

Nano-Fertilisers and Bio-Stimulants: Enhancing Crop Growth Efficiency

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Available online at
www.sunshineagriculture.vitalbiotech.org

Article History

Received: 3. 11.2025

Revised: 7. 11.2025

Accepted: 12. 11.2025

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INTRODUCTION

Efficient farming practices that ensure food security for a growing population worldwide also need to be environmentally sustainable. Conventional fertilizers are widely used; however, they have low nutrient-use efficiency (NUE):

- Nitrogen efficiency $\approx$ 30–50%
- Phosphorus efficiency $\approx$ 15–25%
- Potassium efficiency $\approx$ 50–60%

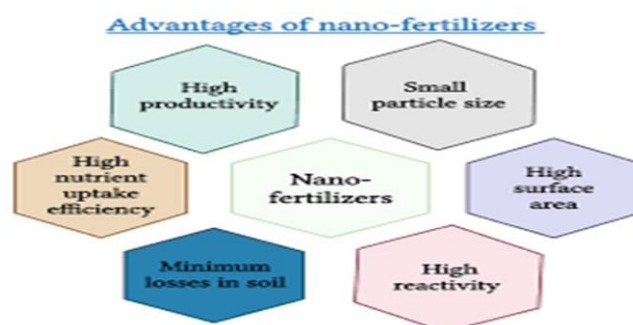
The unabsorbed nutrients are contributing to greenhouse gas emissions, eutrophication, soil degradation, and higher cultivation costs.

Nano-fertilisers and bio-stimulants are innovative products that improve ecrop efficiency, minimise nutrient losses, and ensure climate-smart agriculture. These products correspond with international trends of precision farming, sustainable input use, regenerative agriculture, and nanotechnology-driven agriculture.

2. Nano-Fertilisers: Concept and Classification

2.1 Nano-Fertilizers-What are They?

Nano-fertilizers are those specific fertilizer formulations engineered at the nanoscale level, between 1-100 nm, to introduce additional benefits for nutrient availability, effective targeted delivery, and controlled release. Ultra-small size and high surface area allow better penetration through stomata, roots, and xylem tissues.



Source: <https://www.mdpi.com>

2.2 Types of Nano-Fertilisers

Nano-fertilisers are categorized based on their formulation, nutrient delivery system, and method of synthesis. 1. Nano-Nutrient Formulations: These include nanoscale nutrient particles, such as Nano-N (nanostructured nitrogen), Nano-P (hydroxyapatite-based phosphorus), and Nano-K particles. The really small size enhances the solubility, penetration through the leaves, and absorption through roots, leading to quick uptake and slow and steady release of nutrients to meet the demand by plants. 2. Nano-Encapsulated Fertilisers: This implies the entrapment of nutrients in nano-carriers, including nano-polymers, nano-clays, and carbon nanotubes. Encapsulation protects nutrients from volatilization, leaching, and rapid fixation in the soil, improving the nutrient-use efficiency and maintaining a sustained supply to crops. 3. Nano-Coated Fertilisers: These consist of conventional fertiliser granules coated with nano-polymers or nano-films, which control the rate of dissolution. This restricted release reduces the loss of nutrients and promotes precision in nutrient management. 4. Green Synthesised Nano-Fertilisers: These are prepared by using plant extracts, microorganisms, or agriculture bio-waste through eco-friendly synthesis routes. The biodegradable nature of nano-fertilisers contributes to a reduction in the levels of chemical residues and provides an environmentally friendly approach for improving nutrition in crops.

3. Mechanisms of Action of Nano-Fertilisers

Nano-fertilizers work through very efficient biochemical and biophysical mechanisms that enhance nutrient availability, mobility, and utilization in plants. 3.1 Enhanced Absorption and Translocation: Their nanoscale size enables them to move quickly through leaf stomata, cuticular pores, and apoplast pathways of the root, thus allowing the rapid uptake of nutrients compared to conventional fertilizers. Greater surface area of nano-nutrients increases their solubility and reactivity, enabling fast movement through xylem and phloem to reach metabolically active tissues more efficiently.

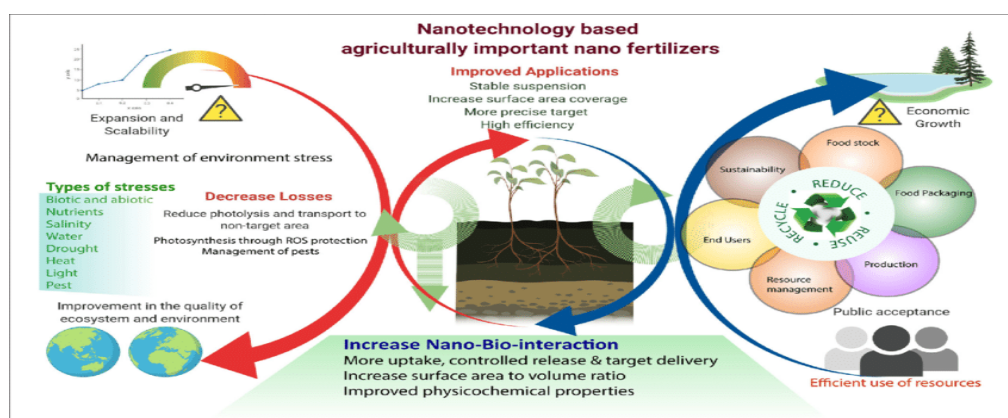
3.2 Controlled Release and Smart Delivery:

Nano-carriers are designed to deliver nutrients in a controlled fashion based on the soil moisture, pH, temperature, and physiological demand of plants. Smart delivery helps in maintaining consistent nutrient supply during critical growth stages without causing nutrient loading, toxicity, and wastage.

3.3 Enhanced Nutrient-Use Efficiency (NUE):

Nano-fertilizers significantly reduce the loss of nutrients by volatilisation, runoff, and leaching. Because of controlled release, the availability of nutrients can be synchronised, thus enhancing NUE and reducing environmental contamination.

3.4 Stress Alleviation: Metallic nano-nutrients like Nano-Cu, Nano-Zn, and Nano-Si improve photosynthetic efficiency, cell membrane integrity, and antioxidant enzyme system activity like SOD, CAT, and POD. Such biochemical modifications promote plant tolerance against drought, salinity, and high-temperature stress.



Source: <https://www.researchgate.net>

4. Bio-Stimulants: Concept and Classification

4.1 What are Bio-Stimulants?

Biostimulants encompass natural products or biological agents that, when applied to plants or the rhizosphere, are able to enhance plant physiological and biochemical processes. Unlike other traditional fertilizers, they do not directly provide nutrients but improve nutrient uptake, metabolism, and plant resilience. Bio-stimulants show an integral part in influencing root development, enzymatic activity, hormonal balance, soil microbial interactions, enhancing growth, yield, and stress tolerance. Their use is becoming especially important in sustainable and climate-resilient agriculture.

4.2 Types of Bio-Stimulants

1. Humic and Fulvic Acids: These organic molecules improve root elongation, nutrient chelation, and soil microbial activity. They improve nutrient mobility and enhance overall soil fertility.

2. Seaweed Extracts: These organic extracts are derived from brown, red, or green algae, rich in natural plant hormones such as auxins, cytokinins, and gibberellins, which are known to stimulate crop vigour, flowering, and yield.

3. Amino Acids and Peptides

These amino acids, the building blocks of proteins, help in chlorophyll formation, stress tolerance, osmotic balance, and overall plant growth.

4. Microbial inoculants: The PGPR which help in nitrogen fixation, phosphate solubilisation, and plant-microbe symbiosis include *Azotobacter*, *Rhizobium*, and *Pseudomonas fluorescens*.

5. Silicon-Based Stimulants: Silicon strengthens cell walls, increases structural rigidity, and reduces susceptibility against pests and diseases.

6. Protein Hydrolysates: These improve enzyme activity, metabolic efficiency, and nitrogen assimilation.

5. Nano-Fertilizers and Bio-Stimulants Used Jointly for E-Crop Efficiency

A synergistic approach to improving growth efficiency of e-crops can be achieved by the integrated application of nano-fertilisers and bio-stimulants, enabling advancements in nutrient delivery, physiological performance, and soil health.

5.1 Synergistic Effects

When used together, they greatly improve root architecture, enabling deeper and more branched roots that improve nutrient and water acquisition. Nano-nutrients enable quick translocation, while

bio-stimulants trigger activity in the enzymes of the roots and interaction with microbes. This has the combined effect of improving soil microbiome diversity and enhancing plants' resilience to stress.

5.2 Enhanced Photosynthetic Efficiency

The combined application of Nano-N and seaweed extracts also enhanced photosynthetic activity through the increase in chlorophyll content, stomatal conductance, and light-use efficiency. This makes carbon assimilation more efficient, thus increasing biomass production, especially under suboptimal environmental conditions.

5.3 Improved Stress Tolerance

Bio-stimulants trigger induced systemic resistance, thus enhancing the plant's defense mechanisms against biotic stresses, while nano-fertilizers regulate osmotic balance and increase antioxidant activity. Together, they enhance tolerance against drought, salinity, and temperature extremes by the stabilization of cellular structures and metabolic functions.

5.4 Improved Soil Health

Bio-stimulants enhance microbial biomass carbon and enzymatic activity, leading to improved soil fertility. Nano-fertilisers reduce the chemical burden on soil by decreasing fertiliser requirement by 30-50%, thus advancing sustainable nutrient cycling and long-term health of soils.

6. Advantages of Nano-Fertilisers and Bio-Stimulants

Both nano-fertilizers and bio-stimulants combined provide a wide range of agronomic, environmental, and economic benefits that contribute directly to increased efficiency in crop growth and sustainable agricultural production.

6.1 Agronomic Benefits

Nanoscale size imparts faster nutrient absorption through plant leaves and roots, facilitating quick nutrient uptake and utilisation. Nutrient assimilation and metabolic activity are further supported by bio-stimulants that promote vigorous growth of crops. The inputs are reduced substantially with enhancement in yield by 10% to 40% based on crop type and management practices. Improvements in the protein content, micronutrient density, and overall crop quality become common phenomena due to enhanced nutrient-use efficiency and strengthened physiological processes.

6.2 Environmental Benefits

Nano-fertilizers reduce nutrient losses from volatilization, leaching, and runoff, while minimizing chemical contamination of water bodies. They also serve to reduce nitrous oxide emissions as part of climate mitigation. Bio-stimulants enhance biodiversity in the soil, foster beneficial microorganisms, improve soil structure, and promote sustainable nutrient cycling. Both combined reduce the ecological footprint of crop production.

6.3 Economic Benefits

Efficient delivery of nutrients means farmers can apply smaller doses less frequently, which reduces the overall cost of fertilisers. Increasing yields, improving the quality of crops, and making them more resilient to stress further raise profitability. Compatibility with precision farming systems ensures better ROI and economic sustainability in the long run.

7. Limitations and Challenges

However, wide applications of nano-fertilisers and bio-stimulants face some scientific, regulatory, and practical challenges despite their huge potential.

7.1 Research and Regulatory Gaps: One of the big limitations is the lack of globally accepted standards and guidelines for formulation, application rate, and safety assessment of nano-fertilizers. The regulatory frameworks in many countries remain evolving; hence, variable quality of products and limited market confidence persist. Additional long-term, multi-location trials will be needed to validate their agronomic performance across diverse environments.

7.2 Potential Toxicity Issues: Because of excessive application or incorrect use, nanoparticles may accumulate in soil and affect microorganisms in the soil and nutrient cycling. So far, long-term interactions between nano-materials, soil ecosystems, and food chains have been insufficiently investigated. Environmental thresholds and exposure limits are still unclear.

7.3 Cost and Awareness Issues: In developing regions, adoption is limited by high initial product costs and a lack of awareness among farmers. In addition to these factors, lack of training, weak extension services, and misconceptions about nano-technology further slow adoption. Large-scale capacity-building programs, demonstrations, and farmer-friendly guidelines are necessary for mainstream use.

8. Future Prospects of Nano-Fertilisers and Bio-Stimulants

This will be the future of modern agriculture, wherein advanced nano-technologies are integrated into biological inputs for ultra-efficiency, sustainability, and climate resilience of cropping systems.

8.1 Smart Nano-Sensors: Next-generation nano-sensors will enable real-time monitoring of soil nutrient status, moisture levels, and plant stress signals at micro- and nanoscale precision. These ultra-sensitive devices will support site-specific nutrient application, reducing losses and aiding in optimizing crop performance.

8.2 AI-Integrated Precision Nutrient Management: AI and machine learning algorithms are the future for real-time field data analysis and automation of recommendations on nano-fertilizers. Such an AI-driven system will enhance the efficiency in decision-making, reduce human error, and allow personalized nutrient schedules based on the stage of growth of crops.

8.3 CRISPR + Nano Delivery Systems

This sets a new frontier in crop improvement through the integration of CRISPR gene-editing technology with nano-carriers. Nanoformulated DNA/RNA delivery systems will facilitate precise gene editing toward the development of drought-tolerant, nutrient-efficient, disease-resistant crop varieties with minimal off-target effects.

8.4 Carbon-Neutral Agriculture: Bio-stimulants enhance the microbial biomass and root activities, hence enhancing soil carbon sequestration. Nano-fertilizers, on the other hand, reduce greenhouse gas emissions by reducing nutrient losses. Together, they support the transition toward carbon-neutral and climate-smart agriculture for long-term sustainability.

9. CONCLUSION

Nano-fertilizers and bio-stimulants therefore offer modern agriculture a promising direction towards sustainability, efficiency, and climate-smart production systems. Precise nutrient delivery, advanced physiological functions, and improved soil-microbe interactions significantly enhance the efficacy of crop growth. When regulatory barriers, lack of awareness, and cost are overcome, their application can be rapidly developed. These technologies can shape the future of high-efficiency, eco-friendly crop production by being integrated with precision

agriculture, nanotechnology platforms, and digital farming systems.

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