NANO-FERTILIZERS AND SUSTAINABLE NUTRIENT MANAGEMENT

CHAPTER 2

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ABSTRACT: Conventional fertilizers' inefficiency is a major problem in contemporary agriculture; nutrient utilization efficiencies are often less than 50%, which results in large financial losses and environmental damage. By delivering vital nutrients to crops in a regulated and targeted manner, nano-fertilizers have become a promising technology that has the potential to completely transform nutrient management. The creation, varieties, workings, and uses of nano-fertilizers in sustainable agriculture are examined in this chapter. Through increased plant absorption, gradual and sustained release mechanisms, and decreased environmental losses from leaching, volatilization, and fixing, nano-fertilizers increase the efficiency of nutrient usage. Numerous formulations, such as fertilizers based on nanoparticles, nutrients encapsulated in nanoparticles, and coating technologies at the nanoscale, provide flexibility in meeting particular nutritional needs for various crops and soil types. The physiological and molecular processes that underlie the efficacy of nano-fertilizers, their effects on microbial populations and soil health, and their contribution to increased crop quality and yield are all covered in this chapter. The practical use of nano-fertilizers is assessed by critically analyzing economic viability, environmental effects, and regulatory issues. While issues like standardization, safety evaluation, and farmer uptake are addressed, case studies show effective implementations in significant agricultural systems. In order to create economically and ecologically sustainable nano-fertilizer technologies that can support global food security while preserving natural resources, the chapter ends by defining future research goals.

Keywords: Nano-fertilizers, Nutrient use efficiency, Controlled release, Sustainable agriculture, Soil health, Crop productivity, Precision nutrition, Environmental sustainability.

INTRODUCTION

Global agriculture faces the formidable challenge of feeding an estimated 9.7 billion people by 2050, while contending with finite natural resources and increasing environmental pressures. Conventional fertilizer use has been instrumental in achieving yield gains during the Green Revolution; however, it is marked by considerable inefficiencies that compromise both economic returns and environmental sustainability (Savci, 2012). Studies indicate that crops typically absorb only 30–35% of applied nitrogen, 18–20% of phosphorus, and 35–40% of potassium, with the remainder lost through leaching, volatilization, runoff, and soil fixation. These inefficiencies result in substantial economic losses for farmers and intensify environmental problems such as eutrophication, greenhouse gas emissions, soil degradation, and biodiversity loss (Bindraban *et al*., 2015). Similar concerns regarding inefficient nutrient utilization and sustainability have been highlighted in integrated nutrient management studies across various crops (Patel *et al*., 2023; Pattanaik & Priyadarshini, 2023).

The environmental consequences of fertilizer mismanagement have become increasingly alarming. Excess nitrogen application contributes to nitrate contamination of groundwater, posing serious human health risks. Runoff of nitrogen and phosphorus stimulates eutrophication and harmful algal blooms in aquatic ecosystems, resulting in hypoxic "dead

zones" that threaten aquatic biodiversity (Diaz & Rosenberg 2008). Furthermore, nitrous oxide emissions arising from nitrogen fertilizers represent a potent greenhouse gas with nearly 300 times the global warming potential of carbon dioxide, making agriculture a significant contributor to climate change. Phosphorus fertilizer production relies on finite rock phosphate reserves, raising concerns over long-term nutrient security. Additionally, the energy-intensive Haber–Bosch process used for nitrogen fertilizer synthesis consumes approximately 1–2% of global energy production (Erisman *et al.*, 2008).

In response to these challenges, nano-fertilizers represent a transformative advancement in nutrient management, offering innovative solutions to overcome the limitations of conventional fertilizers. Nano-enabled formulations containing nutrients at the nanoscale or delivered through nanocarriers enable improved nutrient use efficiency through controlled release, enhanced bioavailability, and targeted delivery to plant systems (Kah *et al.*, 2018). The fundamental objective of nano-fertilizer technology is to synchronize nutrient availability with crop demand in both temporal and spatial dimensions, thereby reducing losses and improving productivity. The effectiveness of nano-based nutrient delivery systems has been demonstrated in field studies, such as nano zinc oxide priming, which significantly enhanced wheat growth and yield (Ram *et al.*, 2023), and nano urea-based nutrient management strategies that improved vegetative growth and biochemical activity in crops (Choudhary *et al.*, 2023).

The superior performance of nano-fertilizers over conventional formulations is attributed to the unique physicochemical properties of nanomaterials, including their high surface area-to-volume ratio, enhanced reactivity, and ability to penetrate plant tissues more effectively (Liu & Lal 2015). Surface functionalization and nanoencapsulation further protect nutrients from premature loss while enabling stimuli-responsive release under specific soil or environmental conditions such as moisture availability, temperature, or pH. These characteristics align nano-fertilizers with the goals of sustainable intensification—maximizing crop productivity with reduced environmental footprints. Complementary agronomic strategies, including integrated farming systems and optimized nutrient regimes, further support sustainable yield improvements across diverse crops (Pattanaik & Priyadarshini 2023; Patel *et al.*, 2023; Mareguddikar *et al.*, 2023). Recent agri-bio innovations and crop improvement efforts, such as varietal selection, stress-resilient cultivation practices, and precision nutrient management, further reinforce the role of advanced technologies in sustainable agriculture (Lal *et al.*, 2024; Makwana *et al.*, 2023; Pandey *et al.*, 2024; Reddy *et al.*, 2023).

Types and Classification of Nano-fertilizers

Nano-fertilizers are categorized according to their composition, structure, and mechanisms of action. Grasping this classification is crucial for the selection of suitable nano-fertilizer types for particular agricultural applications and target crops. The main categories consist of nanoscale fertilizers, which contain nutrients in nanoparticle form, nanoscale additives or coatings applied to conventional fertilizers, and nutrient-loaded nanomaterials functioning as carriers (Subramanian & Tarafdar 2011).

Nanoscale nutrient fertilizers are composed of nutrients formulated as nanoparticles, generally measuring between 1 and 100 nanometers in size. These consist of metal and metal oxide nanoparticles, including zinc oxide, iron oxide, copper oxide, and manganese dioxide, which deliver micronutrients in highly bioavailable forms. The nanoscale dimensions significantly enhance the surface area accessible for plant uptake relative to bulk materials, and their reduced size promotes entry into plant cells via multiple pathways. Nanoscale formulations of calcium phosphate and hydroxyapatite have been developed for phosphorus delivery, alongside nano-zeolites loaded with ammonium ions for nitrogen supply. Nanoscale nutrient particles demonstrate superior solubility and reactivity relative to traditional forms, resulting in enhanced nutrient availability and increased plant uptake (Marchiol *et al.*, 2020).

Nanoencapsulated fertilizers utilize advanced techniques to encapsulate traditional nutrients within nanoscale carriers or coatings, thereby regulating their release. Polymeric nanocarriers, derived from natural polymers such as chitosan, alginate, and starch, as well as synthetic biodegradable polymers like polylactic acid and poly (lactic-co-glycolic acid), function as protective shells encasing nutrient cores (Rameshaiah *et al.*, 2015). Encapsulation systems safeguard nutrients against rapid dissolution, chemical transformation, or microbial degradation in soil, facilitating their gradual release via mechanisms such as diffusion through the polymer matrix, polymer degradation, or osmotic pressure. Release kinetics can be modified through the adjustment of polymer composition, thickness, cross-linking density, and porosity. Lipid-based nanocarriers, such as liposomes and solid lipid nanoparticles, provide alternative encapsulation systems that are particularly effective for hydrophobic nutrients or bioactive compounds, thereby improving nutrient uptake.

The nanoscale coating of conventional fertilizers entails the application of thin nanolayers onto standard fertilizer granules or prills, resulting in slow-release formulations. Coatings, usually made of polymers, silica, or other nanomaterials with thicknesses ranging from nanometers to micrometers, function as semi-permeable barriers that control water ingress and nutrient dissolution (Kottegoda *et al.*, 2017). In contrast to traditional coated fertilizers featuring micrometer-thick coatings, nanocoatings utilize less material and facilitate effective controlled release, thereby lowering production costs. The coating thickness, composition, and architecture can be optimized to achieve specific release patterns that align with crop nutrient requirements during growing seasons. Multi-layer nanocoatings

that integrate materials with varying properties facilitate intricate release profiles, including an initial rapid release for prompt plant response, succeeded by a prolonged slow release for extended nutritional support.

Nanoporous materials infused with nutrients constitute a significant category. Zeolites, mesoporous silica, carbon nanotubes, and metal-organic frameworks exhibit high surface areas and adjustable pore structures, enabling them to adsorb and store substantial amounts of nutrients (DeRosa *et al*., 2010). These materials function as nutrient reservoirs, gradually releasing adsorbed nutrients via ion exchange or desorption processes. Natural zeolites modified at the nanoscale have been thoroughly investigated as carriers for ammonium, potassium, and phosphate ions, demonstrating extended nutrient release relative to traditional fertilizers. Mesoporous silica nanoparticles featuring ordered pore structures exhibit significant loading capacities for diverse nutrients and facilitate controlled release via pore size modification. Carbon nanotubes, although more expensive, exhibit remarkable nutrient loading capabilities and distinctive interactions with plant tissues that could improve nutrient uptake.

Nutrient-enriched nanocomposites integrate various nanomaterials with complementary characteristics to produce synergistic effects. The combination of biochar nanoparticles with nutrient-loaded polymers results in formulations that enhance soil structure and water retention, while facilitating controlled nutrient release (Ghorbani *et al*., 2022). Nanocomposites that integrate both macro and micronutrients facilitate balanced nutrition via single applications, thereby decreasing labor and application expenses. Clay-polymer nanocomposites utilize the cation exchange capacity of nanoclays to enhance nutrient retention, in conjunction with polymer-mediated controlled release mechanisms. The creation of multifunctional nano-fertilizers that integrate nutritional advantages with pest management, enhancement of plant growth, or resilience to stress signifies a novel area in the design of nanocomposites.

Mechanisms of Enhanced Nutrient Use Efficiency

The enhanced efficacy of nano-fertilizers relative to conventional fertilizers arises from various mechanisms functioning at multiple levels, including soil interactions, cellular absorption, and metabolic impacts. Comprehending these mechanisms is essential for enhancing the design and application strategies of nano-fertilizers to maximize advantages while maintaining safety and sustainability.

The primary mechanism by which nano-fertilizers enhance nutrient use efficiency is through controlled and sustained nutrient release. In contrast to traditional fertilizers that quickly release nutrients upon exposure to soil moisture, frequently surpassing the immediate needs of plants, nano-fertilizers offer a gradual release that corresponds with crop demand over longer durations (Chhipa, 2017). The controlled release is facilitated by different mechanisms, which are contingent upon the design of the nano-fertilizer. Nutrients in nanoencapsulated systems diffuse through the encapsulating material at rates influenced by concentration gradients, material properties, and environmental conditions. Biodegradable polymer carriers facilitate nutrient release through the degradation of the matrix by microbial enzymes or hydrolysis reactions. Stimuli-responsive nanocarriers react to specific environmental triggers, including soil pH changes, temperature variations, or moisture levels, facilitating the release of nutrients when conditions suggest active plant growth and uptake capacity. This synchronization of supply and demand reduces nutrient losses and ensures sufficient availability during essential growth phases.

The nanoscale dimensions of nano-fertilizers significantly increase the surface area available for interaction with soil, soil solution, and plant roots. A nanoscale particle with a diameter of 10 nm contains roughly 60% of its atoms on the surface, in contrast to less than 1% for a 1 mm particle of the same material (Naderi & Danesh-Shahraki 2013). The augmented surface area improves dissolution kinetics, reactivity, and accessibility for plant absorption. Nanoscale particles of sparingly soluble nutrients, such as phosphorus, exhibit enhanced dissolution rates and completeness compared to traditional sources, thereby increasing bioavailability. The elevated surface area enhances adsorption sites for nutrient retention in soil, thereby decreasing leaching losses while ensuring accessibility for plant uptake via ion exchange.

Nano-fertilizers exhibit superior mobility and penetration into plant tissues relative to conventional fertilizers. Plants primarily absorb nutrients through their roots; however, they can also take in nutrients via stomatal openings, hydathodes, and cuticular pores in leaves when foliar sprays are applied. The diminutive dimensions of nanoparticles enhance their ability to traverse these pathways, as particles smaller than the pore diameters in plant cell walls penetrate tissues more efficiently (Schwab *et al*., 2016). Upon entering plants, nanoparticles can move through apoplastic or symplastic pathways, traveling from roots to shoots via xylem transport or between cells through plasmodesmata. This improved mobility facilitates a more efficient distribution of nutrients within plant tissues, thereby decreasing the amount of fertilizer necessary for sufficient nutrition. Foliar-applied nano-fertilizers demonstrate superior penetration of leaf surfaces compared to traditional sprays, facilitating prompt rectification of deficiencies and reducing the need for soil application.

The mitigation of environmental losses is a significant benefit of nano-fertilizers. Nitrogen fertilizers used in conventional applications experience significant losses due to ammonia volatilization from urea hydrolysis, denitrification that converts nitrate to gaseous nitrogen, and nitrate leaching beyond root zones. Nanoencapsulation safeguards nitrogen sources from swift hydrolysis and oxidation, facilitating their gradual release as plants assimilate them, thus minimizing gaseous and leaching losses (Manjunatha *et al*., 2016). Phosphorus applied through

conventional fertilizers quickly precipitates with calcium, iron, or aluminum in the soil, resulting in the formation of insoluble compounds that are not accessible to plants. Nano-fertilizers enhance the bioavailability of phosphorus by utilizing controlled release or chelation mechanisms, thereby increasing phosphorus use efficiency. Potassium does not undergo chemical transformation but leaches easily in sandy soils; slow-release nano-formulations mitigate leaching while ensuring sufficient supply.

Nano-fertilizers can alter the soil environment and rhizosphere to improve nutrient availability and uptake. Some nanomaterials affect soil pH, redox potential, and microbial communities, enhancing nutrient solubility and plant accessibility (Rizwan *et al*., 2017). Nano-fertilizers that release nutrients gradually may sustain more stable pH conditions than conventional fertilizers, which can induce temporary acidification or alkalinization. Nano-fertilizers can enhance beneficial rhizosphere microorganisms, such as nitrogen-fixing bacteria and phosphate-solubilizing microbes, leading to synergistic effects that improve nutrient availability. The interactions between nano-fertilizers and soil organic matter can form stable complexes that function as slow-release nutrient reservoirs.

At the cellular and molecular levels, nano-fertilizers affect plant metabolism and gene expression, thereby improving nutrient utilization efficiency. Nanoparticles can enhance the expression of genes related to nutrient transporters, assimilation enzymes, and metabolic pathways (Seleiman *et al*., 2020). Iron oxide nanoparticles enhance the expression of genes related to iron acquisition, thereby improving the efficiency of iron uptake and utilization. Nano-fertilizers may influence plant hormone signaling, thereby affecting the development of root architecture and enhancing nutrient acquisition. Certain nanoparticles can generate reactive oxygen species at controlled levels, which can initiate signaling cascades that activate stress response and nutrient uptake mechanisms. The molecular effects, along with direct nutritional benefits, result in enhanced nutrient use efficiency through multiplicative improvements.

Nitrogen Nano-fertilizers

Nitrogen is the essential nutrient for crop production, necessary in substantial amounts for protein synthesis, chlorophyll formation, and various metabolic processes. Nitrogen fertilizers demonstrate the lowest use efficiency among primary nutrients, with losses occurring via ammonia volatilization, denitrification, and nitrate leaching, resulting in both economic and environmental challenges. Nitrogen nano-fertilizers mitigate these challenges by employing controlled release formulations that align nitrogen supply with crop demand, thereby reducing losses.

Urea-based nano-fertilizers constitute the most extensively researched category of nitrogen nano-fertilizers, attributable to urea's global prevalence as a nitrogen source. Conventional urea quickly dissolves in soil, undergoing hydrolysis to ammonium via urease enzyme activity, with a significant portion of the resulting ammonia volatilizing into the atmosphere prior to plant uptake. The nanoencapsulation of urea in polymer matrices, silica shells, or alternative protective coatings reduces dissolution and hydrolysis rates, facilitating a gradual release of nitrogen over periods ranging from weeks to months (Pereira *et al*., 2017). Multiple polymers such as chitosan, starch, polyurethane, and synthetic biodegradable polymers have been utilized as encapsulating agents, with release rates modifiable via polymer selection, coating thickness, and degree of cross-linking. Field studies indicate that nano-urea formulations decrease nitrogen losses by 30-50% relative to conventional urea, while sustaining or enhancing crop yields, thereby enabling a reduction in application rates by 20-40%.

Nano-zeolite-based nitrogen fertilizers employ the ion exchange characteristics of nanoscale-modified zeolites to adsorb and gradually release ammonium ions. Natural zeolites exhibit microporous structures and high cation exchange capacity; however, their large particle sizes restrict their effectiveness. The processing of zeolites to nano-dimensions significantly enhances surface area and exchange kinetics, while preserving structural integrity (Ramesh *et al*., 2011). Ammonium-loaded nano-zeolites release nitrogen via gradual ion exchange with other soil cations, ensuring sustained availability. These formulations demonstrate significant potential in sandy soils susceptible to leaching, as they mitigate nitrogen losses and enhance moisture retention due to the water-holding capacity of zeolite. The integration of nano-zeolites with traditional urea results in synergistic effects, wherein zeolites absorb ammonium produced from urea hydrolysis and subsequently release it in a gradual manner.

Controlled-release nitrogen formulations utilizing layered double hydroxide (LDH) nanoparticles present a novel methodology. Layered double hydroxides (LDHs) comprise positively charged metal hydroxide layers interspersed with anions that can be substituted with nitrate ions, thereby establishing a reservoir for the gradual release of nitrates (Hussein *et al*., 2013). When applied to soil, LDH-nitrate progressively releases nitrate via anion exchange with soil solution anions, aligning release rates with crop uptake. The kinetics of release can be influenced by modifying the composition of LDH, the size of the particles, and the conditions of calcination. LDH nano-fertilizers exhibit reduced nitrate leaching relative to traditional nitrogen sources, while ensuring sufficient availability for plants.

Chitosan-based nitrogen nano-fertilizers provide the benefits of regulated nutrient release and biostimulant properties. Chitosan, a natural polysaccharide obtained from crustacean shells, creates nanoparticles or coatings that encapsulate nitrogen sources and exhibit intrinsic plant growth-promoting and disease-resistance characteristics (Corradini *et al*., 2010). Chitosan's biodegradability guarantees environmental compatibility, as its degradation products act as carbon sources for soil microorganisms. Research indicates that chitosan-urea nanoformulations

enhance nitrogen use efficiency by 25-35% relative to conventional urea, while also promoting crop biomass and stress tolerance due to the biostimulant properties of chitosan.

Nitrification inhibitors and urease inhibitors integrated into nano-formulations constitute an additional approach to enhance nitrogen use efficiency. These compounds inhibit the conversion of ammonium to nitrate or urea to ammonium, thereby minimizing losses and preserving nitrogen availability. Nanoencapsulation safeguards these inhibitors from degradation and facilitates their co-release with nitrogen sources, thereby enhancing their efficacy (Timilsena *et al.*, 2015). The integration of inhibitors with slow-release nanocarriers establishes comprehensive nitrogen management systems that simultaneously target multiple loss pathways.

Phosphorus and Potassium Nano-fertilizers

Phosphorus is the second most limiting macronutrient in crop production, playing a critical role in energy transfer, nucleic acid synthesis, and various metabolic processes. Phosphorus fertilizers are widely used; however, phosphorus use efficiency is notably low, ranging from 10-25%. This inefficiency is primarily due to the rapid precipitation of applied phosphorus with soil cations, resulting in the formation of insoluble compounds that are not accessible to plants (Shen *et al.*, 2011). This inefficiency diminishes finite rock phosphate reserves and contributes to water pollution via runoff. Phosphorus nano-fertilizers improve phosphorus availability and utilization efficiency via various methods, including nanoscale particle formulations, controlled-release systems, and chelation strategies.

Nanoscale calcium phosphate and hydroxyapatite serve as direct sources of phosphorus, exhibiting improved bioavailability. The synthesis of these compounds at the nanoscale enhances solubility and plant accessibility in comparison to traditional rock phosphate (Kottegoda *et al.*, 2011). The elevated surface area of nanoparticles enhances dissolution kinetics, and their diminutive size may promote direct absorption by plant roots. Research indicates that nano-hydroxyapatite delivers phosphorus more effectively than traditional superphosphate, allowing for a 20-30% reduction in application rates while achieving comparable plant uptake and yields. The gradual dissolution of nanoscale phosphate minerals ensures continuous phosphorus availability during growing seasons, thereby minimizing fixation losses.

Struvite (magnesium ammonium phosphate) nanoparticles serve as an environmentally sustainable source of phosphorus, synthesized through wastewater treatment processes. Nano-struvite offers phosphorus and nitrogen in controlled-release formats, allowing for gradual nutrient dissolution over prolonged durations (Talboys *et al.*, 2016). The utilization of recovered nutrients from waste streams for the production of nano-fertilizers aligns with circular economy principles and addresses the issue of phosphorus scarcity. Field trials indicate that nano-struvite performs comparably or superior to conventional phosphorus fertilizers at reduced application rates, resulting in diminished environmental impacts.

Phosphorus-loaded nanocarriers employing diverse nanomaterials for the transport of phosphate ions offer adaptable solutions for varying soil conditions and crop types. Mesoporous silica nanoparticles characterized by a high surface area and adjustable pore structures exhibit the capacity to adsorb significant amounts of phosphate, which are subsequently released in a controlled manner via desorption (Montalvo *et al.*, 2015). Polymer nanoparticles that encapsulate soluble phosphorus sources prevent the precipitation of phosphate and facilitate controlled release via polymer degradation or diffusion. Phosphorus-containing group modifications of carbon nanotubes and graphene oxide nanosheets yield innovative nanocarriers exhibiting distinct release properties.

Potassium does not undergo chemical transformation in soil as nitrogen and phosphorus do; however, it is susceptible to leaching losses, especially in coarse-textured soils with low cation exchange capacity. Potassium nano-fertilizers utilize slow-release mechanisms to minimize leaching and ensure sufficient availability for plants. Nano-zeolites that are loaded with potassium ions via cation exchange facilitate sustained release as potassium in the soil solution is diminished by plant uptake (Yuvaraj & Subramanian 2018). Exchange kinetics can be altered through modifications in zeolite type, particle size, and pretreatment conditions. Potassium fertilizers with polymer coatings of nano-thickness effectively regulate dissolution rates, thereby prolonging nutrient availability throughout growing seasons.

Combined NPK nano-fertilizers that integrate nitrogen, phosphorus, and potassium into single formulations facilitate application and ensure balanced nutrition. Multinutrient nanoformulations can be engineered with varying release kinetics for each nutrient, considering their unique uptake patterns and soil interactions (Duhan *et al.*, 2017). Nitrogen may be designed for rapid initial release to enhance vegetative growth, whereas phosphorus is released more gradually over the season. Integrated nano-fertilizers decrease labor and application expenses while enhancing nutrient balance.

Micronutrient Nano-fertilizers

Micronutrient deficiencies impact billions globally by influencing the nutritional quality of crops, a phenomenon referred to as "hidden hunger". Micronutrient deficiencies concurrently restrict crop productivity across numerous agricultural systems, especially concerning zinc, iron, manganese, copper, and boron. Conventional micronutrient fertilizers exhibit low efficiency owing to soil fixation, and excessive application may lead to toxicity. Nano-fertilizers

provide targeted micronutrient application at optimal levels, enhancing agronomic efficiency and crop biofortification for human nutrition (Dimkpa & Bindraban 2018).

Zinc oxide nanoparticles are the most researched micronutrient nano-fertilizer, targeting the prevalent zinc deficiency that impacts approximately one-third of cultivated soils worldwide. Nano-ZnO demonstrates superior solubility and bioavailability relative to bulk ZnO or zinc sulfate, facilitating effective deficiency correction at reduced application rates. Research on various crops, such as cereals, legumes, and vegetables, indicates that the application of nano-ZnO, either foliarly or through soil, at concentrations ranging from 25 to 100 ppm enhances plant growth, photosynthetic efficiency, enzyme activities, and zinc content in grains (Tarafdar *et al*., 2014). The mechanisms include increased zinc absorption and the influence of nano-ZnO on plant metabolism, which encompasses enhanced antioxidant systems and improved stress tolerance. Biofortification of staple crops with zinc via nano-fertilizers mitigates human zinc deficiency and enhances crop productivity.

Iron oxide nanoparticles serve as an effective means of iron supplementation, especially for crops cultivated in calcareous or alkaline soils, where traditional iron fertilizers quickly precipitate as unavailable ferric hydroxides. Nano-Fe_2O_3 and nano-Fe_3O_4 keep iron in forms that are readily available, thereby enhancing its uptake through plant iron acquisition mechanisms (Rui *et al*., 2016). The foliar application of iron nanoparticles effectively alleviates chlorosis symptoms, thereby restoring photosynthetic capacity and promoting growth. Research indicates that nano-iron formulations enhance iron use efficiency by 40-60% relative to traditional iron chelates, concurrently decreasing the frequency of application. The integration of nano-iron with organic acids or polymers improves stability and enhances plant availability.

Copper-based nano-fertilizers mitigate copper deficiency and provide antimicrobial properties that inhibit plant diseases. Copper oxide and metallic copper nanoparticles deliver copper nutrition at concentrations generally 10-20 times lower than those of conventional copper sulfate (Peng *et al*., 2015). Copper nano-fertilizers are particularly valuable in crops susceptible to bacterial and fungal diseases due to their dual functionality in micronutrient supply and pathogen control. Careful dosage control is crucial, as copper has narrow margins between deficiency and toxicity. Nanoformulations facilitate accurate delivery of copper within optimal parameters.

Manganese dioxide nanoparticles improve manganese availability in crops, significantly enhancing photosynthetic efficiency due to manganese's essential role in oxygen evolution during photosynthesis. Research demonstrates that nano-MnO_2 enhances chlorophyll content, photosynthetic rates, and antioxidant enzyme activities at application rates considerably lower than those of conventional manganese sulfate (Adhikari *et al*., 2016). The enhanced bioavailability of nano-manganese decreases the amounts needed for deficiency correction, thereby reducing costs and potential toxicity risks.

Boron nano-fertilizers mitigate boron deficiency, which impacts cell wall formation, membrane functionality, and reproductive development in plants. Due to boron's limited range between deficiency and toxicity, accurate delivery via nano-formulations presents considerable benefits. Boron-loaded nanocarriers facilitate a gradual release of boron, ensuring optimal tissue concentrations are maintained while avoiding toxic levels (Duhan *et al*., 2017). Boron nano-fertilizers demonstrate significant potential in crops that have elevated boron needs, including fruit trees, oilseeds, and vegetables.

Table 1: Summary of Key References Related to Nanofertilizers and Sustainable Agriculture.

Sr. No.	Author(s) & Year	Title	Source / Journal / Book
1	Adhikari *et al*. (2016)	Effect of copper oxide and manganese dioxide nanoparticles on seed germination of selected crops	*Journal of Agricultural Science and Technology*, 18(2), 457–465
2	Bindraban *et al*. (2015)	Revisiting fertilisers and fertilisation strategies for improved nutrient uptake by plants	*Biology and Fertility of Soils*, *51*(8), 897–911
3	Chen & Yada (2011)	Nanotechnologies in agriculture: New tools for sustainable development	*Trends in Food Science & Technology*, *22*(11), 585–594
4	Chhipa (2017)	Nanofertilizers and nanopesticides for agriculture	*Environmental Chemistry Letters*, *15*(1), 15–22
5	Corradini *et al*. (2010)	A preliminary study of the incorporation of urea into chitosan nanoparticles	*Express Polymer Letters*, 4(8), 509–515
6	DeRosa *et al*. (2010)	Nanotechnology in fertilizers	*Nature Nanotechnology*, 5(2), 91
7	Diaz & Rosenberg (2008)	Spreading dead zones and consequences for marine ecosystems	*Science*, *321*(5891), 926–929
8	Dimkpa & Bindraban (2018)	Nanofertilizers: New products for the industry?	*Journal of Agricultural and Food Chemistry*, *66*(26), 6462–6473
9	Duhan *et al*. (2017)	Nanotechnology: The new perspective in precision agriculture	*Biotechnology Reports*, *15*, 11–23
10	Erisman *et al*. (2008)	How a century of ammonia synthesis changed the world	*Nature Geoscience*, *1*(10), 636–639

Nanotechnology Applications for Agriculture

Multi-micronutrient nano-formulations that incorporate zinc, iron, manganese, copper, and boron effectively target various deficiencies with a single application. These formulations can be customized to address specific soil deficiency profiles or crop needs, thereby optimizing micronutrient balance. The nano-format facilitates the compatibility of micronutrients that may exhibit antagonistic interactions in traditional formulations, as controlled release and targeted delivery reduce interference. Comprehensive micronutrient nano-fertilizers facilitate management and ensure thorough micronutrient nutrition.

Environmental and Economic Sustainability

The broad use of nano-fertilizers depends on their environmental sustainability, which necessitates a thorough analysis of their ecological effects in comparison to traditional fertilizers. Although enhanced nutrient usage efficiency in nano-fertilizers promises to minimize environmental pollution, the dangers of releasing nanoparticles into ecosystems must be carefully considered (Kah *et al*., 2018).

When taking into account the whole production to disposal chain, life cycle assessment studies that compare nano-fertilizers with traditional fertilizers show significant environmental advantages. Reduced nutrient losses to air and water bodies are the main environmental benefits. When compared to standard urea, nitrogen nano-fertilizers significantly reduce greenhouse gas contributions by lowering ammonia volatilization by 30–50% and nitrous oxide emissions by 20–40% (Chen & Yada 2011). By reducing runoff and leaching, phosphorus nanofertilizers lower the danger of eutrophication in aquatic environments. Energy usage in fertilizer production, transportation, and application processes may be decreased by 20–50% while preserving yields proportionately. Global fertilizer usage might be cut by 15–30% if nano-fertilizers are widely used, according to studies. This would result in considerable reductions in resource consumption and carbon footprints.

However, great thought must be given to the nanoparticles own environmental safety. At high quantities, metallic and metal oxide nanoparticles may be hazardous to earthworms, soil microbes, and other useful creatures. Depending on the kind of nanoparticle, concentration, exposure time, and characteristics of the soil, studies reveal varying effects. At application-relevant dosages, some nanoparticles have negligible effects, while others disrupt the microbial communities in the soil (Ge *et al*., 2011). The durability and biological impacts of nanoparticles are influenced by their destiny and transformation in agricultural settings. In soil, a lot of nanoparticles aggregate, dissolve, or change chemically, which might alter their toxicity and bioavailability. For instance, in soil, silver nanoparticles sulfidate, lowering antibacterial action and possible ecological hazards.

For sustainable applications, the creation of ecologically safe and biodegradable nanofertilizers is a top goal. By breaking down into non-toxic components, polymer-based nanocarriers made from natural materials like chitosan, starch, and alginate reduce their environmental persistence (Kashyap *et al*., 2015). Green synthesis techniques provide environmentally acceptable substitutes for chemical synthesis approaches by producing metal nanoparticles using plant extracts or microorganisms. Environmental safety and agricultural advantages are maintained by designing nano-fertilizers that break down or change into benign forms after fulfilling their nutritional purposes.

A key factor in determining whether nano-fertilizers can be widely adopted by farmers is their economic viability. Despite their superior effectiveness, many nano-fertilizers are now more expensive to produce than traditional fertilizers, which hinders their widespread use. Simple nanoparticle formulations may be cost-competitive, but complex nanoencapsulated systems continue to be costly, with prices varying greatly based on synthesis techniques, materials, and manufacturing scale (Solanki *et al*., 2015). However, rather of focusing just on input costs, economic analysis must take into account the overall expenses of the system. Nano-fertilizers often exhibit beneficial economics when taking into account decreased application volumes, decreased application frequency, increased yields, higher crop quality, and avoided environmental cleanup costs. Research shows that by improving crop yields by 10–30%, nano-fertilizer systems may increase net profits while lowering overall fertilizer expenditures by 15–40%. Technological advancements in manufacturing techniques are necessary to scale up the production of nano-fertilizers to fulfill the demand for agricultural products worldwide while preserving consistency in quality and price. Spray drying, sol-gel, and continuous flow synthesis all have promise for low-cost, large-scale manufacturing (Ghormade *et al*., 2011). Through research funding, subsidies, and advantageous laws, government policies that assist the development, use, and research of nano-fertilizers may hasten commercialization and increase farmer affordability. Working together, public research organizations, private businesses, and agricultural communities may ensure sustainable adoption while distributing costs and rewards fairly.

CHALLENGES AND FUTURE PERSPECTIVES

Notwithstanding their encouraging promise, there are a number of obstacles that need to be overcome before nano-fertilizers may be widely used in agriculture. Standardizing synthesis procedures to guarantee uniform nanoparticle characteristics, establishing formulations that are stable in a range of storage and environmental circumstances, and developing commercially feasible manufacturing methods that are scalable to agricultural levels are some of the technical difficulties. Because synthesis techniques, particle characterisation, and quality control are not standardized, the quality and performance of current nano-fertilizer products vary greatly (Fraceto *et al*., 2016). Reliability and

farmer trust will be increased by establishing industry standards for nano-fertilizer specs, testing procedures, and labeling regulations.

Extensive study is required to fill up the information gaps about the behavior of nano-fertilizers in intricate agricultural systems. To completely assess nano-fertilizer effectiveness, environmental destiny, and ecological consequences across many growth cycles, long-term field research spanning a variety of soil types, climatic conditions, and cropping systems are required. In order to provide farmers with evidence-based suggestions, research should examine the best times, rates, and techniques for applying various forms of nanofertilizer to crops (Singh *et al.*, 2017). For sustained soil health, it is essential to comprehend how soil microbiomes and nano-fertilizers interact, particularly how these interactions affect beneficial organisms and nutrient cycle mechanisms. Safety rules and customer acceptability will be influenced by research on the impact of nanofertilizers on food safety, particularly the buildup of nanoparticles in edible plant parts and possible health consequences.

Most nations' regulatory systems for nanofertilizers are still in their infancy, which leaves consumers and producers in the dark. In order to promote innovation, comprehensive but reasonable laws should include nano-fertilizer registration, safety testing specifications, labeling standards, and use instructions (Parisi *et al.*, 2015). Global safety standards will be guaranteed and commerce will be facilitated by the harmonization of regulatory systems. Regulatory decisions will be guided by risk assessment frameworks created especially for agricultural nanomaterials, taking into account their special characteristics and exposure paths.

Adoption of nano-fertilizers by farmers is contingent upon observable advantages, cost-effectiveness, user-friendliness, and technological confidence. Farmers' understanding and confidence may be increased via extension services and demonstration programs that highlight the advantages of nano-fertilizer under actual agricultural circumstances (Sekhon, 2014). Adoption will be aided by training programs that teach farmers, agricultural advisers, and agribusiness experts about the safe handling, application, and management of nano-fertilizer. Implementation obstacles are reduced by creating application tools and protocols that work with current farming methods. Adoption may be accelerated by financial incentives like subsidies or higher pricing for crops produced using sustainable nano-fertilizer systems.

The creation of next-generation nanofertilizers with sophisticated features should be the main goal of future research. The ultimate objective of precision nutrition is represented by smart or intelligent nano-fertilizers that detect and react to the nutritional state of plants, releasing nutrients only when plant signals indicate need (Liu & Lal 2015). Comprehensive crop management solutions are provided by multifunctional nano-fertilizers that combine nutrition with growth promotion, insect control, or improved stress tolerance. Performance will be maximized by precision agricultural technologies that provide customized nano-fertilizers suited to certain soil types, crop types, and farming methods. Data-driven nutrient management will be made possible by the integration of nano-fertilizers with sensors, digital farming platforms, and decision support systems.

CONCLUSIONS

A game-changing technology, nano-fertilizers have the ability to completely change agricultural nutrient management and meet the dual demands of boosting food production and minimizing environmental effects. When compared to conventional fertilizers, nano-fertilizers greatly increase nutrient use efficiency through controlled release mechanisms, enhanced bioavailability, and decreased nutrient losses. This allows farmers to achieve comparable or superior yields with 20–50% lower fertilizer application rates. While lower input prices and increased agricultural output and quality result in economic gains, increased efficiency also directly helps the environment by reducing greenhouse gas emissions, water pollution, and the depletion of precious nutrient supplies.

Customization for particular nutrients, crops, and agro-ecological circumstances is made possible by the adaptability of nano-fertilizer technologies, which include a variety of materials, formulations, and delivery methods. The variety of methods, which include smart responsive nanocarriers, nanoscale nutrient particles, and nanoencapsulated formulations, offers versatility in addressing a range of agricultural concerns. Effective use in multinutrient, micronutrient, and macronutrient systems.

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