which the seeds are treated with nano fertilizer solution of known concentration.

Mode of action of nano fertilizers:

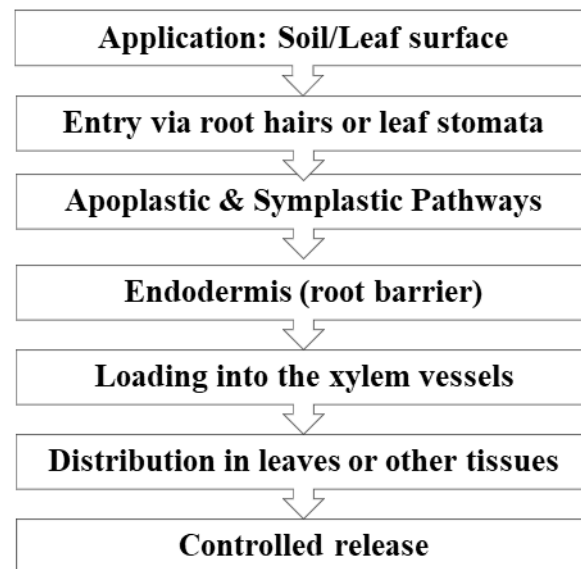


Fig.1

Nutrients are applied to the soil or leaf surface. Then they enter through the plant's root hairs (for soil nutrients) or stomata (tiny pores) in the leaves. After reaching into the plant's system the nutrients travel through the apoplastic (space outside cells) and symplastic (inside cells) pathways. In roots, the nutrients pass through the endodermis, which acts as a barrier and allows specific nutrients to pass through it. Nutrients are then loaded into xylem vessels, which are responsible for transporting water and minerals. The nutrients are then distributed to various parts of the plant, like leaves or other tissues. Finally, the nutrients are released at the target site where the plant needs them (Fig.1).

Despite from the various advantages of nano fertilizers, these do have some disadvantages which we have to take into consideration for the safe and effective use of nano fertilizers in future.

Constraints of nano fertilizers:

- a. **High production cost:** The high production cost of nano fertilizers remains one of the primary challenges hindering their widespread adoption in agriculture.

These fertilizers involve advanced manufacturing techniques such as nanoparticle synthesis, encapsulation, and surface modification, all of which require specialized equipment, skilled labour and stringent quality control processes. Additionally, the raw materials used in nano formulation are often more expensive than those in conventional fertilizers. These factors contribute to a significantly higher price point, making it difficult for many farmers, especially in developing regions, to afford or justify their use.

b. Environmental concerns: Due to their extremely small size and high reactivity, nanoparticles can interact with soil microorganisms, potentially disrupting soil ecology and nutrient cycles. There is also a risk of nanoparticle accumulation in the soil and water systems, which could lead to toxicity in non-target organisms, including beneficial insects, aquatic life and even plants themselves. Furthermore, the long-term environmental fate and behaviour of many nanomaterials are still not fully understood, raising concerns about bioaccumulation and persistence in ecosystems.

c. Health risks: Due to their nanoscale size, these particles can easily become airborne or enter the human body through inhalation, ingestion, or skin contact during handling and application. Once inside the body, nanoparticles may penetrate biological membranes and accumulate in organs, potentially causing oxidative stress, inflammation or other toxic effects. Workers involved in the production and application of nano fertilizers are particularly at risk if proper safety measures are not in place. Additionally, the potential for nanoparticle residues on food crops raises concerns about long term exposure in consumers.

CONCLUSION

The use of nano fertilizers has emerged as a promising approach in modern agriculture, offering multiple benefits that enhance crop productivity and sustainability. These fertilizers significantly increase nutrient concentration in plants by improving nutrient uptake efficiency, leading to enhanced crop yield and quality. Integrating nano fertilizers with conventional chemical fertilizers significantly reduces the overall quantity of chemical inputs required, paving the way for more sustainable agricultural practices.

Nano fertilizers contribute to better crop economics by reducing fertilizer application frequency and optimizing resource use. Nano fertilizers also have certain limitations, such as potential environmental risks, high production costs and concerns related to nanoparticle accumulation in ecosystems. Addressing these challenges through further research, regulations and sustainable application practices will be essential to ensure the safe and effective use of nano-fertilizers in the future.

Future thrust

Extensive field trials and long-term studies should be conducted to assess the real-world efficacy of nano-fertilizers in various agroclimatic regions. Research should aim to determine safe threshold concentrations and develop guidelines for their use. Besides laboratory trials, more field-based testing under natural conditions can help in deciphering possible relationship between nano-assisted fertilizers and corresponding plant responses.

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