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Nano Fertilization: Paving the Way for Sustainable Plant Nutrition

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Abstract

Nanotechnology involves manipulating materials at the nanoscale (1 to 100 nm), resulting in enhanced physical, chemical, biological, mechanical, magnetic, optical, and electrical properties. In agriculture, nanotechnology has diverse applications, including in fertilization, irrigation, pest control, packaging, and food processing. Nano fertilizers are particularly important for advancing sustainable agriculture and promoting environmental health. These fertilizers utilize nanoparticles with unique properties that improve effectiveness, leading to increased fruit productivity, enhanced yield quality, and extended shelf life. Nano fertilizers achieve these benefits by influencing various plant traits, such as morphological, physiological, and molecular characteristics. They are created by combining plant nutrients with nanomaterials, coating nutrients with nanomaterial layers, or forming nano-sized emulsions. Additionally, nano biofertilizers, which combine both natural and synthetic elements, enhance nutrient bioavailability and soil fertility, making them more efficient than traditional fertilizers. By improving sustainability in global food production, nano fertilizers represent a promising solution for addressing agricultural challenges. This review aims to explore the role of nano fertilizers in agricultural production, discussing their advantages over conventional fertilizers and distinguishing between different types of nano fertilizers.

Keywords: Fertilizers of the Future, Nanotechnology, Nano Plant Nutrition, Sustainable Agriculture.

1. Introduction

The growing global population has led to a significant increase in food demand, which, in turn, has resulted in an expanded use of fertilizers. However, the limited availability of resources and the low productivity associated with conventional fertilizer applications have caused rising costs for farmers. In this context, nanotechnology presents a promising opportunity to develop fertilizers with specific chemical compositions that enhance nutrient efficiency, reduce environmental impact, and stimulate plant growth. The controlled release and targeted delivery of nanoscale ingredients allow for more precise and sustainable agricultural practices (Nisar et al., 2019).

In recent decades, both chemical and organic fertilizers have been developed to meet the demands for affordable and safe food. Alongside these conventional approaches, alternative technologies such as genetically modified plant varieties and nano fertilizers (NFs) have emerged as safer and more efficient solutions (Silva et al., 2018). While conventional mineral fertilizers are commonly used to improve soil fertility in agriculture, their efficiency in nutrient utilization is often suboptimal, particularly due to poor agricultural practices and the adverse effects of climate change. This inefficiency frequently results in nutrient leaching, which depletes soil fertility (Stojanova, 2018; Yadav et al., 2023).

Sustainable agriculture is pivotal in addressing global challenges such as food security, soil degradation, and climate change. Current agricultural practices face significant obstacles, including deteriorating soil health, inefficient nutrient delivery, and environmental pollution stemming from the overuse of traditional fertilizers. The development of nano fertilizers, through nanotechnology, holds considerable potential to improve nutrient use efficiency (NUE) and combat nutrient deficiencies in crops (Shebl et al., 2019). Nano fertilizers, which contain essential minerals and nutrients such as nitrogen (N), phosphorus (P), potassium (K), iron (Fe), and manganese (Mn), either individually or in combination with nanoscale adsorbents, are particularly effective in addressing these challenges.

This review examines the role of nanotechnology in advancing smart and efficient agricultural practices through the application of nano fertilizers, which enhance nutrient uptake efficiency and optimize nutritional management (Nongbet et al., 2022). In addition to improving nutrient efficiency, nano fertilizers contribute to environmental sustainability by reducing nutrient runoff and leaching, thus minimizing pollution. By increasing fertilizer use efficiency, these fertilizers promote higher crop yields while reducing fertilizer costs, particularly in regions where traditional fertilizers are either inefficient or ineffective. Nano fertilizers offer a more cost-effective and environmentally friendly alternative to conventional fertilizers, presenting a promising solution to meet the growing global food demand while simultaneously enhancing agricultural sustainability (Yadav et al., 2023).

Nano fertilizers have emerged as an effective solution with enhanced efficiency and reduced environmental impact. They can be categorized based on their function, nutrient composition, and consistency. These categories include controlled-release nano fertilizers, nano fertilizers for targeted delivery, plant growth-stimulating nano fertilizers, fertilizers designed to control water and nutrient loss, as well as inorganic and organic nano fertilizers. Additional classifications include hybrid nano fertilizers, nutrient-loaded nano fertilizers, and consistency-based fertilizers such as surface-coated, synthetic polymer-coated, biological product-coated, and nanocarrier-based nano fertilizers.

The increasing global population and the subsequent rise in food demand underscore the need for sustainable agricultural practices. Nutrient-based nano fertilizers represent a key innovation that addresses this challenge by improving nutrient availability, uptake, and utilization in plants (Mikula et al., 2020).

This review aims to emphasize the importance of conventional fertilizers, while highlighting the role of nano fertilizers in agricultural production, and distinguishing between the various types of nano fertilizers.

2. Importance of Fertilizer Application in Agricultural Production

Agricultural production, encompassing viticulture, fruit growing, gardening, floriculture, and farming, is a critical activity and a cornerstone of the global economy, as it provides food for the population. In modern agriculture, achieving high and consistent yields, along with crop quality, depends on factors such as the biological characteristics of plant varieties, favorable climatic and soil conditions, and controlled, precise plant nutrition. Fertilizers, whether mineral or organic, play an essential role in enhancing the physical, chemical, biological, and microbiological properties of the soil. They supply crucial nutrients that influence various physiological and biochemical processes, such as metabolism, oxidation-reduction reactions, photosynthesis, and respiration, which, in turn, impact the overall growth and development of vegetative and generative plant organs. These processes contribute to higher yields and improved fruit quality (Stojanova, 2022).

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Fertilization helps replenish natural nutrient sources in the soil, compensating for nutrients lost during harvests and improving unfavorable soil properties. It also enhances the soil's water and air regimes and stimulates microbiological activity. Proper fertilization is vital for achieving high and stable yields across agricultural crops, ensuring good product quality and profitability (Stojanova, 2018). The aim of plant nutrition is to supply an optimal amount of nutrients throughout the growing season. Each crop has specific nutrient requirements, which vary based on factors like type, variety, cultivation system, expected yields, soil conditions, and environmental influences. Over time, soil can become nutrient-depleted, necessitating careful replenishment and management (Stojanova, 2023).

To produce food, humans transform a significant portion of the natural biosphere into agroecosystems by adapting ecosystems for intensive agricultural production. This transformation offers both opportunities and responsibilities to maintain balance within these agroecosystems, achievable through various agrotechnical practices. The need to maintain this balance emphasizes the complexity of human involvement, evident not only in daily operational decisions on agricultural lands but also in global strategies and changes.

Fertilizers play a crucial role in enhancing crop productivity. However, typically only about half of the chemical fertilizers applied are utilized by plants, with the remaining minerals potentially seeping into the soil, causing air pollution when trapped. Despite their benefits, overreliance on chemical fertilizers is not a sustainable long-term solution for increasing crop yields, as it can deplete soil fertility and disrupt the natural balance of soil minerals (Khuram et al., 2013).

The significance of fertilization in agricultural production is acknowledged at various levels, including legislation, where distinctions between conventional, integrated, and organic farming often focus on fertilizer application and crop protection methods. To fully realize the potential of fertilization, it is essential to consider the broader impacts of fertilizer use on agriculture and the agroecosystem.

The environmental impact of agriculture is a key factor in ensuring food production sustainability and environmental protection. One of the most pressing environmental concerns related to fertilizer application is the overuse of nitrogen and phosphorus. This issue is exacerbated when fertilizers are applied at inappropriate times (e.g., during unsuitable plant growth stages) or when incorrect forms of nutrients are used (e.g., applying nitrate nitrogen in autumn). Furthermore, improper fertilizer application methods, such as spreading manure on the surface without incorporating it into the soil, further contribute to environmental burdens.

The consequences of improper fertilization practices, such as applying fertilizers during inappropriate periods (e.g., late autumn or winter), can lead to nutrient availability exceeding crops' seasonal needs. This results in nutrient losses, such as nitrate leaching, direct runoff of soluble nutrients, and nitrogen volatilization. Fertilization plays a more crucial role in soil fertility than other agricultural practices, such as cultivation, pest management, or crop selection. It has the greatest impact on increasing crop yields, often boosting production by around 50%. Proper fertilization not only improves crop yields but also helps maintain and enhance the soil's natural fertility, maximizing the return on labor and resources invested in agricultural production. However, fertilization must be tailored to meet the specific needs, age, and condition of the crop. Over-application of fertilizers can lead to environmental pollution, particularly in groundwater, due to nutrients not absorbed by plants. Conversely, insufficient fertilizer application results in minimal effects on crop yield (Vukadinović and Vukadinović, 2011).

Effective soil fertility refers to the amount of nutrient elements in the soil available for plant uptake. This fertility is dynamic, fluctuating throughout the growing season and from year to year. Human activity plays a major role in maintaining, enhancing, or depleting effective fertility, depending on soil management practices (Stojanova, 2018). Temporal fluctuations in soil properties, influenced by factors such as precipitation and temperature, can significantly alter nutritional conditions for crops during the growing season. This variability makes fertilization a complex and demanding task, with achieving high agronomic and/or physiological fertilization efficiency often uncertain and problematic (Vukadinović and Vukadinović, 2011).

Agronomic efficiency = Pg – Pn / G

Physiological efficiency = Pg – Pn / Euf – Eun

where:

Pg = yield kg·ha^{-1} achieved on a fertilized plot;

Pn = yield achieved on an unfertilized plot;

G = active substance (a nutrient in fertilizer) in kg·ha^{-1};

Euf = nutrient uptake in kg·ha^{-1} on a fertilized plot;

Eun = Nutrient uptake on an unfertilized plot in kg·ha^{-1}.

A significant anthropogenic alteration in the agrosphere is the intensification of nutrient cycling dynamics, achieved through the use of mineral, organic, and green manures. Among these, the nitrogen cycle plays a particularly critical role, as the natural nitrogen cycle alone is insufficient to support high crop yields. The necessity for intensified nutrient cycling arises not from a shortage of total nutrient elements such as nitrogen, phosphorus, and potassium in the soil, but from the mismatch between the dynamics of available nutrients and the crop's nutrient requirements throughout the growing season (Stojanova, 2018).

Increasing nutrient availability will not indefinitely boost yields, as there is a threshold beyond which further nutrient availability will no longer positively affect crop growth. This renders additional fertilization ineffective in increasing yields. Furthermore, increasing fertilization before reaching the maximum yield potential may no longer be economically viable. The costs associated with raising fertilizer doses, such as the unit price of fertilizer, labor for mechanization, and human labor for application, can exceed the additional income generated by the increased yield (Stojanova et al., 2024).

Thus, the economically optimal fertilization rate is likely to be lower than the biological optimum that would yield the highest output. Proper fertilization of soils with insufficient or low nutrient availability boosts nutrient availability, enhances yield, and improves the economic profitability of production, further emphasizing the need for fertilization.

Increasing nutrient availability reduces the need for additional fertilization, as further investment in fertilizers becomes unprofitable beyond a certain point. These examples, illustrating how fertilization impacts agricultural systems with their interconnectedness and dependencies, highlight the complexity and importance of fertilization tasks (Stojanova, 2018).

Traditional soil fertilization strategies and technologies often fail to be fully effective due to nutrient immobilization in the soil and significant nutrient losses through leaching or evaporation. As a result, there is considerable interest in the rapid advancement of bionanotechnology, which offers promising solutions to address these challenges. However, it is important to recognize that numerous unresolved issues persist in the development and application of bionanotechnology. These issues range from the physicochemical properties and formulations of nanoparticles, especially for foliar applications, to the lack of regulation and control over nutrient uptake and integration of nutrients into plant biomass (Vukadinović and Vukadinović, 2011).

Foliar nutrition, involving the direct application of nutrients to plant leaves, is a commonly used supplementary agrotechnical practice. It offers an attractive alternative to overcoming unfavorable soil processes. The nutrients applied through foliar feeding can penetrate the leaves and reach the chloroplasts, where photosynthesis occurs, more quickly. However, nutrient transfer is often hindered by the barrier created by the leaf surface, along with limitations in nutrient transfer and mobility, whether using standard foliar sprays or nanoparticles (Stojanova, 2018).

These innovations enhance the agronomic efficiency of fertilizers compared to conventional mineral fertilizers, reduce the quantity of active substances required, provide nutrients over extended periods, particularly when plants need them most, and help avoid or significantly reduce water and air pollution. Nanoparticles used in fertilizers can originate from various sources, often utilizing cheaper natural minerals like nanoclays (aluminum silicates in multilayer particles of around 10 nm in size), by-products from mechanical or industrial processes such as combustion and evaporation, and other materials. For instance, hydroxyapatite minerals ($Ca_{10}(PO_4)_6(OH)_2$), with their high surface area to volume ratio, can bind large amounts of nutritional elements and other substances while also being biocompatible. Nanohybrids of hydroxyapatite and urea (nano-encapsulated fertilizers) serve as excellent "slow-release nitrogen sources." Similarly, thermoplastic starch/urea combinations also release urea slowly, reducing ammonia (NH_3) evaporation compared to pure urea (Vukadinović and Bertić, 2013).

Prolonged soil fertilization has resulted in a significant decline in crop yields due to nutrient imbalances and organic matter deficiencies. Excessive use of phosphorus and nitrogen fertilizers has contributed to issues such as nutrient leaching and eutrophication, problems which have been widely reported (Wangdi, 2019).

3. Nanotechnology in Agriculture

Nanotechnology is the process of designing, characterizing, producing, and applying structures, devices, and systems at the nanoscale, offering a revolutionary approach to agriculture, including livestock and aquaculture. This technology provides numerous advantages, particularly in areas such as controlled nutrient release, improved pest monitoring efficiency, and reduced chemical leakage (Iavicoli et al., 2017). The integration of nanomaterials into agriculture has led to the development of innovations like nano fertilizers, nano herbicides, nano pesticides, nanosensors, and nano tracers. These innovations often involve various types of nanoparticles, including silica, carbon, iron, zinc, titanium, silver, gold, and magnesium, each contributing unique properties to agricultural practices (Fernández-Luqueño et al., 2014).

Nanoscience and nanotechnology represent an emerging frontier for researchers, offering novel solutions to agricultural challenges and enabling enhanced productivity. By manipulating particles at the nanoscale, nanotechnology has the potential to create innovative materials and devices with unique properties, drawing on fields such as applied colloidal science, physics, and supramolecular chemistry (Nandhakumar et al., 2023).

In agriculture, nanotechnology provides a novel method for creating slow-release fertilizers, allowing for the controlled release of nutrients into the soil. This approach ensures a consistent and timely nutrient supply to plants over an extended period, improving agronomic efficiency by reducing the quantity of fertilizer required. In doing so, it helps minimize pollution and prevent water eutrophication. Nano fertilizers can encapsulate nutrients in various nanoporous materials, coat them with thin protective films that may include microelements, or deliver them as emulsions. Additionally, carbon nanotubes can penetrate seeds, enhancing germination and accelerating the growth of seedlings and young plants, further improving agricultural productivity and sustainability (Vukadinović and Vukadinović, 2011).

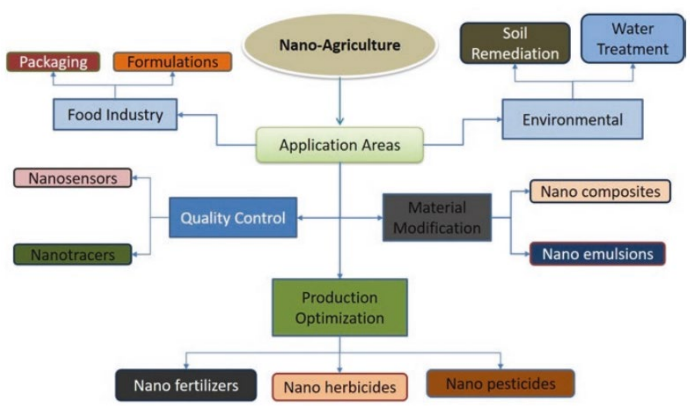

Figure 1. Nanotechnology developments in agricultural fields (Silva et al., 2018).

Crop improvement in agriculture is an ongoing process, with a significant focus on enhancing fertilizer efficiency through the use of nanoclays and zeolites, as well as restoring soil fertility by releasing fixed nutrients (Figure 1). Nanotechnology holds vast potential in addressing a range of agricultural challenges. Key applications include controlling nutrient release and availability, characterizing soil minerals, studying the weathering of minerals, exploring the soil rhizosphere, and understanding nutrient ion transport within the soil-plant system. Moreover, nanotechnology can be applied to address issues such as dust and aerosol emissions from agricultural soils, implementing soil and water conservation strategies, improving water treatment and management, remediating soil and water pollution, and utilizing precision farming techniques (Jyothi and Hebsur, 2017).

The term "nano," derived from the Greek word for "dwarf," refers to particles typically smaller than 100 nm in at least one dimension. Nanoparticles possess distinct physicochemical properties, including a high surface-to-volume ratio, crystallinity, and increased reactivity, which differentiate them from bulk materials (Kah et al., 2013). These properties allow nanoparticles to interact more effectively with plant roots and soil microorganisms, thereby enhancing nutrient uptake and improving plant metabolism.

Nanotechnology is an important scientific discipline that manipulates materials at the molecular level to alter their physical and chemical properties. In contrast, biotechnology leverages biological knowledge and techniques to manipulate molecular, genetic, and cellular processes, leading to innovations across fields such as medicine and agriculture. Nanotechnology, which focuses on manipulating matter at the nanoscale (one billionth of a meter), plays a crucial role in agriculture by not only boosting production but also ensuring food safety for consumption (Wangdi, 2019).

The use of nano fertilizers in agriculture contributes to sustainability and helps increase global food production. As the pressure to meet the nutritional needs of a growing global population intensifies, enhancing soil fertility through the addition of nutrients becomes increasingly essential to address the challenge of low soil fertility (Khatri and Bhateria, 2022).

4. Nano Fertilizers in Smart Nutrition

Nano fertilizers are specialized fertilizers enhanced through chemical, physical, or biological methods using nanotechnology. These modifications improve their characteristics and composition, ultimately boosting crop productivity. Nano fertilizers provide several advantages over conventional fertilizers, especially regarding quality parameters in farming (Silva et al., 2018).

The effectiveness of nanoparticles is influenced by factors such as their particle size and surface structure. Soil properties, including organic matter content, texture, and pH, also impact their efficacy. Nano fertilizers can be absorbed by plants through roots or leaves, and these absorption mechanisms play a crucial role in determining their bioavailability (Khatri and Bhateria, 2022).

Nanotechnology is emerging as a promising alternative in the form of nano fertilizers, which enhance crop quality. Nano fertilizers consist of nutrient nanoformulations that provide sustained and uniform absorption by plants. They improve nutrient utilization, reduce soil toxicity, and minimize the negative effects associated with excessive chemical fertilizer use and frequent applications. Furthermore, nano fertilizers significantly reduce waste, saving money and protecting the environment (Nandhakumar et al., 2023).

Nano fertilizers play a vital role in improving the production of various crops. The nutrient use efficiency of conventional fertilizers is generally low – around 30-35% for nitrogen (N), 18-20% for phosphorus (P), and 35-40% for potassium (K) – and has remained relatively stable over the years. In contrast, nano fertilizers are designed to release nutrients gradually over more than 30 days, improving nutrient efficiency without negative effects. By providing nutrients steadily over time, nano fertilizers reduce nutrient loss, contributing to environmental safety (Subramanian et al., 2015).

Nano fertilizers represent an innovative approach to improving plant growth and crop yields while addressing some of the environmental challenges posed by conventional fertilizers. As you mentioned, modern synthetic fertilizers, which typically contain essential nutrients like nitrogen, phosphorus, and potassium, play a crucial role in increasing agricultural productivity. However, their excessive or improper use can lead to environmental concerns such as nutrient runoff, water pollution, and soil degradation (Nisar et al., 2019).

Nano fertilizers work by providing controlled and efficient nutrient release. They can deliver nutrients directly to plants through various mechanisms, including root absorption or foliar uptake. This precise delivery reduces nutrient loss and ensures that the plants receive nutrients at the optimal time. These fertilizers are made up of various types of nanomaterials, such as nano-porous materials, nano-emulsions, and nanoparticles. These materials can encapsulate essential nutrients, enhancing the efficiency of their use in agriculture. The use of polymer coatings, clay-based encapsulation, and biopolymer matrices helps regulate the release of nutrients, making them available over an extended period (Prasad et al., 2014).

By encapsulating nutrients, nano fertilizers prevent rapid nutrient leaching and volatilization, ensuring that nutrients are available to plants for longer periods. This not only improves nutrient uptake efficiency but also reduces the frequency of fertilizer applications, minimizing environmental impact. Since nano fertilizers ensure slow and controlled release, they significantly reduce nutrient loss and pollution. The reduced environmental footprint of nano fertilizers makes them a sustainable alternative to conventional fertilizers, which are often linked to problems like eutrophication and water contamination (Saurabh et al., 2024).

The type of nano fertilizer selected depends on several factors, such as the specific crop being cultivated, the soil's nutrient requirements, and the surrounding environmental conditions. By tailoring nano fertilizers to specific needs, they can be more effective than conventional fertilizers. In conclusion, nano fertilizers hold significant promise for improving agricultural productivity while minimizing environmental impact. Their ability to release nutrients in a controlled and efficient manner makes them a sustainable alternative, especially as the world faces increasing challenges related to food security and environmental conservation (Khatri and Bhateria, 2022).

According to Yield et al. (2018), nano fertilizers can be classified into the following groups:

1. Nutrient-based Nano Fertilizers

Inorganic nano fertilizers are made up of metals, metalloids, and non-metallic nanoparticles (NPs), which supply essential nutrients such as nitrogen, phosphorus, and potassium to plants. These fertilizers are designed to improve the efficiency with which plants absorb nutrients, thereby boosting agricultural yields. The formulation of inorganic nano fertilizers is intended to enhance nutrient uptake, ensuring that plants receive the necessary elements for optimal growth and productivity (Krishnani et al., 2022).

1.1. Inorganic nano fertilizers

Inorganic nano fertilizers offer a distinct advantage by being customizable to meet the specific nutrient requirements of different plants. This tailored approach allows for targeted applications, which can significantly enhance crop yields. At present, inorganic nano fertilizers are already being used in agricultural practices, and their adoption is anticipated to increase as more farmers adopt precision agriculture techniques. This shift is driven by the desire for more efficient, sustainable farming methods that optimize nutrient delivery and minimize waste.

1.1.1. Macronutrients nano fertilizers

Macronutrient nano fertilizers offer significant benefits for plant growth and environmental sustainability. Nitrogen-based nano fertilizers, for example, improve nitrogen utilization efficiency, helping to reduce eutrophication and greenhouse gas emissions. Phosphorus nano fertilizers enhance nutrient absorption in plants and have shown promising results in soil reclamation (Basavegowda and Baek, 2021). Potassium-based nano fertilizers have higher absorption rates and are more resistant to leaching, which improves soil physical properties. Calcium-based nano fertilizers are associated with higher crop yields, better fruit and vegetable quality, and increased resistance to diseases (Shilpa et al., 2022). Magnesium-based nano fertilizers support crop growth, enhance quality, and improve resistance to diseases and pests, making them beneficial for various crop types. Lastly, sulfur-based nano fertilizers offer slow-release options for a sustained nutrient supply, reducing the risk of soil acidification.

According to Yadav et al. (2023) and Kah et al. (2018), macronutrient nano fertilizers are based on nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur.

1.1.2. Micronutrient nano fertilizers

Micronutrient nano fertilizers are innovative agricultural products that use nanoparticles (NPs) to deliver essential micronutrients to plants more efficiently than conventional fertilizers. These micronutrients, such as boron, copper, iron, nickel, zinc, and titanium, are required in small amounts but are vital for plant growth, development, and overall health. These nano fertilizers offer several advantages, including improved nutrient uptake, higher yields, and enhanced resistance to both biotic and abiotic stresses, as highlighted by Yadav et al. (2023) and Kah et al. (2018). Furthermore, macronutrient nano fertilizers may also include formulations based on elements like iron, zinc, copper, boron, nickel, and titanium.

1.2. Organic nano fertilizers

Organic nano fertilizers are created from nanoparticles (NPs) derived from organic materials, designed to gradually release nutrients into the soil. These environmentally friendly fertilizers are sourced from natural materials and can help retain soil moisture and regulate pH levels, which in turn allows plants to absorb essential nutrients more efficiently. Organic nanoparticles are formulated in various forms, including capsules, polymer conjugates, vesicles, micelles, liposomes, polymersomes, dendrimers, and polymeric nanoparticles.

Organic nano fertilizers promote plant growth by enabling a slow and controlled nutrient release. This delayed release leads to better nutrient absorption and utilization, resulting in improved plant development and higher yields. Additionally, using organic nano fertilizers can enhance soil structure by improving aggregation and porosity, which aids in water infiltration, aeration, and root penetration. The presence of organic matter also supports the growth and activity of soil microorganisms (Fatima et al., 2021).

1.3. Hybrid nano fertilizers

Nanotechnology-based fertilizers, which contain nanoparticles (NPs) with specific nutrients, have been designed to improve the efficiency of traditional fertilizers. By coating the nanoparticles with a protective layer, the release of nutrients can be controlled, making them more accessible to plants. Hybrid nano fertilizers combine conventional fertilizers with nanotechnology-based formulations, enabling a slow and sustained release of nutrients, thus enhancing nutrient availability. These nano fertilizers not only improve fertilizer efficiency but also minimize the environmental impact associated with the production and use of fertilizers (Kah et al., 2013).

1.4. Nutrients-loaded nanomaterials

Nano-porous zeolites are nutrient-loaded nano fertilizers that effectively provide essential nutrients to crops. These minerals are created through a reaction between volcanic ash and alkaline lake water, forming a honeycomb-like structure with high porosity. This porosity allows zeolites to absorb and retain moisture, nutrients, and other compounds, making them an excellent option for soil amendment and fertilization.

To produce a tailored nano fertilizer for different crop needs, natural zeolite is ground into a powder and combined with nitrogen, phosphorus, and potassium. This process enhances the surface area of the zeolite particles, improving the soil's ability to absorb and retain nutrients.

Engineered nano-porous zeolites, or aluminosilicates, are distinguished by micro-pores (2 nm), meso-pores (2–50 nm), and macropores (>50 nm). These pores boost their ability to act as fertilizer carriers, enhancing ion exchange and adsorption capabilities. As a result, nano-porous zeolite fertilizers improve soil fertility, making it more conducive to crop growth (Yadav et al., 2018).

Zeolites' high porosity allows for rapid and efficient cation exchange and the binding of heavy metal cations, preventing their migration into the plant root system. This function aids in passive soil decontamination and helps preserve soil moisture, creating better conditions for plant growth. Additionally, zeolites increase the soil's ability to retain nutrients (Stojanova et al., 2024a).

2. Consistency-based Nano Fertilizers

Affordable nano fertilizers encompass surface-coated nano fertilizers, synthetic polymer-coated fertilizers, and biological product-coated nanobiofertilizers. These fertilizers aim to boost nutrient efficiency and reduce costs. Surface-coated nano fertilizers have a protective layer that regulates the release of nutrients. Synthetic polymer-coated fertilizers utilize polymers to extend the nutrient release process. On the other hand, biological product-coated nanobiofertilizers are created by applying organic compounds or microorganisms to the nanoparticles, enhancing their ability to nourish plants and improve soil quality.

3. Nanocarrier-based Nano fertilizers

4. Based on Composition

This group consists of: nanostructured metal-based fertilizers, nanostructured polymer-based fertilizers, nano-biofertilizers, nanocoated/nanoencapsulated fertilizers, nanocomposite fertilizers, nanochelates, and bio-based nano fertilizers (Saubarh et al., 2024).

5. Based on Release Mechanism

This group consists of: Controlled-release nano fertilizers, Slow-release nano fertilizers, and responsive nano fertilizers (Saubarh et al., 2024).

5. Effect of Nano Fertilizers Enhance Soil Fertility and Crop Yield

Mineral fertilizers are commonly used to enhance soil productivity by replenishing nutrients lost through harvests, evaporation, or atmospheric loss. However, while they offer benefits, their misuse can lead to negative consequences. Mineral fertilizers can harm the environment and human health, causing issues such as water pollution from nitrates, eutrophication of surface waters due to excessive phosphorus, and the emission of harmful gases into the atmosphere (Stojanova, 2018).

On the other hand, nano fertilizers are designed to release nutrients gradually, improving nutrient use efficiency while minimizing environmental damage. These fertilizers release nutrients slowly over time, which reduces nutrient loss and ensures environmental safety. Unlike traditional fertilizers, which can be costly and pose risks to both human health and the environment, nano fertilizers contribute to maintaining soil fertility and boosting crop yields (Congreves et al., 2015).

Nano fertilizers provide numerous benefits that improve nutrient efficiency in crops. Due to their smaller particle size, these fertilizers can penetrate plant tissues more effectively than traditional fertilizers, as their particles are smaller than the pore size of roots and leaves. This results in better nutrient uptake and enhanced nutrient use. Additionally, nano fertilizers help minimize nutrient loss, making them a more sustainable choice. Their slow-release nature reduces the need for frequent applications and prevents nutrient wastage from leaching or runoff. These fertilizers also improve soil quality by increasing its water-holding capacity and boosting microbial activity (Nandhakumar et al., 2023).

Nano fertilizers support plant growth through both direct and foliar application methods, improving nutrient use efficiency, which benefits nutrient management practices. These fertilizers are often bound to nano-absorbents and can be applied alone or combined with other substances. This slow-release feature helps reduce nutrient leaching into groundwater and enhances nutrient use efficiency overall. In the face of increasing pressure to adopt alternatives to chemical fertilizers, nano fertilizers play a key role in improving food security in both the agriculture and horticulture sectors (Liu and Lal, 2015).

One notable benefit of nano fertilizers is the precise release of nitrogen, which can be timed to match crop demands. Studies by researchers like DeRosa et al. (2010) have shown that nano fertilizers enhance crop efficiency compared to conventional composts. Additionally, innovative strategies are being developed to improve nano fertilizers' responsiveness to environmental conditions, such as changes in pH, temperature, moisture, and humidity (Silva et al., 2018).

The use of nano fertilizers also positively affects seed germination and plant growth. These fertilizers can easily penetrate the soil and roots, leading to increased nutrient release, better chlorophyll formation, and enhanced dry matter production, all of which contribute to stronger plant growth (Suriyaprabha et al., 2012).

6. Advantages of Nano fertilizers over Conventional Chemical Fertilizers

Nano fertilizers offer several advantages over traditional fertilizers, primarily due to their more efficient delivery of nutrients directly to plants. This enhanced efficiency not only reduces the amount of fertilizer required but also lowers the environmental impact associated with their use. By maximizing crop yields while minimizing the environmental footprint of fertilization, nano fertilizers present a significant advancement in agricultural practices.

Unlike conventional fertilizers, nano fertilizers are non-toxic and present a lower risk to both human health and the environment. In addition to improving soil fertility, nano fertilizers contribute to increased crop yield and quality, reduce costs, and help optimize profits (Carmona et al., 2021). Slow-release nano fertilizers further enhance these benefits by providing a consistent and gradual supply of nutrients over an extended period, thereby improving plant growth and increasing yields.

Both mineral and organic fertilizers play significant roles in agrotechnology and plant nutrition. Mineral fertilizers are typically applied in larger quantities compared to organic fertilizers. They dissolve quickly in water, producing rapid effects in the soil. These fertilizers are rich in both macro and microelements, and their granular or liquid forms allow for adaptability to the needs of various agricultural crops and growth stages. In contrast, organic fertilizers, derived from plant and animal sources, decompose more slowly in the soil, releasing nutrients over a longer period. While mineral fertilizers focus primarily on providing immediate nutrients, organic fertilizers also improve soil structure, offering long-term benefits (Stojanova, 2023).

Biofertilizers represent a promising alternative to synthetic fertilizers. These fertilizers not only enhance soil quality but also provide essential nutrients for plant fertility and productivity. Biofertilizers are cost-effective, renewable, and environmentally friendly. Key microorganisms involved in nitrogen fixation, such as *Azotobacter*, *Anabaena*, and *Rhizobium*, along with phosphate-solubilizing bacteria like *Pseudomonas* spp., facilitate nutrient uptake in plants. Additionally, these microorganisms produce bioactive compounds, organic acids, vitamins, growth hormones, and antagonistic substances that help protect plants from diseases (Nongbet et al., 2022).

Table 1. Advantages and disadvantages of nano fertilizers over conventional fertilizers (Yadav et al., 2023).

Property	**Nano fertilizer**	**Conventional fertilizers**
Nutrient uptake efficiency	Increases fertilizer utilization efficiency and the ratio of plant nutrient uptake while saving fertilizers.	Less effective since its bulk composites are poorly absorbed by plants.
Control release modes	Encapsulation, in conjunction with a covering of polymer resin, waxes, and sulfur, permits precise control over the release of nutrients.	Excessive release results in toxicity and undermines ecological balance.
Solubility and dispersion of nutrients	Increases the solubility and dispersion of insoluble mineral components in soil, making them more bioavailable to plants.	Less available to plants due to lower solubility and larger particle size.
Effective duration of release	Improves and prolongs the plant's nutrient acquisition rate	During delivery, nutrients required by plants are lost as insoluble salts.

A low rate of fertilizer needed	Reduces nutrient losses resulting from leaching, runoff, and drift.	High fertilizer levels are lost due to leaching, runoff, and drift.

Among the various benefits of using nano fertilizers, the most notable are discussed by Silva et al. (2018).

- Higher product quality with minimum remnants;
- Eco-friendly synthesis;
- Custom-made products;
- Lower-cost production, reducing the amount of fertilizers used;
- Less negative impacts and toxicity;
- Controlled release of plant nutrients.

The application of nanomaterials has the potential to transform agricultural practices, with numerous uses in areas such as soil remediation, pest control, reducing chemical usage, nutrient delivery, water treatment, desalination, and disinfection, among others (Nuruzzaman et al., 2016).

7. Conclusion

The use of nano fertilizers in agriculture presents a transformative opportunity with the potential to revolutionize farming practices and significantly enhance global food security. Their role in improving both the quantity and quality of crop yields is crucial, with nano fertilizers offering substantial advantages over traditional fertilizers. One of the most notable benefits is their ability to enhance nutrient transport within plants. Nano fertilizers facilitate more efficient nutrient uptake, which results in improved plant growth and higher yields. This efficiency is particularly important as global food demands continue to rise due to the increasing population. In addition, nano fertilizers have the ability to deliver nutrients more precisely to plants, ensuring that crops receive the right nutrients at the right time, which can substantially increase agricultural productivity.

Beyond boosting crop yields, nano fertilizers also contribute to maintaining an ecologically clean environment, which is a key distinction from conventional fertilizers. Traditional fertilizers, while effective, often contribute to environmental pollution through nutrient runoff and leaching, which can lead to water contamination and eutrophication. In contrast, nano fertilizers are designed for controlled nutrient release and targeted delivery, which minimizes nutrient loss and reduces the environmental impact of fertilizer use. This makes them a more sustainable option for modern agriculture, helping to protect ecosystems while still meeting the nutritional needs of crops.

Furthermore, nano fertilizers offer numerous advantages for sustainable agriculture, such as promoting soil health and reducing the need for excessive water usage. As water scarcity becomes a pressing global concern, the ability of nano fertilizers to reduce nutrient runoff and retain water in the soil becomes increasingly valuable. This can lead to more efficient water usage and enhanced soil fertility over time.

To fully harness the potential of nano fertilizers, however, continued research is essential. Addressing potential risks and concerns related to their application, such as the potential for nanoparticles to affect soil health or accumulate in the food chain, will be critical to their long-term success. A collaborative approach that brings together researchers, agricultural experts, policymakers, and farmers will be key in ensuring that nano fertilizers are developed and applied in a safe and effective manner. Educating farmers about the benefits and proper use of nano fertilizers will also play a pivotal role in promoting their widespread adoption and maximizing their impact.

Ongoing monitoring and assessment of the effects of nano fertilizers on plant growth, crop yields, soil health, and the broader environment will be essential. This will help ensure that any potential risks are identified and mitigated while also optimizing the benefits. By carefully evaluating and adapting to new findings, nano fertilizers can be integrated into agricultural systems in a way that maximizes their positive impact while minimizing adverse effects. Ultimately, the continued development and thoughtful application of nano fertilizers will be a key driver in advancing agricultural sustainability, increasing food production, and ensuring global food security in the face of environmental challenges and a growing global population.

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