

## Nano-Fertilizers for Sustainable Agriculture: Advances and Future Trajectories

### Abstract

The rapid evolution of nano-fertilizers marks a paradigm shift in sustainable agriculture, offering innovative solutions to enhance nutrient use efficiency, crop productivity, and environmental stewardship. Unlike conventional fertilizers, nano-fertilizers are made with very tiny particles and are designed to release nutrients slowly and exactly when plants need them. This means plants get more of the nutrients, and less is wasted. Recent types of nano-fertilizers, like nano-NPK and nano-micronutrients, have shown that they help plants absorb nutrients better, grow stronger roots, and handle stress better. This has led to bigger harvests for important crops like wheat, maize, potatoes, and rice. Nano-fertilizers also help reduce pollution, use resources more efficiently, and improve soil health and helpful bacteria in the soil. These benefits are complemented by reduced environmental pollution, optimized resource utilization, and positive impacts on soil health and microbial activity. Nano-fertilizers thus directly support several United Nations Sustainable Development Goals (SDGs), including zero hunger, climate action, and responsible consumption and production. This review looks at the latest progress in nano-fertilizers, what might happen in the future, and how they fit with global sustainability goals. It also points out that while nano-fertilizers have great potential, we need good rules and research from many fields to use them safely and effectively.

**Key words:** Nano-fertilizers, Sustainable agriculture, Nutrient efficiency, Environmental impact, Sustainable Development Goals (SDGs)

### 1. Introduction

Nano-fertilizers represent a significant breakthrough in agricultural technology, leveraging nanotechnology to improve nutrient delivery, uptake efficiency, and environmental sustainability in crop production (Shang et al., 2019; Liu & Lal, 2015). By encapsulating essential nutrients within nanomaterials, these advanced fertilizers enable controlled and targeted nutrient release directly to plant roots, markedly reducing nutrient losses from leaching, volatilization, and runoff compared to conventional fertilizers (DeRosa et al., 2010; Kalia & Sharma, 2020). This precision not only enhances crop nutrient use efficiency but also helps mitigate environmental issues such as waterway eutrophication and soil contamination commonly associated with traditional fertilization practices (Sekhon, 2014). However, despite these promising advantages, the widespread adoption of nano-fertilizers in mainstream agriculture is challenged by concerns regarding scalability, long-term safety, and the need for comprehensive regulatory frameworks (Selvarani et al., 2025). Using nano-fertilizers supports several United Nations Sustainable Development Goals, especially Zero Hunger (SDG 2), Good health and Well-being (SDG 3), Clean Water and Sanitation (SDG 6), Responsible consumption and Production (SDG 12), Climate Action (SDG 13), and Life on Land (SDG 15). Nano-fertilizers help plants use nutrients more efficiently and increase crop yields, which improves food security and reduces harm to the environment (Parisi et al., 2015; Prasad et al., 2017). Because they can be applied in smaller amounts and deliver nutrients directly to

plant roots, nano-fertilizers also help lower greenhouse gas emissions and keep soil healthy, making farming more sustainable and better for the climate (Lal, 2021).

Even though nano-fertilizers have great potential, using them widely in farming still faces some problems. These include making them on a large scale, making sure they are safe to use for a long time and creating clear rules for their use (Kah et al., 2018). There are also worries about whether the tiny particles in nano-fertilizers might be harmful, how long they stay in the environment, and how they affect the helpful microbes in the soil. More research is needed to make sure nano-fertilizers can be used safely and effectively (Fraceto et al., 2016). Still, nano-fertilizers could help increase food production while also protecting the planet. This shows why it is important to keep improving these fertilizers and to use them responsibly.

This peer review article discusses the following goals:

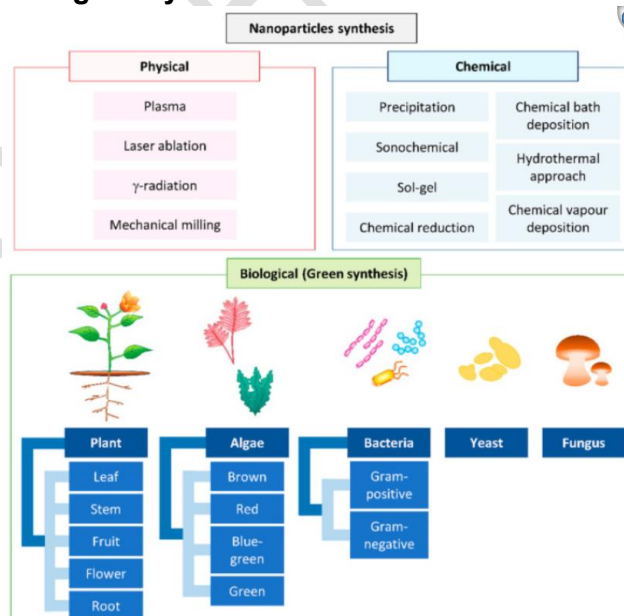
- To give an overview of nano particle synthesis and the latest progress in how nano-fertilizers are made and used in sustainable farming.
- To carefully compare how nano-fertilizers and regular fertilizers affect the use of nutrients, crop yields, and the environment.
- To point out the current challenges, such as safety, large-scale use, rules and regulations, and possible risks to health and the environment.

## 2. Current status in Nano-Fertilizers for Sustainable Agriculture

Nano-fertilizers represent a transformative innovation in sustainable agriculture, offering enhanced nutrient delivery, improved crop yields, and reduced environmental impact. Recent advances have helped scientists make many new types of tiny fertilizer particles, called nano-fertilizers. These include: including nano-NPK (nitrogen, phosphorus, potassium), nano-nitrogen, nano-phosphorus, nano-potassium, nano-iron, hydroxyapatite (HAP)-modified urea nanoparticles, nano-zeolite composites, and nano-chelated micronutrients (Eyasu *et al.*, 2025).

### 2.1. Synthesis of Nano fertilizer

Nanoparticles can be synthesised through various methods (Fig.1) but biological synthesis method ensures ecofriendly.



**Fig 1. Different approaches used for nanoparticle synthesis.** Source: Alsaari et al., 2023. ✓

**2.1.1 Green Synthesis Using Plant Extracts and Microorganisms:** Microbe-assisted synthesis (e.g., using bacteria or fungi) and plant extract-based synthesis are gaining traction for producing biocompatible and non-toxic nano-fertilizers. These methods often utilize polysaccharides, proteins, or organic acids as reducing and stabilizing agents. ✓

**Table 1. Case studies on green synthesis**

Case Study	Biological Source	Nanoparticle	Key Findings	Reference
<i>Pistacia atlantica</i>	Plant extract (leaf & fruit)	AuNPs	Antibacterial, antioxidant, non-cytotoxic	Antunes Filho et al., 2023 ✓
<i>Tectona grandis</i>	Plant extract (seeds)	AgNPs	Antimicrobial activity, cell permeability disruption	Rautela et al., 2019 ✓
<i>Musa balbisiana</i> , <i>A. indica</i> , <i>O. tenuiflorum</i>	Plant leaf extracts	AgNPs	Safe, antimicrobial, eco-friendly	Banerjee et al., 2014 ✓
<i>Diospyros lotus</i>	Plant extract (leaves)	AgNPs	Antibacterial, catalytic activity	Alsaari et al., 2023 ✓
<i>Lactobacillus plantarum</i> , <i>L. brevis</i>	Lactic acid bacteria	AgNPs	Strong against Gram-negative bacteria	Syame et al., 2020. ✓
<i>Enterobacter cloacae</i>	Bacteria	ZnO NPs	Green zinc oxide NP synthesis	Shabani et al., 2024 ✓

**2.1.2. Sol-Gel and Hybrid Nanostructures:** In-situ sol-gel synthesis is used to create hybrid materials, such as humic acid-silica hybrids, which combine organic and inorganic components for improved stability and functionality in aqueous environments. Modified sol-gel methods are used to synthesize urea-silica nanohybrids, allowing urea (a major nitrogen fertilizer) to be gradually released. Such nanohybrids have demonstrated a significantly slower, sustained release of urea compared to commercial granular urea, reducing leaching and improving nitrogen availability to plants. This technology offers potential for more efficient fertilizer application and reduced environmental impact. Living agricultural microorganisms can be encapsulated in hybrid sol-gel matrices to protect them and deliver them effectively to fields. These systems are used in biotechnology and agriculture for improved biofertilizers and biopesticides. Such nanohybrids have demonstrated a significantly slower, sustained release of urea compared to commercial granular urea, reducing leaching and improving nitrogen availability to plants. This technology offers ✓

potential for more efficient fertilizer application and reduced environmental impact (Madhavi et al,2020). ✓

**2.1.3. Polymer-Based Nanoformulations:** Biodegradable polymers like chitosan, polylactide, and cellulose are employed to encapsulate nutrients, ensuring slow release and protection from degradation. Iopolymeric nanoparticles derived from natural polymers such as chitosan, alginate, cellulose, and pectin are developed to encapsulate and control the release of fertilizers, pesticides, and herbicides. These nanoformulations improve the solubility and targeted delivery of agrochemicals, reducing toxicity and environmental contamination while increasing efficacy. Chitosan-based nanoparticles encapsulating pesticides have shown enhanced plant protection and growth promotion by improving bioavailability and reducing harmful effects. Controlled and slow release of active ingredients leads to efficient use of agrochemicals and reduced environmental impact (Shakiba et al., 2020). ✓

**2.1.4. Humic Acid-Nano-Hydroxyapatite (HA-HAP) Hybrids:** These hybrids combine the nutrient-holding capacity of hydroxyapatite with the soil conditioning properties of humic acids, resulting in slow nutrient release and improved soil health. A novel biocompatible nanofertilizer combining humic substances and hydroxyapatite nanoparticles was developed by self-assembling natural or synthetic humic substances with nano-hydroxyapatite via a simple dipping process. This HA-HAP nanofertilizer was tested on maize (*Zea mays*) and showed significant improvements in early plant growth, productivity, stimulation of rhizosphere bacteria growth, and resistance to salt-induced abiotic stresses compared to commercial fertilizers and bare hydroxyapatite nanoparticles. The synergistic effect comes from the co-release of phosphate ions (from hydroxyapatite) and humic substances, which act as plant nutrients and stimulants, respectively. The amount of humic substances adsorbed can tune the nutrient release pattern. Under salt stress, maize treated with HA-HAP maintained better plant health, chlorophyll content, and growth metrics than controls, highlighting enhanced abiotic stress tolerance linked to humic acid presence. This multifunctional nanofertilizer combines nutrient delivery, plant growth stimulation, and microbial rhizosphere enhancement via a scalable, environmentally benign synthesis procedure, promising for large-scale agricultural use (Yoon et al., 2020). ✓

**2.1.5. Chitosan-NPK Nanostructures:** Chitosan is used as a carrier for NPK (nitrogen, phosphorus, potassium) nutrients, enabling slow release and reducing synthetic fertilizer use. Chitosan nanoparticles (ChNPs) can be used as carriers for controlled release of fertilizers like nitrogen, phosphorus, and potassium (NPK). For example, Abdel-Aziz et al. (2016) studied the foliar application of Chitosan-NPK nanoparticles on wheat seedlings. The nanoparticles were quickly taken up through stomata and transported via phloem tissue, leading to significant improvement in wheat yield parameters such as plant height, spike weight, and crop yield compared to controls using conventional bulk NPK fertilizers. Chitosan-based nanofertilizers improved wheat yield where the Chitosan-polymethacrylic acid-NPK nanoparticles showed better plant height, spike weight, and harvesting index than bulk NPK fertilizers at equivalent nutrient levels. ✓

- 2.1.6. Microbe-Assisted Nanofertilizers:** *Enterococcus*-based silver nanoparticles (SR9AgNPs) have demonstrated improved germination and biomass gain in wheat, with no apparent toxicity at tested concentrations. Upadhyay et al., 2024 conducted a field study on wheat and maize at the Indian Agricultural Research Institute explored the combined use of nano nitrogen (nano-urea) and nano zinc fertilizers along with conventional fertilizers. This approach maintained or improved soil microbial biomass carbon and microbial community diversity, especially boosting beneficial groups like Actinobacteria and Proteobacteria. Crop yields improved, and nitrogen fertilizer use could be reduced by up to 25% with nano-fertilizer inclusion, demonstrating sustainable nutrient management linked to enhanced soil microbial health. Bionanofertilizers—nanoparticles combined with biofertilizers—show great promise in enhancing agricultural productivity. Several studies have illustrated that microbes such as *Pseudomonas aeruginosa* and *Trichoderma* sp. delivered with nanocarriers improve plant seed germination, growth, nutrient uptake, and stress tolerance. For example, in *Zea mays* (maize), the application of nano-Zn combined with biofertilizer improved grain yield by 1.5 to 2 times. In *Vigna radiata*, growth and survival were enhanced using nanostructured NPK fertilizers combined with beneficial microbes (Arora et al., 2024).



## 2.2. Application and Impact in Agriculture

- **2.2.1. Enhanced Nutrient Delivery:** Nano-fertilizers are engineered for controlled and targeted nutrient delivery, allowing deeper soil penetration and more efficient plant absorption compared to conventional fertilizers (ShivamKumar et al., 2025). Case study by Zhang et al., 2018, utilized an anion-responsive nanofertilizer based on hollow mesoporous carbon nanoparticles modified with polyethylenimine to deliver selenium in a controlled manner. This targeted nutrient delivery approach increased selenium utilization efficiency, resulting in a 60% increase in plant growth without nutrient loss. The study of Saurabh et al., 2024 evaluated the impact of integrating nanofertilizers, specifically nano-urea, with conventional fertilizers on rainfed maize production. Soil application combined with foliar sprays of nano-urea was shown to significantly improve nutrient uptake, plant growth, and crop yield while reducing environmental impacts. Applying 75% of the recommended nitrogen dose with two foliar sprays of nano-urea produced grain yields comparable to 100% nitrogen application using conventional fertilizers. This approach led to a 25% reduction in nitrogen fertilizer use without yield loss, promoting efficient nutrient use. Nano-urea enhanced nitrogen uptake through controlled and sustained release, improving biomass accumulation and photosynthetic activity. Environmental benefits included a 25% reduction in greenhouse gas emissions and improved energy use efficiency.

**2.2.2. Improved Crop Yields:** The growing global need for agricultural products has caused farmers to use too many traditional fertilizers. This has led to pollution, damage to soil and water, and health problems for people. Globalization has made these problems worse, so there is a need for better and more sustainable farming methods. Nanotechnology offers a new way to improve how nutrients are delivered to plants while reducing harm to the environment. Application of nano-fertilizers has led to significant yield improvements in major crops:

Wheat: 20–55% yield increase

Potato: 20–35% yield increase ✓

Maize: 20–40% yield increase ✓

Rice: 13–25% yield increase (Goyal et al., 2025)

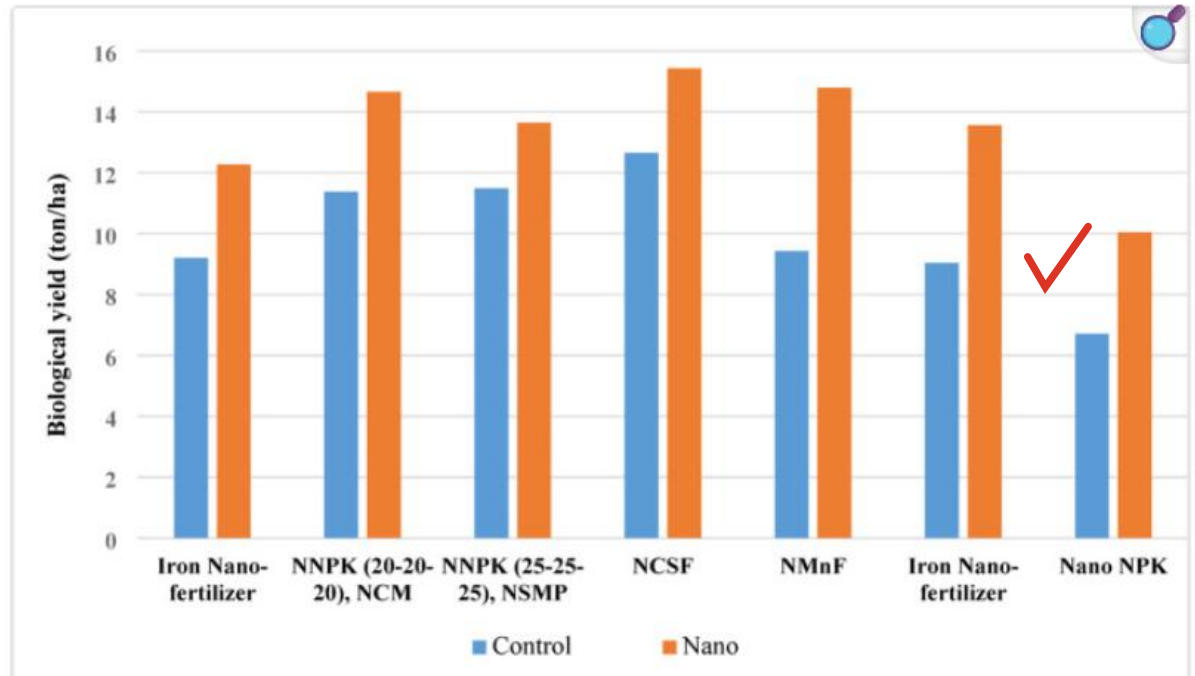


Fig 2- Biological yield of wheat plants treated with various nano-fertilizers (in ton/ha)  
Source: (Goyal et al., 2025).

Report showed

~~Figure 2~~ shows that wheat plants treated with nano-fertilizers grew taller than the plants that were not treated (control group). The nano-fertilized plants were consistently taller during the entire growth period. This means that using nano-fertilizers help the plants grow better, probably because the plants can absorb and use nutrients more efficiently. Source: (Goyal et al., 2025).

**2.2.3. Plant Growth and Metabolism:** Nano-fertilizers accelerate seed germination, seedling development, photosynthetic activity, and the synthesis of carbohydrates and proteins, resulting in healthier, more robust plants (Shivam Kumar et al., 2025). Using nano fertilizers in sustainable farming can help increase crop yields and protect the environment. They reduce the loss of nutrients through runoff and leaching, which lowers pollution. Nano fertilizers help plants use nutrients more effectively and reduce harmful effects on the environment. Because of this, nano fertilizers are very important for developing better and more sustainable farming methods in the future.

### 3. Integration with Biofertilizers: Nano-Biofertilizers

**3.1. Synergistic Effects:** Combining nanoparticles with biofertilizers (nano-biofertilizers) enhances plant growth, nutrient uptake, and stress tolerance under both biotic and abiotic stresses. Using nanoparticles together with biofertilizers helps plants grow stronger and tolerate stress better. When combined, they form a new tool called nano-biofertilizers (NBF), which is more affordable, eco-friendly, and useful for farming. These NBFs are made by coating tiny particles of minerals like silicon, zinc, copper, iron, nickel, titanium,

and silver, along with natural materials such as chitosan, cellulose, and starch. This helps avoid pollution caused by regular fertilizers. Although NBFs are still new in farming, they have great potential to change traditional farming into smarter and better methods (Sharma et al. 2022). ✓

**3.2. Microbial Encapsulation:** Encapsulation of beneficial microbes with nanoparticles improves their survival, colonization, and efficacy in the rhizosphere, further boosting nutrient cycling and plant health (Kannikka et al., 2024). a biofertilizer is ideally defined as a beneficial strain(s) of microorganism(s) that generates plant growth promoting properties, can be included in a carrier, and possess nutrient storage and release properties specified by the producer and can be readily applied to the soil or the plant (Malusá et al., 2012). Looking at the advantages, biofertilizers are now considered as fundamental to modern agriculture because of its low cost, renewable and eco-friendly nature.

**3.3. Sustainability:** Nano-biofertilizers offer a promising, long-lasting, and versatile solution for precision and smart agriculture, addressing the limitations of both conventional fertilizers and standalone nanomaterials. ?

### 3.4. Critical Assessment: Impact of Nano-Fertilizers vs. Conventional Fertilizers

#### Nutrient Use Efficiency (NUE)

- **Nano-fertilizers:**

- ✓ • Exhibit a significantly higher surface area and improved solubility, allowing for better contact and interaction with plant roots (Demeke et al., 2025)
- ✓ • Enable controlled and targeted nutrient release, reducing losses from leaching and volatilization, and synchronizing nutrient availability with plant demand.
- ✓ • Studies show that nano-fertilizers lead to more efficient absorption and utilization of nutrients, resulting in higher NUE compared to conventional fertilizers.
- ✓ • For example, products like NanoCote™ Core demonstrated improved nitrogen stabilization, reducing nitrogen loss to 5.8% compared to 15.1% for standard urea after 36 hours (<https://www.nano-yield.com/nanocote-core-compared-to-conventional-fertilizers-alone>)

- **Conventional fertilizers:**

- ✓ • Often suffer from low NUE due to immediate nutrient release, which leads to significant losses via leaching, runoff, and volatilization.
- ✓ • A large fraction of applied nutrients is not absorbed by plants, contributing to inefficiency and environmental pollution.

Include it in reference Rosqvist, 2023

#### Conclusion

The article concludes that nano-fertilizers represent a major advancement in sustainable agriculture by improving nutrient use efficiency, boosting crop yields, and reducing environmental harm compared to conventional fertilizers. Nano-fertilizers deliver nutrients more precisely and slowly, which helps plants absorb them better and reduces nutrient loss through leaching and runoff, protecting soil and water quality. They have shown significant yield increases in key crops like wheat, maize, potatoes, and rice, while also supporting soil health and beneficial microbes. Combining nano-fertilizers with biofertilizers to form nano-biofertilizers further enhances plant growth, stress tolerance, and sustainable farming

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practices. However, challenges remain, including large-scale production, long-term safety, environmental impact, and regulatory guidelines. Continued research and careful management are necessary to realize their full potential for global food security and environmental sustainability. ✓

### ✓ Declaration of Competing Interest

The other authors declare no competing financial or personal interest.

### ✓ Data availability

Data and images were described with original source.

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