



MINI REVIEW

Unveiling the potential of nano fertilisers: A comprehensive review on their superiority over conventional systems

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Abstract

The widespread use of conventional urea fertilisers supports global food security while causing significant environmental externalities: groundwater nitrate surges endanger drinkable supplies, nitrate leaching surpasses 50 % of applied nitrogen, causing eutrophication and N₂O emissions contribute 300 Tg CO₂-equivalents annually to global warming. Nitrogen consumption rises as arable land is expected to decrease by 1.5 % every 10 years due to a population of 9.7 billion by 2050, exacerbating these challenges and highlighting the need for energy-smart alternatives. This approach is challenged by nano fertilisers, which are designed at scales of 1–100 nm and have targeted delivery and slow-release kinetics. Through improved stomatal penetration and quantum confinement effects that improve foliar assimilation, IFFCO nano-derived nanoparticles (20–50 nm) reach 80–90 % nitrogen utilisation efficiency (NUE) on par with prilled urea, which achieves 30–40 %. In India, field tests on rice-wheat systems show that microbial diversity and soil organic carbon are preserved while yields are increased by 20–30 %, N₂O flux is reduced by 50–70 % and leaching is reduced by 40 %. This review critically analyses these differences: nano-formulations reduce fertiliser footprints by 50–75 %; economically, they save ₹ 250–400 ha⁻¹ from halved dosages and agronomically, they outperform bulk urea in nutrient synchronisation (e.g., zero-order release curbing luxury uptake). However, regulatory gaps continue, scalability depends on cost-competitive synthesis and the persistence of nano urea poses a risk of nano toxicity in rhizospheres. In a time of limited resources, nano-fertilisers promote sustainable intensification by rethinking nitrogen stewardship and balancing farmer viability, planetary health and productivity.

Keywords: conventional fertilisers; foliar spray; IFFCO nano fertiliser; sustainable agriculture

Introduction

High-yielding cultivars were brought about by the Green Revolution and are now crucial to contemporary farming. It is necessary to use more fertiliser in greater amounts to fulfil the higher nutritional requirements of these types. Fertilisers are necessary to boost agricultural yields and maintain food security; conventional fertilisers usually cause environmental and financial issues (1). This highlights the necessity of incorporating nano fertilisers into contemporary farming practices to optimise yields and ensure sustainable agricultural productivity. Fertilisers are necessary to boost agricultural yields and maintain food security. Conventional fertilisers usually cause environmental and financial issues. By applying nanotechnology to address some of the issues caused by conventional fertilisers, nano fertilisers provide a workable alternative as shown in Fig. 1 (2). By 2050, it is expected that there will be more than 9 billion people on the planet, which would need a significant increase in agricultural production to keep up with demand for food (3). Over the past century, conventional fertilisers have been essential to generating

increased yields. But its reckless usage has raised questions about greenhouse gas emissions, water contamination and soil erosion (4). A paradigm transition toward more sustainable fertilisation techniques is required in light of these disadvantages. Using the special qualities of nanoparticles to increase the efficiency with which nutrients are delivered to plants, nano fertilisers provide a possible option. Nanoparticles allow for more accurate nutrient delivery, enhanced absorption and fewer losses from volatilisation or leaching (5). Additionally, nutrients may be released gradually from nano fertilisers to fit plant requirements while reducing environmental effects.

Nano fertilisers may have advantages, but there are concerns about their safety, long-term consequences on soil health and regulatory framework (6). With the development of nano fertilisers by IFFCO, several of the major problems with traditional fertilisers, such as soil deterioration, nutrient loss and contamination of the environment, may be resolved. Utilising nanotechnology, Nano fertilisers are expected to reduce waste,

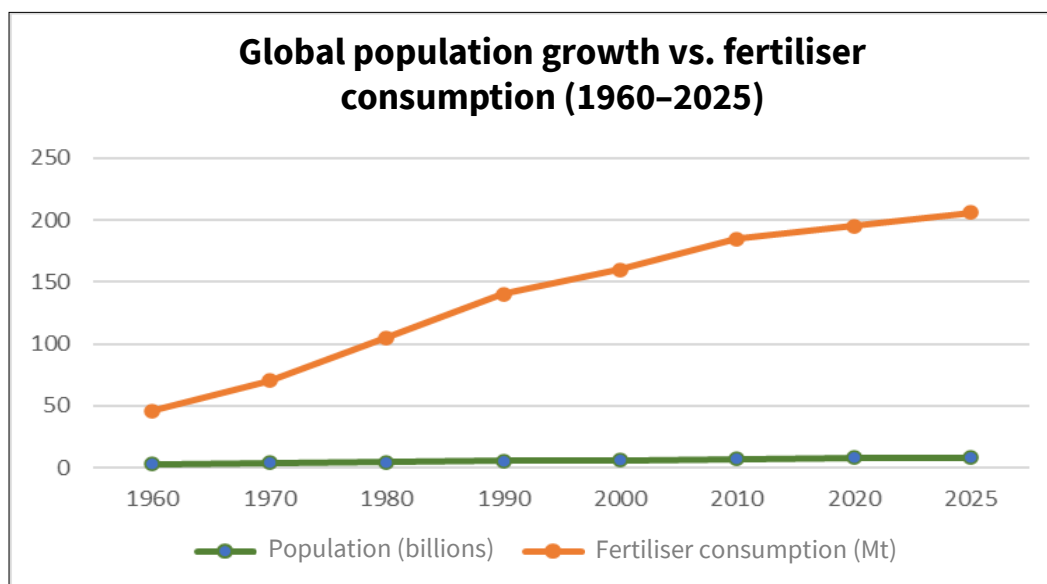


Fig. 1. Global population growth vs. fertiliser consumption (1960–2025)

improve fertiliser delivery efficiency and lessen the negative environmental effects of conventional fertilisation methods (7). Raising concerns about the toxicity of nanoparticles and their build-up in the environment highlights the necessity of thorough analysis and risk assessment. In addition, there are still major issues that need to be resolved before nano fertilisers can be widely used by farmers, especially in underdeveloped nations. These issues include scalability and cost-effectiveness.

This review article provides a thorough examination of the formulation, effectiveness, environmental impact and the possible implications for agricultural sustainability of IFFCO nano fertilisers. This article attempts to clarify the advantages and challenges of using nano-fertilisers in contemporary agriculture by combining the results of previous studies with the opinions of professionals in the field. This review aims to critically examine the body of research on conventional and nano fertilisers, including their effectiveness, effects on the environment and socioeconomic ramifications. This study hopes to inform policymakers, researchers and agricultural stakeholders on the advantages and challenges of using nano fertilisers in contemporary agriculture by combining existing knowledge and highlighting research gaps.

Environmental impacts of conventional fertilisers

The projected global population of 9.7 billion by 2050 will increase food demand by about 70 %, requiring greater agricultural productivity on limited arable land. This underscores the need for efficient fertiliser usage (8). However, rising fertiliser prices, exceeding those of food, have significantly reduced their economic viability. Human-induced greenhouse gas emissions contribute to global climate change, posing new challenges for agriculture and the fertiliser industry. Limited geological resources for fertiliser production, combined with market fluctuations, intensify competition and food security (9). Improperly utilised nitrogen fertilisers can contaminate groundwater and water bodies, leading to eutrophication, oxygen depletion and a decline in water quality. This process can disrupt aquatic ecosystems, increase unwanted species, cause odour issues and pose health risks like methemoglobinemia from nitrate in drinking water. Acidic nitrogen fertilisers contribute to soil and air pollution, while nitrous oxide and methane emissions contribute to greenhouse gases. Other minerals like phosphate, potassium, calcium and

magnesium also pose pollution risks, albeit to a lesser extent. Soil characteristics such as texture and pH influence fertiliser uptake and fate, with acidic fertilisers exacerbating soil degradation on already acidic soil. To mitigate these environmental impacts, fertilisers should be applied gradually rather than all at once and precautions like maintaining ground cover near water bodies and avoiding application during heavy rainfall should be taken (10). Productive soils can retain significant amounts of nitrogen (N) and phosphorus (P) in the upper root zone during active crop growth. These levels can be maintained through fertilisation or natural processes like decomposition of organic matter or P desorption from soil solids. Soils lacking this capacity, like sandy soils, present challenges in management and may remain unproductive. During crop growth, nitrate levels in the soil solution must be kept above 10 ppm of nitrate-N, often higher. In some regions, soil P concentrations range from 20–350 ppb, averaging around 90 ppb (11). These high N and P levels, crucial for plant growth, should be minimised before entering runoff or percolating water to prevent environmental contamination. Agricultural drainage often has better quality than the receiving streams (12). Excessive environmental nitrogen has several harmful effects, including soil and water acidification, coastal marine ecosystem eutrophication, biodiversity loss in both land and water habitats, proliferation of nitrogen-loving weeds, elevated levels of greenhouse gases like N_2O , stratospheric ozone depletion, heightened ozone-related damage to crops and ecosystems and increased atmospheric haze and airborne particulate matter production (13). Fertilisers play a crucial role in plant growth and development. Many factors render most applied fertilisers inaccessible to plants, including leaching, photolysis, hydrolysis and decomposition. The extent of loss correlates with the concentration of elements in the soil solution and the volume of drained water. Nutrient leaching is gaining significance as it signifies a direct loss to crops and an economic setback to farmers (14).

Science and facts of nano fertiliser over conventional fertilisers in the plant physiological pathway

Nano-fertilisers represent a cutting-edge approach to nutrient delivery in agriculture, leveraging nanotechnology to enhance plant growth and productivity. The physiological pathway through which nano-fertilisers operate involves several key steps:

Nanostructure design: Nano-fertilisers are engineered at the nanoscale, typically with particle sizes ranging from 1–100 nm (15). These nanoparticles can be made from various materials, such as metals, metal oxides, or polymers, depending on the specific nutrient or compound being delivered.

Uptake by plants: Nano-fertilisers are applied to the plants either through foliar spray or soil application. When applied to the leaves, nanoparticles can penetrate the leaf surface through stomata or cuticles, while soil-applied nanoparticles may be taken up by plant roots (16).

Foliar spray application

When nano-fertilisers are applied as a foliar spray, they are typically formulated as colloidal suspensions containing nanoparticles of desired nutrients or compounds (17). Upon spraying onto the leaves, the nano-fertiliser droplets come into contact with the leaf surface (18). Nanoparticles can penetrate the leaf surface through two primary pathways:

Stomatal uptake: Nanoparticles can enter the leaf interior through stomata, which are microscopic pores on the leaf surface responsible for gas exchange (19). Stomata open and close in response to environmental conditions, allowing nanoparticles to pass through (20).

Cuticular penetration: Nanoparticles may also penetrate the waxy cuticle layer covering the leaf surface (21). The cuticle is a hydrophobic barrier, but nanoparticles with appropriate surface chemistry and size can traverse this barrier through diffusion or other mechanisms (22).

Soil application

Nano-fertilisers applied to the soil deploy nanoparticle-infused granules or suspensions straight into the rhizosphere, dynamically interacting with soil colloids, organic matter and microbial consortia. Recent 2024–2026 studies emphasise its revolutionary potential (23). IFFCO nano-urea (20–50 nm) demonstrates sustained release in paddy soils, retaining 80 % N availability over 60 days compared to 30 % for pelleted urea, as confirmed in TNAU rice-wheat cycles (24). Nano-fertilisers applied to the soil are typically in the form of nanoparticle-containing granules or solutions. When applied to the soil surface or incorporated into the soil, nano-fertiliser particles interact with the soil matrix (25). Plant roots absorb water and nutrients from the soil through a process called rhizosphere interaction. Nanoparticles in the soil solution can be taken up by plant roots through several mechanisms.

Passive diffusion: Nanoparticles can diffuse through the soil water-filled pores and come into contact with the root surface. Modern uptake methods incorporate sophisticated dynamics and passive diffusion dominates in nanoporous soils, with 30 nm nano-ZnO passing through aquaporins (e.g., ZmPIP2; 5 in maize) at five times the bulk rates, enhancing Zn translocation to grains by 25 % in Zn-deficient vertisols (26).

Chemical interactions: Nanoparticles may chemically interact with soil components, altering their surface properties and facilitating root uptake (27). Chemical interactions drive apoplastic-symplastic shifts. Nano-Fe oxides chelate with rhizosphere ligands (e.g., citrate), upregulating FER1/LI genes in tomato roots for 35 % Fe homeostasis under calcareous stress (28).

Endocytosis: Endocytosis, elucidated by 2025 TEM investigations, internalises 40 nm silica-chitosan nanoparticles through clathrin-

mediated vesicles in wheat radicals, enhancing silicon content by 40 % and increasing lodging resistance (29).

Field applications spotlight crop-specific breakthroughs: In finger millet (*Eleusine coracana*), TNAU trials with soil nano-Se (10–20 nm) spiked GPX/SOD antioxidants by 50 %, curbing blast incidence 30 % (30). Sorghum biofortification with nano-Mo activated nitrate reductase (NR) 2-fold, lifting fodder N by 22 % in rainfed Deccan plateaus (31).

Internal transport

Upon cellular internalisation through root or foliar pathways, nano-fertilisers navigate the plant's vascular architecture-xylem facilitating acropetal apoplastic flux from roots to shoots, phloem enabling basipetal symplastic recirculation to sink tissues like meristems, florets and developing grains (32). Translocation dynamics are modulated by nanoparticle traits: optimal diameters < 50 nm negotiate Casparian barriers, cationic surface charges enhance xylem adhesion and polymeric coatings (e.g., chitosan) prolong phloem residence (33). In rice (*Oryza sativa*), xylem-mobile nano-N sustains panicle N supply, elevating filled grains 18 %; soybean nano-P variants, phloem-translocated, bolster pod biomass under deficiency via PHT1 transporter induction (23). Nanoparticles, once absorbed by the roots or leaves, can be transported through the vascular system via one of two pathways:

Xylem transport: Nanoparticles may enter the xylem vessels located in the roots and be carried upwards along with the water flow towards the stems, leaves and other aerial parts of the plant. This is known as xylem-mediated transport (34).

Phloem transport: Nanoparticles may be transported through the phloem tissue, either actively or passively, to various plant tissues. This allows for bidirectional movement of nanoparticles within the plant, facilitating distribution to both above-ground and below-ground organs (35).

Release of nutrients: Nano-fertilisers are designed to release nutrients gradually, ensuring a sustained supply to the plant over time. This controlled release mechanism prevents nutrient leaching and wastage, maximising nutrient uptake efficiency (36).

Nano-fertiliser design: Nano-fertilisers are engineered to encapsulate or incorporate nutrients within nanostructured materials, such as nanoparticles, Nano capsules, or nanocomposites. These nanostructures are designed to gradually release nutrients in a controlled manner, prolonging the availability of nutrients to plants (37).

Matrix material: The matrix material surrounding the nutrient-loaded nanoparticles plays a crucial role in controlling nutrient release. This matrix can be composed of biodegradable polymers, inorganic materials, or organic substances with specific properties that regulate nutrient diffusion (38).

Diffusion mechanisms: Nutrient release from nano-fertilisers occurs primarily through diffusion mechanisms (39). As water penetrates the nano-fertiliser matrix, nutrients dissolved in the water gradually diffuse out of the matrix and into the surrounding soil or plant root zone. The rate of nutrient diffusion is controlled by factors such as the properties of the matrix material, the size and surface area of the nanoparticles and environmental conditions such as soil moisture and temperature (40).

pH-dependent release: Some nano-fertilisers are designed to release nutrients in response to changes in pH. For example,

certain polymer-based nanostructures may swell or degrade in acidic or alkaline environments, leading to enhanced nutrient release under specific soil pH conditions (41).

Environmental stimuli: Nano-fertilisers can also be engineered to respond to environmental stimuli such as temperature, moisture, or microbial activity (42). Stimuli-responsive nanostructures undergo conformational changes or degradation in response to these stimuli, triggering nutrient release when conditions are optimal for plant uptake (43).

Foliar application benefits of nano fertilisers

In rice (*Oryza sativa*), 20–50 nm nano-urea increases plant height by 15 %, leaf area index by 25 % and chlorophyll 'a' by 30 % through upregulated expression of OsNRT2.3 nitrate transporters, improving photosynthetic rates (Pn up 22 %) and dry matter accumulation. These benefits are amplified across crops by nano-fertilisers (44). Trials on maize (*Zea mays*) reveal that nano-ZnO (30 nm) increases zeaxanthin epoxidase genes and superoxide dismutase (SOD) activity by 40 %, reducing oxidative stress and increasing grain yields by 18–24 % over bulk ZnSO₄ (45). In tomatoes (*Solanum lycopersicum*), nano-Fe chelates cause ferritin gene upregulation, spiking Fe content by 35 % and lycopene biosynthesis via PSY1 transcripts, with 28 % increase in fruit yield and reduced leaching (46). Foliar feeding delivers trace elements straight to plant leaves and foliar feeding speeds up nutrient absorption during crucial development stages like tillering and booting (47). It also gets around soil fixation limitations that restrict the bioavailability of micronutrients like Zn and Fe to just 10–20 % (48). Due to stomatal absorption rates surpassing 80 % within hours, foliar sprays of liquid fertilisers perform better than soil treatments in the delivery of macro and micronutrients, as demonstrated by 20–30 % greater rice yields and halved N losses in wheat experiments (49). Nanoscale dimensions (< 100 nm) and high surface-to-volume ratios improve solubility, phloem/xylem mobility and metabolic flux, such as activating AMPK-like pathways for N remobilisation, resulting in 50 % less input for similar effectiveness (50). Nano fertilisers reduce runoff by 60–75 % while maintaining water quality and soil microbiology, which increases the resilience of agroecosystems. This invention scales precision feeding for sustainable intensification while reducing expenses (₹ 200–300 ha⁻¹) (51).

Interaction with plant cells

Within plant cells, nanoparticles may interact with cellular components such as membranes, organelles and enzymes. These interactions can influence cellular processes involved in growth, metabolism and stress response (52).

Membrane interaction: Nanoparticles can interact with the lipid bilayer membranes that surround plant cells. These interactions may involve adsorption or insertion of nanoparticles into the membrane structure, altering its permeability and fluidity (53). Changes in membrane properties can affect ion transport, nutrient uptake and signalling processes across the membrane (54).

Organelle interaction: Nanoparticles may also interact with various organelles within plant cells, such as chloroplasts, mitochondria and endoplasmic reticulum. These interactions can influence organelle function and morphology, impacting cellular processes such as photosynthesis, respiration and protein synthesis. For example, nanoparticles may accumulate within chloroplasts and affect chlorophyll synthesis or alter mitochondrial membrane

potential, affecting ATP production (55).

Enzyme interaction: Nanoparticles can interact with enzymes present in plant cells, either directly or indirectly. Direct interactions may involve binding of nanoparticles to enzyme active sites, affecting enzyme activity and substrate binding. Indirect interactions may occur through modulation of enzyme expression or post-translational modifications, altering enzyme levels or activity (56).

Cellular signalling: Nanoparticle interactions with cellular components can trigger intracellular signalling pathways involved in plant growth, development and stress responses. These signalling pathways may involve protein kinases, phosphatases and secondary messengers such as calcium ions and reactive oxygen species (57). Nanoparticles can act as signalling molecules themselves or modulate the activity of signalling molecules, influencing gene expression and physiological responses (58).

Stress response: Excessive nanoparticle accumulation or disruption of cellular processes may trigger oxidative stress, leading to the production of reactive oxygen species and activation of antioxidant defence systems (59). Nanoparticles may also induce changes in gene expression patterns, resulting in the upregulation of stress-responsive genes involved in defence mechanisms (60).

Impact on metabolic integration

Enhanced nutrient absorption facilitated by nano-fertilisers in plants can be attributed to various physiological mechanisms. The small size and large surface area of nanoparticles allow for efficient nutrient uptake by plant roots (61). The increased surface area-to-volume ratio enhances the contact between nanoparticles and root surfaces, promoting nutrient adsorption and uptake. Additionally, the unique physicochemical properties of nanoparticles can enhance nutrient solubility, making nutrients more readily available for uptake by plant roots (62). Furthermore, nanoparticles may improve nutrient mobility within the soil matrix, facilitating their movement towards root surfaces. Once absorbed by roots, nanoparticles can enhance nutrient bioavailability within plant tissues, ensuring optimal nutrient uptake and utilisation for various physiological processes such as growth, metabolism and stress response (63).

Nano-fertilisers deliver essential nutrients in a highly bioavailable form, allowing for efficient uptake by plant roots (64). The nutrient availability promotes root growth, increasing root surface area and facilitating nutrient absorption. With an ample supply of essential nutrients, plants experience improved metabolic processes, including chlorophyll synthesis, leading to increased leaf area and chlorophyll content (65). The enhancement in chlorophyll content boosts photosynthetic efficiency, resulting in higher rates of carbon assimilation and biomass production (66). Additionally, nano-fertilisers may induce hormonal changes within plants, promoting cell division, elongation and differentiation, thereby enhancing overall plant vigour (67). The culmination of the physiological responses contributes to improved plant growth and development, ultimately translating into enhanced yield potential and productivity (68).

Environmental and economic aspects

Nano-fertilisers, with their tiny size and slow-release properties, offer

a promising solution. Nano-urea, pioneered by IFFCO, boasts nanometer-scale particles, extended shelf life and eco-friendly attributes. Its adoption could revolutionise farming, curbing chemical usage, enriching soil and promoting sustainable agriculture. Compared to regular urea, it shows superior efficiency, lower environmental footprint, controlled nutrient delivery and economic advantages (69). Improved fertiliser contact enables plants to uptake nitrogen more effectively, boosting nitrogen use efficiency. This means crops utilise a greater portion of the applied nitrogen, minimising waste and potential environmental harm (70). Unused nitrogen is stored in plant vacuoles and released gradually to support plant growth. Nano Urea (Liquid) is offered to farmers without government subsidy, priced 10 % lower per bag compared to subsidised urea (71). Switching to conventional fertilisers is advised over nano-fertilisers, especially in sandy soils, to prevent potential leaching of conventional urea and groundwater contamination (72). Using nano urea along with conventional urea increases the levels of nitrogen, phosphorus, potassium, iron and zinc as well as enhancing their absorption by the plant (73). Combining nano-urea with traditional nitrogen fertiliser has the potential to boost crop yields, improve nutrient absorption and reduce greenhouse gas emissions (74). Nano urea accelerates the availability of nutrients to developing plant tissues, promoting the formation of dry matter and chlorophyll synthesis. This leads to enhanced agricultural yields and improved plant quality (75). One prominent method involves encapsulating urea nanoparticles in polymer coatings or matrices, allowing for controlled nutrient release in response to environmental conditions (76). Nano urea offers both environmental and economic advantages in agricultural practices. Its production and distribution at a lower cost compared to conventional urea contribute to significant economic benefits for farmers, as mentioned in Table 1. Overall, the adoption of nano urea represents a promising step towards sustainable agriculture, balancing ecological stewardship with economic viability.

Conclusion

The comparison between nano fertilisers and conventional fertilisers highlights the significant potential of nano fertilisers in revolutionising agricultural practices. Nano fertilisers offer unique advantages such as controlled nutrient release, reduced

environmental impact and improved crop yield and quality compared to conventional counterparts. Comparative evaluation underscores nano-fertilisers transformative edge over conventional formulations, delivering synchronised nutrient release, 60–70 % slashed losses and 15–30 % yield premiums across rice-wheat, maize and horticultural systems. These innovations curb leaching, elevate biofortification and yield ₹250–400 ha⁻¹ economics for smallholders redefining sustainable intensification amid arable decline. In the future, drone-assisted precise foliar applications, AI-enhanced formulations and coordinated legislation will expedite the adoption in the Global South by 2030, strengthening climate-resilient agriculture for a population of 9.7 billion while preserving ecosystems for future generations. Despite challenges such as cost-effectiveness and widespread adoption, the transformative benefits of nano fertilisers underscore their importance in advancing agricultural sustainability and meeting the demands of a growing global population. Continued research and investment in nano-fertiliser technology are crucial for realising their full potential and ensuring a more resilient and environmentally friendly agriculture in future.

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Authors' contributions

EM designed the concept EM and KT conceptualised the study and developed the methodology. EM contributed to the original draft, while KT also provided supervision. RK, MH, VS, DA, and KMS contributed to the original draft, participated in review and editing, and provided supervision. VM, GP, and SPS participated in review and editing and provided supervision. All authors read and approved the final manuscript.

Table 1. Research evidences

Crop	Treatment	Results	Reference
Rice	Nanofertilizers	Enhanced growth, development, TPC and antioxidant activity	(77)
Rice	NPK nano-fertilisers	Balanced yield and quality, efficient fertiliser use, sustainable agriculture	(78)
Rice	Inorganic nano fertilisers with NPK + Urea	Effective in rice cultivation	(79)
Maize	Nanozeourea	Superior growth, yield, quality and nutrient absorption compared to conventional urea	(80)
Maize	75 % RDP via SSP, 5 % RDP via hydroxyapatite nanoparticles (NP1) in soil, 1 % RDP via NP1 in foliar application	Highest growth parameters, yield attributes and maize yield, 25 % P fertiliser savings	(81)
Various crop	Nano chelated super fertiliser (1 kg ha ⁻¹ via foliar nutrition)	Enhanced growth, yield, nutrient uptake and agronomic efficiency	(82)
Wheat	Nano chelated Specific, nano micro complete, nano-manganese	Most effective for growth, yield, nutrient concentration in grains and agronomic efficiency	(83)
Rice follows cotton	50 % RDN&P, 100 % potassium, foliar spray of super nano urea (1 %) and nano DAP (0.5 %) at 25 and 45 DAS	Optimal dosage for enhancing growth parameters under high-density planting	(84)
Summer irrigated greengram	100 % or 80 % RDN, foliar application of nano urea (4mL L ⁻¹) during flower initiation and 15 days later	Enhanced productivity and profitability	(85)

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

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