Impact Factor (QJIF): 5.82 E-ISSN: 3049-1487, P-ISSN: 3049-4095

Received: 05/March/2026 **IJARE:** 2026; 3(1):23-41 **Accepted:** 02/May/2026

Nanofertilizers in Sustainable Agriculture: Application, Mechanism and Challenges

[1]Kartik Mehra, [*2]Dipti Grover, [3]Shivani Garg, [4]Pooja Arora and [5]Bhawna Dahiya

[1]Student, Institute of Environmental Studies, Kurukshetra University, Kurukshetra, Haryana, India.

[*2, 3, 4, 5]Assistant Professor, Institute of Environmental Studies, Kurukshetra University, Kurukshetra, Haryana, India.

Abstract

Global agriculture faces unprecedented challenges in achieving sustainability while meeting the growing demand for food. Conventional fertilizers, despite their role in agricultural intensification, contribute significantly to environmental degradation through nutrient losses, greenhouse gas emissions, and ecosystem contamination. Nanofertilizers have represented a paradigm shift, offering a promising alternative through improved nutrient delivery, reduced nutrient losses, and enhanced bioavailability. This review examines cutting-edge application techniques and fundamental mechanisms of diverse nanofertilizer platforms, including smart nanocarriers, stimuli-responsive systems, and biohybrid formulations. Despite their potential, several challenges impede widespread adoption, including phytotoxicity, bioaccumulation in aquatic and plant systems, human health risks associated with nanoparticle exposure, regulatory uncertainties, production costs, and scale issues. Nanoparticle behavior in soil-plant systems, environmental fate, and long-term ecological consequences represent significant research gaps. Future research should prioritize the development of efficient regulatory frameworks, precise nanofertilizer formulations, sustainable production practices, and comprehensive evaluations of nanoparticle toxicity. Integration of nanosensors with precision agriculture techniques enables real-time monitoring of nanofertilizer performance and efficient resource utilization. Successful deployment requires coordinated efforts in stakeholder education, farmer training, and the establishment of standardized safety protocols.

Keywords: Nanofertilizers, Nutrient Use Efficiency, Sustainable Agriculture, Bioavailability, Smart Delivery Systems, Precision Agriculture.

1. Introduction

Rapid population growth continues to increase global food demand, placing greater pressure on agricultural systems. Although conventional fertilizers have substantially improved crop productivity, their low nutrient use efficiency (NUE) contributes to soil degradation, water pollution, greenhouse gas emissions, and economic losses through leaching, volatilization, runoff, and microbial immobilization (Zahra *et al*. 2022; Shang *et al*. 2019). Nanofertilizers overcome many of these limitations by improving nutrient penetration, absorption, and bioavailability through their nanoscale size and large surface area, making them a promising strategy for sustainable agriculture under changing climatic conditions (Deepika *et al*. 2020; Khatri *et al*. 2023).

Nanofertilizers consist of nanoscale materials (1–100 nm) designed to deliver nutrients in a controlled and targeted manner, thereby enhancing NUE while minimizing environmental impacts (Seleiman *et al*. 2020; Ameen *et al*. 2018). Nanocarriers such as nanoclays, carbon-based materials, and polymeric nanoparticles provide gradual nutrient release, reduce nutrient losses, and improve uptake through greater soil interaction and foliar absorption (Ibáñez *et al*. 2023; Kumar *et al*. 2021). Figure 1 summarizes the major applications, benefits, and challenges of nanofertilizers.

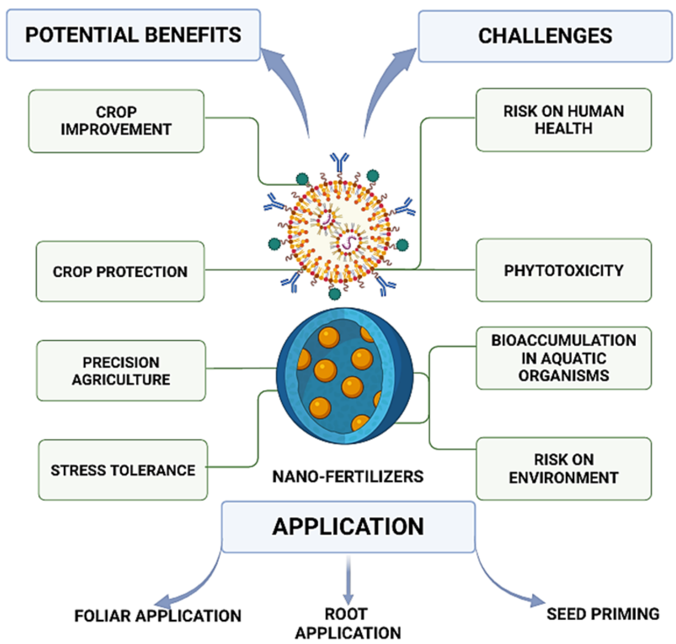

Fig 1: Potential benefits, challenges, and applications of nanofertilizers

***Corresponding Author:** Dipti Grover

Growing interest in nanofertilizers is driven by their potential to enhance nutrient delivery, reduce fertilizer inputs, and lower environmental impacts (Meena *et al.* 2021). However, issues including phytotoxicity, regulatory uncertainty, production costs, and large-scale commercialization remain significant barriers to widespread adoption (Zalewska *et al.* 2021). Improved understanding of nanoparticle behavior in soil–plant systems is essential for developing safe and effective agricultural applications (Ahamed *et al.* 2024).

This review critically examines the applications, mechanisms, and challenges of nanofertilizers in sustainable agriculture. It discusses their role in nutrient delivery, interactions with soil–plant systems, associated environmental and health concerns, and future research priorities to support the development of safe and efficient nanotechnology-based agricultural practices.

The evolution of fertilizer technology can be divided into four major stages. Early agriculture relied on organic amendments such as animal manure and crop residues to maintain soil fertility. The chemical revolution introduced synthetic fertilizers, enabling large-scale agricultural intensification. During the Green Revolution, intensive fertilizer use substantially increased food production but also accelerated nutrient losses, eutrophication, greenhouse gas emissions, and soil degradation. Since the early 2000s, growing awareness of these environmental impacts has driven the development of controlled-release fertilizers, organic alternatives, and nanotechnology-based nutrient delivery systems, leading to the emergence of modern nanofertilizers (Liu & Lal, 2015). Figure 2 illustrates the historical evolution of fertilizer development.

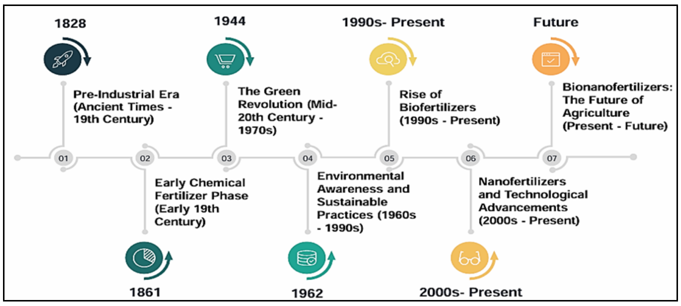

Fig 2: Historical timeline of fertilizer development and key milestones

2. Research Trends

Research trends in nanofertilizers and sustainable agriculture were analyzed using VOSviewer to evaluate publication patterns and keyword density. The resulting density plot (Figure 3) illustrates the evolving research landscape by identifying major thematic areas and emerging topics. The keyword density map shows that highly connected terms such as nanoparticles, nanotechnology, and sustainable agriculture dominate the field, reflecting their central role in current research. Frequently associated keywords, including fertilizer, micronutrients, yield, biofertilizers, and iron, indicate a strong emphasis on improving nutrient delivery and crop productivity using nanomaterials such as zinc oxide and copper oxide nanoparticles. The occurrence of crop-specific terms such as maize, soybean, and rice further highlights the focus on staple crops for evaluating nanofertilizer performance. Emerging themes include oxidative stress, toxicity, bioaccumulation, and heavy metals, demonstrating increasing attention to the environmental and biological safety of nanomaterials. Keywords such as nanocarriers, nanosensors, graphene oxide, and carbon nanotubes reflect growing interest in smart delivery systems and precision agriculture. Overall, the analysis indicates that nanofertilizer research is evolving from improving nutrient-use efficiency toward developing safe, sustainable, and precision-based agricultural technologies.

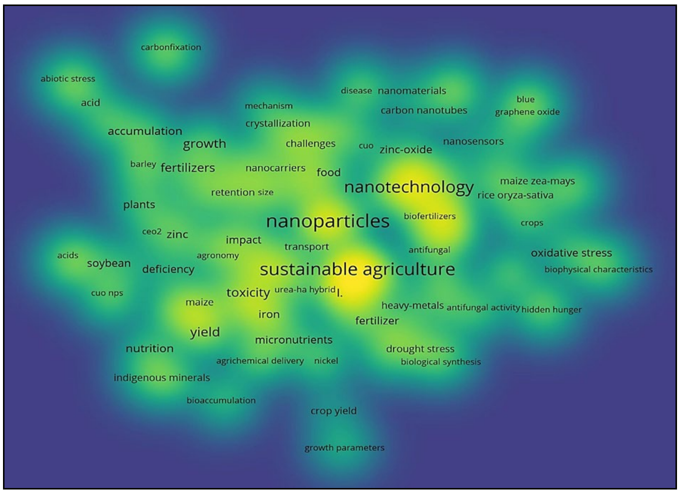

Fig 3: Density plot of keywords in nanofertilizer research generated via VOSviewer

3. Types of Nanofertilizers

Nanofertilizers are classified according to their composition and function into macronutrient-based, micronutrient-based, polymer-based, trace element-based, and nanocarrier-assisted formulations. These formulations are designed to improve nutrient delivery, minimize nutrient losses, and enhance crop productivity under diverse agroecological conditions (Figure 4).

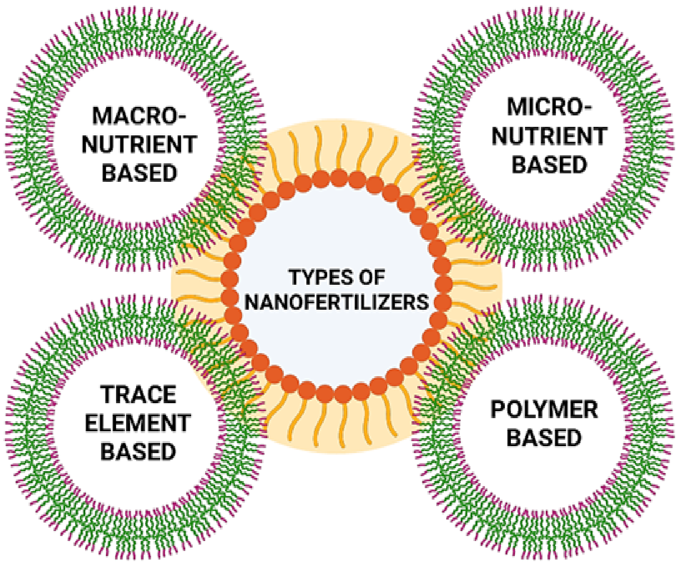

Fig 4: Types of Nanofertilizers depicting a) Macronutrient-Based, b) Micronutrient-Based, c) Trace Element-Based, d) Polymer-Based formulations.

i). **Macronutrient-Based Nano-fertilizers:** Macronutrient nanofertilizers primarily supply nitrogen (N), phosphorus (P), and potassium (K) using nanocarriers that improve nutrient retention and controlled release. Nitrogen nanoformulations based on hydroxyapatite, zeolites, and chitosan reduce nitrogen losses while enhancing plant uptake (Gade *et al.* 2023; Preetha *et al.* 2017). Recent nano-urea formulations have reduced fertilizer application by up to 80% without compromising crop yield. Similarly, smart phosphorus nanofertilizers provide pH-responsive nutrient release to overcome phosphorus fixation in alkaline soils, whereas potassium nano-chelates improve bioavailability and reduce leaching losses (Ramírez-Rodríguez *et al*. 2020; Zahedifar *et al*. 2019).

ii). Micronutrient-Based Nanofertilizers: Micronutrient nanofertilizers supply essential elements such as Fe, Zn, Mn, Cu, B, Mo, and Cl in highly bioavailable forms. Iron oxide nanoparticles enhance chlorophyll synthesis, photosynthesis, and plant growth while reducing fertilizer requirements (Feng *et al*. 2022). Manganese nanoparticles improve metabolic activities, antioxidant defense, and stress tolerance with lower phytotoxicity than conventional sources (Alejandro *et al*. 2020; Ye *et al*. 2019). Zinc oxide nanoparticles are among the most extensively studied nanofertilizers, enhancing seed germination, root development, nutrient uptake, and stress tolerance at appropriate concentrations, although excessive doses may induce phytotoxicity (Adil *et al*. 2022; El-Saadony *et al*. 2021). Other micronutrients, including molybdenum, copper, and boron, also contribute to nitrogen fixation, respiration, enzyme activation, membrane stability, and cell division.

iii). Polymers-Based Nanofertilizers: Polymeric nanocarriers, including chitosan, alginate, and albumin, provide controlled nutrient release and targeted delivery. Chitosan enhances seed germination, nutrient uptake, photosynthesis, crop yield, and disease resistance, while chitosan-based nanoparticles have improved growth in wheat, maize, and tomato (Deshpande *et al*. 2017; Saharan *et al*. 2013; Mahanta *et al*. 2019). Alginate-based nanofertilizers extend nutrient release for 40–50 days, substantially improving nutrient-use efficiency (Seleiman *et al*. 2020). Albumin nanoparticles offer excellent biocompatibility, biodegradability, and surface functionalization, with recent formulations incorporating pH- and enzyme-responsive nutrient release. However, further research is required to improve sustainable production and assess long-term environmental safety (Karimi *et al*. 2016; Meng *et al*. 2022).

iv). Trace Elements Based Nanofertilizers: Trace element nanofertilizers contain biologically important elements such as Fe, Zn, Cu, Mn, Co, Mo, and Se. Green synthesis using plant extracts and microorganisms has emerged as an environmentally friendly alternative to chemical synthesis, producing nanoparticles with improved stability, bioavailability, and lower toxicity (Ramrakhiani & Ghosh, 2018; Altammar, 2023). These nanoparticles have demonstrated applications not only in crop production but also in animal nutrition and health (Wu *et al*. 2021; Gowtham *et al*. 2022).

v). Nanocarriers: Nanocarriers facilitate efficient nutrient transport, controlled release, and targeted delivery, thereby improving nutrient availability while reducing environmental losses. Advanced systems include stimuli-responsive, multilayered, magnetic, and mesoporous silica nanocarriers that regulate nutrient release according to plant demand and rhizosphere conditions. Other promising materials include carboxymethyl cellulose, nanocellulose–clay composites, nanofibers, and silk fibroin. Despite their advantages, widespread adoption remains limited by high production costs, environmental concerns, and insufficient knowledge of long-term impacts, emphasizing the need for further research and optimization (Yadav *et al*. 2023).

4. Advantages of Nano-fertilizers over Conventional Fertilisers

Nanotechnology has emerged as an effective approach for improving agricultural productivity while reducing the environmental impacts associated with conventional fertilizers (Subramanian *et al*. 2015). Compared with traditional fertilizers, nanofertilizers enhance nutrient delivery, increase nutrient use efficiency (NUE), minimize nutrient losses, and support sustainable crop production. Nutrient use efficiency is expressed as:

Nutrient use efficiency (%) = Crop nutrient absorption (kg ha^{-1})/Nutrient supply via fertilization (kg ha^{-1}).

A comparison between nanofertilizers and conventional fertilizers is presented in Table 1.

Table 1: Comprehensive Comparison of Nanofertilizers and Conventional Fertilizers.

Properties	Nano-Fertilizers	Conventional Fertilizers
Nutrient uptake efficiency	It improves the effectiveness of fertilizer usage as well as the ratio of plant nutrient absorption, all while reducing the amount of fertilizer that is used.	Less effective due to the inadequate absorption of its bulk composites by plants.
Control release modes	Encapsulation, combined with a coating of polymer resin, waxes, and sulfur, enables meticulous regulation of nutrient delivery.	Excessive discharge leads to toxicity and disrupts ecological equilibrium.
Solubility and dispersion of nutrients	Enhances the solubility and dispersion of insoluble mineral constituents in soil, hence increasing their bioavailability to plants.	Because of its bigger particle size and poor solubility, it is less accessible to plants.
Effective duration of release	Enhances and extends the plant's rate of nutrient acquisition	The nutrients that plants need are lost as insoluble salts during delivery.
Low rate of fertiliser needed	Minimises nutrient depletion caused by leaching, runoff, and drift.	Drift, runoff, and leaching all contribute to the loss of high amounts of fertilizer.

i). High Nutrient Absorption Efficiency: Conventional fertilizers exhibit low nutrient-use efficiency because substantial proportions of applied nitrogen and phosphorus are lost through leaching, volatilization, or conversion into unavailable forms, resulting in environmental pollution and economic losses (Raliya *et al*. 2018). Nanofertilizers overcome these limitations through their high surface area, nanoscale particle size, controlled nutrient release, and protective nanocoatings, which improve nutrient availability and plant uptake (Ghormade *et al*. 2011).

ii). Field studies have demonstrated significant improvements in nutrient uptake and crop performance. Zinc oxide nanoparticles increased zinc absorption, root growth, and biomass in wheat compared with conventional zinc fertilizers (Munir *et al*. 2018). Iron oxide nanoparticles enhanced iron uptake, chlorophyll content, and wheat yield (Feng *et al.* 2022). Likewise, hydroxyapatite-based nano-urea formulations slowed nitrogen release by approximately 44%, reducing nitrogen losses while maintaining adequate nutrient availability (Dimkpa *et al.* 2020). Urea nanohybrids containing hydroxyapatite with magnesium or zinc further improved nutrient uptake, grain quality, and yield while reducing nitrogen fertilizer requirements by up to 75% compared with conventional urea (Sharma *et al.* 2022).

iii). **Controlled Release of Fertilisers:** Controlled nutrient release is one of the major advantages of nanofertilizers. Their nanoscale size enhances penetration through plant tissues, while functionalized nanoparticles enable targeted nutrient delivery to specific tissues (DeRosa *et al.* 2010; Liu *et al.* 2015; Wang *et al.* 2016). Modern controlled-release systems employ biodegradable polymer coatings, pH-responsive materials, enzyme-triggered release, temperature-sensitive polymers, and microbial degradation to synchronize nutrient release with plant demand. These mechanisms reduce nutrient leaching, improve fertilizer efficiency, lower application rates, and enhance crop productivity (Ghormade *et al.* 2011; Seleiman *et al.* 2020). For example, Nano-ZnO promotes faster seed germination and root development than conventional zinc sulfate (Prasad *et al.* 2012).

iv). **Improved Microbial Activity:** Nano-biofertilizers combine nanoparticles with beneficial microorganisms to simultaneously enhance nutrient availability and improve soil health. These formulations stimulate plant growth by improving nutrient absorption, soil fertility, and microbial activity (Bairwa *et al.* 2023). Gold nanoparticles have been reported to enhance colonization of plant growth-promoting rhizobacteria and increase biological nitrogen fixation, while chitosan nanoparticles improve the delivery and survival of nitrogen-fixing bacteria in plant roots (Shukla *et al.* 2015; Panichikkal *et al.* 2021). Nanoparticles can also extend the shelf life of biofertilizers by protecting microorganisms from heat, desiccation, and ultraviolet radiation, thereby improving their effectiveness under field conditions (Sambangi *et al.* 2023).

v). **Improved Soil Activity:** Nanofertilizers improve soil fertility by enhancing microbial activity, nutrient cycling, enzyme activity, organic matter decomposition, and nitrogen mineralization (Yaseen *et al.* 2020; Gupta *et al.* 2022). They also improve soil physical properties, including porosity, water retention, and nutrient availability, thereby promoting healthier root-zone conditions. However, repeated or excessive application may adversely affect soil microbial diversity and enzyme activities. High concentrations of copper hydroxide nanofertilizers have been shown to reduce microbial diversity and suppress important soil enzymes, highlighting the need to optimize application rates and evaluate long-term impacts on soil ecosystems (Tang *et al.* 2021).

5. Limitations of Nanofertilizers

Despite their considerable advantages, nanofertilizers present several environmental, health, and economic challenges that limit their large-scale adoption. Major concerns include human toxicity, phytotoxicity, bioaccumulation, ecological impacts, regulatory uncertainty, and commercialization barriers (Iqbal *et al.* 2019). Figure 5 summarizes the principal risks associated with nanofertilizer application.

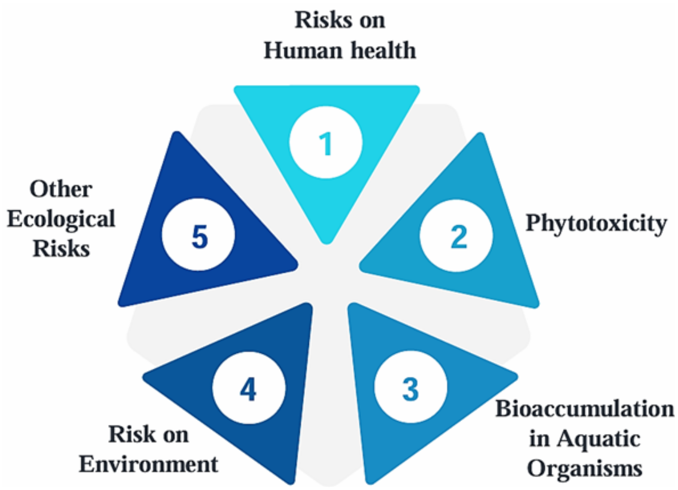

Fig 5: Potential risks and environmental Impacts associated with the application of nanofertilizers

i). **Human Health Concerns:** The small size, high surface area, and high reactivity of nanoparticles enable them to penetrate biological barriers and accumulate in tissues, raising concerns regarding human health (Oberdorster *et al.* 2004; Xuan *et al.* 2023). Experimental studies have reported gastrointestinal, liver, kidney, and neurological damage following nanoparticle exposure, with some nanoparticles capable of crossing the blood–brain barrier (Gupta *et al.* 2018; Zia *et al.* 2023). Potential exposure occurs through food consumption, inhalation during application, and dermal contact. Reported risks include bioaccumulation, oxidative stress, cytotoxicity, genotoxicity, immunotoxicity, and neurotoxicity. Nanoparticles may also alter gene expression after entering cells and interacting with intracellular components (Chaitra *et al.* 2021). For example, cerium oxide nanoparticles have demonstrated translocation within plants and potential accumulation in food chains, while ZnO nanoparticles have shown mitochondrial and DNA damage under experimental conditions (Ma *et al.* 2017; Fernández-Cruz *et al.* 2013). These findings highlight the need for comprehensive long-term toxicological studies before widespread agricultural use.

ii). **Phytotoxicity (Bioaccumulation in plants) and Plant Stress Responses:** Although nanofertilizers enhance crop productivity at optimal concentrations, excessive nanoparticle exposure may impair plant growth and metabolism. Phytotoxicity depends on nanoparticle concentration, composition, size, surface characteristics, plant species, and application method (Meghana *et al.* 2021; Wang *et al.* 2022).

iii). Major toxicity mechanisms include excessive reactive oxygen species production, membrane damage, DNA injury, nutrient imbalance, hormonal disruption, protein dysfunction, and inhibition of photosynthesis. Nanoparticles may also alter gene expression and interfere with nutrient and water uptake through root surface accumulation (Chaitra *et al.* 2021; Karami Mehrian *et al.* 2016). For example, Y_2O_3 nanoparticles delayed tomato seed germination and reduced root growth at concentrations above 10 mg L^{-1}, illustrating the concentration-dependent nature of nanoparticle toxicity (Hong *et al.* 2015; Wang *et al.* 2022). Therefore, determining safe application thresholds remains essential for sustainable use.

iv). **Bioaccumulation in Aquatic Organisms:** Nanofertilizers entering aquatic ecosystems through agricultural runoff may accumulate in aquatic organisms and move through food chains. Potential consequences include bioaccumulation, biomagnification, chronic toxicity, altered aquatic community structure, and disruption of ecosystem functions. Because nanoparticle behavior varies among aquatic environments and species, their long-term ecological fate remains insufficiently understood, requiring further investigation (Lead *et al.* 2018; van der Zande *et al.* 2020).

v). **Environmental Risk Assessment:** Nanoparticles released into soil, water, and air may persist, transform, and affect non-target organisms (Ghormade *et al.* 2011; Fincheira *et al.* 2023). Their accumulation can alter soil fertility, microbial communities, nutrient cycling, and groundwater quality while increasing the potential for trophic transfer and biomagnification (Shoults-Wilson *et al.* 2011; Nowack *et al.* 2007). Comprehensive environmental risk assessments are therefore necessary to evaluate nanoparticle persistence, transport, ecotoxicity, and long-term ecosystem impacts before large-scale application.

vi). **Ecological Risks:** Nanofertilizers may adversely affect beneficial organisms, including earthworms, pollinators, mycorrhizal fungi, and nitrogen-fixing microorganisms (Handy *et al.* 2008; Dimkpa *et al.* 2017). Nanoparticle exposure has been associated with reduced survival, reproduction, soil enzyme activity, and microbial diversity, potentially disrupting nutrient cycling, plant–microbe interactions, and ecosystem stability (Hu *et al.* 2019; Gogos *et al.* 2015). Further ecological studies are required to establish environmentally safe application practices.

vii). **Scale-Up and Economic Challenges:** Commercial adoption of nanofertilizers remains constrained by high production costs, limited scalability, quality control issues, storage instability, specialized application requirements, and the absence of standardized regulatory frameworks. Current production costs are generally two to five times higher than those of conventional fertilizers, although some formulations have demonstrated sufficient efficiency to become economically competitive under specific cropping systems (Su *et al.* 2022). Reducing manufacturing costs, establishing regulatory guidelines, and improving farmer acceptance are essential for successful commercialization.

6. Application Methods and Optimization

Nanofertilizers can be applied through foliar spray, soil application, and seed nanopriming (Figure 6), each offering distinct advantages depending on crop type, growth stage, soil properties, and nutrient requirements.

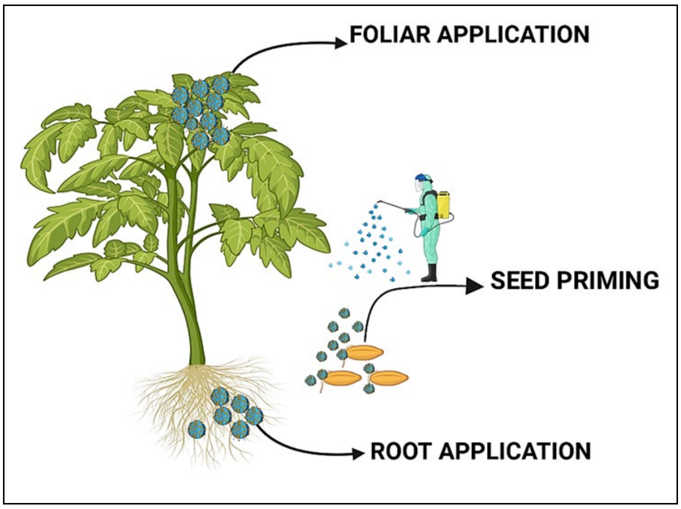

Fig 6: Methods of application of nanofertilizers a) Foliar application b) Soil application c) Seed Priming.

i). **Foliar Spray:** Foliar application is an efficient approach for correcting nutrient deficiencies and supplying micronutrients directly to plant tissues. Compared with soil application, foliar fertilization facilitates rapid nutrient absorption and provides quicker remediation of deficiencies. Nanoparticle spraying has been reported to be more effective for nutrient delivery than conventional soil amendments due to enhanced nanoscale absorption (Zimbovskaya *et al.*, 2020). It is particularly advantageous for soil-immobilized nutrients such as iron, copper, and manganese.

Foliar application enables rapid uptake through stomata and the cuticle, bypasses soil fixation processes, improves nutrient use efficiency, and reduces soil contamination. However, its effectiveness depends on appropriate timing, sufficient leaf area, favorable weather conditions, and optimized nanoparticle concentrations to avoid phytotoxicity. Nutrient translocation from leaves to other plant parts may also be limited.

ii). Several studies demonstrate the effectiveness of foliar fertilization. Foliar application increased manganese and zinc concentrations in citrus leaves to nearly twice those achieved through soil application (Uthman *et al.*, 2022). Similarly, foliar application of Fe-EDTA enhanced iron translocation and chlorophyll content in grapevines (Yunta *et al.*, 2013), while iron sprays increased maize yield by 0.4 Mg ha^{-1} under iron-deficient conditions (Stewart *et al.*, 2020). Positive responses to foliar micronutrient applications have also been reported in soybean production systems (Thapa *et al.*, 2021).

iii). **Soil Application:** Soil application remains the most widely adopted method for nutrient supplementation. Its efficiency is influenced by soil texture, pH, organic matter content, microbial activity, moisture availability, and application depth (Raliya *et al*., 2016). Compared with foliar application, soil incorporation exposes nanoparticles to greater concentrations and prolonged interactions with soil constituents.

This method provides sustained nutrient release, targets the root zone directly, integrates readily with conventional fertilization practices, and reduces labor requirements. Nevertheless, nutrient immobilization, leaching losses, microbial degradation, uneven distribution, and environmental persistence remain major concerns. Soil physicochemical characteristics strongly influence nanoparticle stability, mobility, and nutrient availability. In addition, most agricultural soils possess lower anion exchange capacity than cation exchange capacity, increasing the susceptibility of anionic nutrients such as nitrate to leaching losses (González-Melendi *et al*., 2008; Ding *et al*., 2023).

iv). **Seed Nanopriming:** Seed nanopriming is an emerging pre-sowing strategy that induces physiological and biochemical changes, resulting in faster germination, improved seedling vigor, and enhanced stress tolerance (Pereira *et al*., 2021). The technique can reduce fertilizer consumption by up to 50% while maintaining crop performance by facilitating the penetration of nanoparticles into seeds and stimulating growth-promoting processes. Nanopriming enhances water uptake, activates germination-related metabolic pathways, improves antioxidant defense mechanisms, regulates phytohormone balance, accelerates reserve mobilization, and strengthens tolerance against abiotic and biotic stresses. Nanofertilizers used in seed priming have also been shown to regulate reactive oxygen species (ROS), enhance antioxidant activities, and influence hormone-mediated signaling pathways involved in germination and plant development (Sharma *et al*., 2023). Furthermore, seed priming promotes the expression of stress-responsive genes, thereby improving plant resilience (Liu *et al*., 2015).

Compared with conventional priming, nano-priming delivers nanomaterials directly onto the seed surface, minimizing pathogen penetration and reducing undesirable chemical interactions under stress conditions. Chitosan nanoparticle priming (0.1–0.3% for 3 h) significantly improved germination, radicle growth, antioxidant enzyme activity, chlorophyll content, proline accumulation, and salt tolerance in bean seedlings exposed to 100 mM NaCl stress (Zayed *et al*., 2017). These findings suggest that nanopriming can serve as an effective strategy for enhancing seed quality, promoting early crop establishment, and mitigating environmental stresses (Sharma *et al*., 2023).

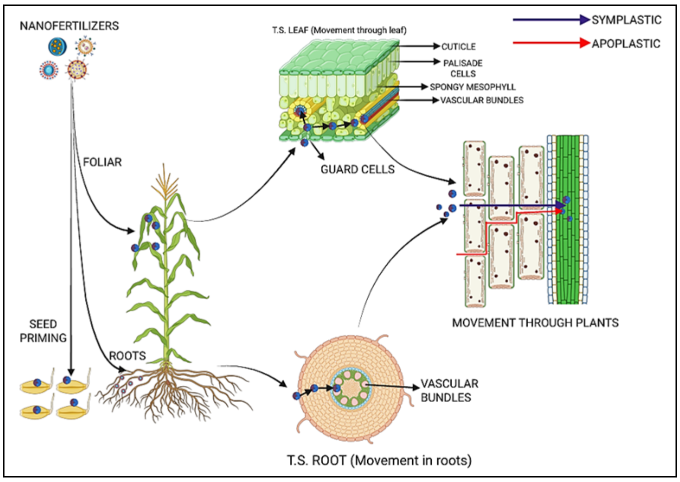

Fig 7: Mechanism of foliar and root uptake

7. Mechanism of Nanofertilizer Uptake and Translocation

Understanding nanoparticle uptake, transport, and distribution within plants is essential for optimizing nanofertilizer design and application. Nanoparticle absorption largely depends on plant physiology and occurs through stomata, trichomes, hydathodes, and stigmas, followed by systemic transport via vascular tissues (Schwab *et al*., 2016; Wang *et al*., 2016).

i). **Foliar Uptake Mechanism:** Nanoparticles are translocated through two principal pathways: apoplastic and symplastic. The apoplastic pathway involves movement through cell walls and intercellular spaces without crossing membranes, but transport is restricted by cell wall size exclusion limits (SELs) of approximately 5–20 nm and physical barriers such as pectin networks and cellulose microfibrils (Bernela *et al*., 2021). In contrast, the symplastic pathway enables movement through the cytoplasm via plasmodesmata, which possess SELs ranging from 3–50 nm and facilitate cell-to-cell and long-distance transport. This pathway generally requires membrane crossing through endocytosis and is subject to active regulation (Łamaj *et al*., 2004; Etxeberria *et al*., 2006; Paterlini, 2020).

Nanoparticle entry is influenced by stomatal dimensions (5–20 nm), trichome morphology, and plasmodesmatal connectivity (Fleischer *et al*., 1999; Schwab *et al*., 2016; Lucas *et al*., 2004; Heinlein *et al*., 2004). The Casparian strip further regulates nanoparticle movement into vascular tissues (Aubert *et al*., 2012; Palmgren, 2018). Interestingly, nanoparticles larger than SEL thresholds, including particles around 50 nm, have also been detected within plant tissues, suggesting the existence of additional uptake mechanisms beyond passive diffusion. For example, foliar-applied CeO_2 nanoparticles were absorbed and distributed throughout cucumber plants (Hong *et al*., 2014), while Ag nanoparticles applied to cabbage leaves were translocated to different plant organs (Larue *et al*., 2014).

ii). **Root Uptake Mechanism:** Nanoparticles (NPs) are transported from roots to aerial plant parts through the epidermis, endodermis, and xylem (Zulfiqar *et al*., 2019; Rajput *et al*., 2020; Ali *et al*., 2021). Uptake occurs through apoplastic, symplastic, transcellular, and crack-entry pathways, particularly at root tips and lateral root emergence sites where discontinuities in the Casparian strip exist. To reach the vascular tissues, nanoparticles must cross cell walls and plasma membranes before entering the xylem.

Cell wall pores, generally ranging from 3–8 nm, impose a size limitation on nanoparticle penetration (Carpita *et al*., 1993; Schwab *et al*., 2016). However, nanoparticles may induce larger pore formations, facilitating intercellular transport (Navarro *et al*., 2008; Schwab *et al*., 2016). Uptake efficiency is strongly influenced by particle size, surface charge, coating, root exudates, plant species, and root architecture. Smaller nanoparticles generally exhibit greater uptake; for instance, tomato roots absorb 3.5 nm AuNPs but exclude 18 nm particles, whereas *Arabidopsis thaliana* roots can internalize silica nanoparticles ranging from 14 to 200 nm (Zulfiqar *et al*., 2019).

iii). **Seed Nanopriming Uptake Mechanisms:** Nanopriming is an emerging seed enhancement technique in which seeds are treated with nanoparticle suspensions to improve germination, seedling vigor, stress tolerance, and nutrient use efficiency. Nanoparticles enter seeds through natural openings such as micropyles and the hilum and are transported into the seed matrix by water during imbibition (Mahakham *et al*., 2017).

As hydration progresses, the seed coat becomes more permeable, facilitating the diffusion of nanoparticles, particularly those smaller than 100 nm. Uptake efficiency is influenced bynanoparticle size, shape, surface charge, and surface modifications, with neutral or slightly negatively charged particles generally exhibiting higher penetration efficiency (Adhikari *et al*., 2021). Following entry, nanoparticles are translocated to embryonic tissues through apoplastic and symplastic pathways and are internalized mainly via endocytosis, aided by transport proteins and aquaporins (Jampílek & Kráľová, 2022).

Within cells, nanoparticles localize in organelles such as mitochondria and vacuoles, where they stimulate metabolic activities, activate hydrolytic enzymes including amylases and proteases, regulate reactive oxygen species (ROS), enhance antioxidant defense systems, and improve redox balance (Liu *et al*., 2016; Latef *et al*., 2021). These processes accelerate germination, enhance seedling vigor, promote efficient reserve mobilization, and increase tolerance to abiotic stresses.

8. Nanofertilizers and Greenhouse Gas Mitigation

Nanofertilizers can contribute to greenhouse gas (GHG) mitigation by improving nutrient use efficiency, reducing fertilizer inputs, and minimizing nutrient losses, although comprehensive life-cycle assessments are still required to confirm these benefits under diverse agricultural conditions (Yadav *et al*., 2023). Conventional nitrogen fertilizers are major sources of nitrous oxide (N_2O), a greenhouse gas with a global warming potential 298 times greater than CO_2. Controlled-release nanofertilizers, particularly nano-zeolite formulations, have demonstrated the ability to reduce N_2O emissions by synchronizing nutrient release with crop demand, enhancing root uptake, reducing volatilization, and modifying soil microbial processes associated with nitrification and denitrification (Saraiva *et al*., 2023).

Studies have shown that nano-zeolite fertilizers decrease nitrogen oxide emissions in rice cultivation, while zinc oxide nanoparticles reduced N_2O emissions in tea plantation soils by up to 33%. Similarly, urea-doped calcium phosphate nanoparticles enabled a 40% reduction in nitrogen application in wheat without compromising yield or quality (Ramírez-Rodríguez *et al*., 2020). Slow- and controlled-release nanofertilizers also reduce nutrient losses through leaching, runoff, and volatilization, thereby supporting climate change mitigation strategies (Mejías *et al*., 2021; Saraiva *et al*., 2018).

Nanofertilizers may also reduce methane (CH_4) emissions, particularly in rice systems. Lower CH_4 emissions have been reported from nano-fertilizer-treated soils (Mohanraj *et al*., 2019), while functionalized biological nanoparticles have been shown to suppress methanogenic microorganisms, potentially reducing methane production by 15% (Altermann *et al*., 2022). Oxygen nanobubble irrigation decreased methane emissions by 21% in rice fields by altering soil redox conditions, whereas high-yielding rice cultivars were associated with lower methane emissions due to increased root porosity and enhanced methanotrophic activity (Jiang *et al*., 2017).

Overall, nanofertilizers represent a promising strategy for reducing agricultural greenhouse gas emissions while maintaining crop productivity through improved nitrogen utilization, enhanced soil aeration, and reduced environmental losses (Saraiva *et al*., 2023; González-Feijoo *et al*., 2024; Lei *et al*., 2023). Their integration into sustainable agricultural systems may contribute significantly to climate change mitigation, resource conservation, and long-term food security.

9. Cost-benefit Analysis and Economic Viability

Nanofertilizers enhance nutrient use efficiency (NUE) by enabling precise nutrient delivery, thereby reducing required application rates compared to conventional fertilizers. For instance, to achieve yields above 8 t ha^{-1}, around 200 kg ha^{-1} of conventional fertilizers may be required, whereas only about 40 kg ha^{-1} of nanofertilizers may suffice under high efficiency conditions ($\gamma \approx 6$).

Despite their agronomic advantages, nanofertilizers are currently 2–5 times more expensive than conventional fertilizers due to specialized synthesis methods, stringent quality control, and high-cost raw materials (Nichepom, 2023). However, their higher efficiency, reduced application frequency, and yield improvements (10–40%) can offset initial costs through enhanced productivity and reduced input use. Additional economic benefits arise from lower labor and application costs, reduced environmental remediation expenses, and potential market premiums for sustainably produced crops. Scale-up of industrial production is expected to further reduce costs over time.

Economic models indicate that profitability increases with higher efficiency (γ). For example, at $\gamma = 3$, combined application of conventional and nanofertilizers can yield a net revenue of approximately \$510 ha^{-1}, while at $\gamma = 9$, revenue may increase up to \$982 ha^{-1} (Su *et al*., 2022). However, high initial costs remain a major barrier to widespread adoption, particularly in resource-limited regions.

10. Physiological Stress Mitigation Using Nanofertilizers

Nanofertilizers enhance plant tolerance to abiotic and biotic stresses by improving physiological performance, antioxidant defense systems, and nutrient utilization, thereby functioning as both nutrient sources and stress-mitigating agents.

i). **Drought Stress:** Drought is a major constraint to agricultural productivity worldwide (Seleiman *et al*., 2020). Nanofertilizers alleviate drought stress by enhancing water uptake, osmotic adjustment, antioxidant activity, stomatal regulation, root development, and membrane stability. They also reduce oxidative damage by lowering reactive oxygen species (ROS), malondialdehyde, and hydrogen peroxide levels (Janmohammadi *et al*., 2016). Silicon nanoparticles improved drought tolerance in hawthorn seedlings (Ashkavand *et al*., 2016), while TiO_2 nanoparticles increased wheat growth and yield under water stress (Jaberzadeh *et al*., 2013). Enhanced drought resistance has also been reported in lentil, strawberry, and sage following treatment with Ag nanoparticles, Fe nanoparticles combined with salicylic acid, and nano-zeolite formulations, respectively (Hojjat *et al*., 2016; Mozafari *et al*., 2018; Mahmoud *et al*., 2020).

ii). **Salinity Stress:** Salinity affects over 20% of cultivated land globally and disrupts plant growth, photosynthesis, and nutrient uptake through osmotic stress and ion toxicity (Rasool *et al*., 2013; Seleiman *et al*., 2020). Nanofertilizers mitigate salinity stress by maintaining ion homeostasis, enhancing osmotic adjustment, strengthening antioxidant defenses, preserving membrane integrity, and regulating stress-responsive hormones. SiO_2 nanoparticles increased chlorophyll, proline content, antioxidant activity, and biomass under saline conditions (Kalteh *et al*., 2018; Gao *et al*., 2006; Shoukat *et al*., 2024). Similarly, nano-calcium, nano-NPK, and nano-chitosan significantly improved growth, yield, and germination in tomato, pea, and bean plants under salt stress (Tantawy *et al*., 2014; El-Hefnawy, 2020; Zayed *et al*., 2017).

iii). **Temperature and Heat Stress:** Heat stress induces oxidative damage, reduces photosynthesis, and impairs plant growth (Kai *et al*., 2014). Nanofertilizers alleviate heat stress by promoting antioxidant activity, stabilizing membranes, protecting photosynthetic machinery, inducing heat shock proteins, and regulating stress-responsive hormones. Selenium nanoparticles improved water relations, chlorophyll content, and antioxidant defense under high temperatures (Haghighi *et al*., 2014). Silver nanoparticles enhanced growth and biomass accumulation in heat-stressed wheat (Iqbal *et al*., 2019), while SeNPs improved pollen viability and seed production in sorghum exposed to elevated temperatures (Djanaguiraman *et al*., 2018).

iv). **Biotic Stress:** Pests and diseases account for annual crop losses of 20–40% worldwide (Pestovsky *et al*., 2017). Nanofertilizers exhibit antimicrobial properties through membrane disruption, ROS generation, ion release, enzyme inhibition, and activation of plant defense mechanisms. Nano-Cu effectively controlled *Xanthomonas* species in mung bean and rice (Vigneshwaran *et al*., 2006; Singh *et al*., 2021), whereas chitosan nanoparticles inhibited fungal and bacterial pathogens by altering membrane integrity and suppressing replication (Tripathi *et al*., 2020). Chitosan formulations significantly reduced the growth of *Macrophomina phaseolina*, *Alternaria alternata*, and *Rhizoctonia solani*, while MgO, Cu, and ZnO nanoparticles demonstrated broad-spectrum antimicrobial activity against several phytopathogenic microorganisms (Saharan *et al*., 2013; Cai *et al*., 2018; Ramyadevi *et al*., 2012; Bayat *et al*., 2021; Nawaz *et al*., 2011; Khan *et al*., 2021).

Table 2 summarizes the applications of different nanofertilizers in various crops under stress conditions.

Table 2: Application of different types of nanofertilizers on different crops and plants.

Nanofertilizers	Mode of Application	Crops	Experiment Conditions	Benefits	Location	References
Nano-KH_2PO_4	Hydroponics	Rice	To transplant the seedlings, the Yoshida nutritional solution was used.	Enhanced immediate water usage efficiency in rice plants, in addition to higher physiological efficiency for phosphorus in both the roots and the shoots of the plant.	Mexico	Miranda-Villagómez *et al*, 2019
Nitrogen, phosphorus, and potassium (NPK) + phosphorus, zinc, and silicon nanoparticle	Soil	Rice	Clayey soil was found at the experimental site during the 2019 and 2020 seasons. The organic matter content of the soil was 1.59% and 1.53%, the pH was 8.12 and 8.18, and the electrical conductivity (EC) was 2.55 and 2.25 dS m^{-1}.	By adding 2/3 NPK and Zn_{50} NPs, the grain yield, straw yield, yield traits, chemical makeup in the plant, and grinding properties were all improved. Also, both 2/3 NPK + P_{3000} NPs and 2/3 NPK + Si_{200}NPs were good for all the factors that were looked at.	Egypt	Elekhtyar, N. *et al*, 2023
Urea-Doped Calcium Phosphate Nano particles (U-ACP)	Foliar	Grapevines	A pot experiment was done using a sand-peat-clay mixture in a volumetric ratio of 50:35:15. The average temperatures were 19.2 °C and 18.8 °C, while the rainfall was 843 mm and 839 mm during the growth seasons of 2019 and 2020, respectively.	Nanofertilizers made of U-ACP may reduce nitrogen rates without sacrificing yield or quality by delivering nitrogen via the soil-root system and leaf stomata.	Italy	Gaiotti, F. *et al*, 2021
Plant growth-promoting microbes	Foliar	Soybean	The clayey soil had an original pH of 8.23 and was used as an	The synergistic use of PGPMs and Si-ZnNPs mitigated the	Egypt	Osman, H. S *et al*, 2021

(PGPMs) and nanoparticles (Si-ZnNPs)			experimental field site. There were 9.92 mg Kg^{-1} of total nitrogen and 11.55 g Kg^{-1} of organic carbon, respectively.	adverse impacts of water stress and soil salinity by optimizing root length, enhancing nodule dry weight, expanding leaf area, elevating total soluble solids (TSS), and augmenting antioxidant enzyme activity, hence resulting in improved soybean production and growth.		
CuO bio-nanofertilizer (Bacillus circulans NCAIM B. 02324) & Se bio-nanofertilizer (Bacillus cereus TAH)	Soil	Strawberry	Pot research used a growth medium composed of 1 Kg of foam, 300 L of peat moss, and 30 Kg of vermiculite. The peat moss exhibited a pH of 4.10, an electrical conductivity (EC) of 0.189 dS m^{-1}, and the following nutrient concentrations (mg L^{-1}): N (323), P (1.8), K (130), Ca (951), Mg (225), Cu (11.6), Mn (28.1), Fe (11.3), and Zn (59.5).	In comparison to the control group, seedlings subjected to nanofertilizers exhibited improved growth, increased photosynthetic pigments, elevated antioxidant levels, and superior nutritional status.	Egypt	El-Bialy *et al*, 2023
Nano-chitosan NPK	Foliar	Wheat	Sandy soil was used in the pot research.	The following values were observed in wheat plants that were treated with nanocomposites NPK fertilizer: plant height, spike length, main spike weight, shoot length, 100 kernel weight, grains per main spike, grain yield per plant, straw yield, crop yield, harvest index, and crop index.	Egypt	Abdel-Aziz *et al*, 2016
K-nano-chelate	Soil	*Ocimum basilicum*	The OM was 2.3%, EC was 0.65 dSm^{-1}, pH was 7.84, and the pot experiment was conducted on silty clay loam calcareous soil.	By lowering root-level Cd absorption and accumulation in plants cultivated in polluted soil, K-nano-chelate decreased the possibility that Cd would reach the human food chain.	Iran	Zahedifar *et al*, 2019
Nano Zinc-Iron oxide + Biofertilizers	Foliar	Wheat	Field experiment conducted in a semi-arid temperate zone with loam-textured soil, pH 8.2, electrical conductivity of 2.68 dS m^{-1}, and total nitrogen, available phosphorus, and potassium levels of 0.75 mg Kg^{-1}, 8.4 mg Kg^{-1}, and 275 mg Kg^{-1}, respectively.	The use of nanoparticles and biofertilizers enhanced enzyme activities, proline, and soluble sugars. The use of Azotobacter and nano Zn-Fe oxide enhanced grain production by 88% under drought conditions.	Pakistan	Seyed Sharifi *et al*, 2020
ZnO NPs	Soil	Wheat	The pot experiment used sandy loam soil with a pH of 7.35. The nitrogen, phosphorus, and potassium content were 0.052%, with phosphorus at 32 mg Kg^{-1} and potassium at 160 mg Kg^{-1}, respectively.	The use of ZnO nanoparticles (0.12 g per pot) markedly enhanced shoot and spike lengths by 30.7% and 27.6%, root fresh and dry weights by 74.5% and 63.1%, and wheat grain yield by 42.2% in saline conditions.	Pakistan	Adil *et al*, 2022
Micronutrient nanofertilizer (ZnO, MnO_2, MoO_3) (MN-NPs)	Foliar	Common bean (*Phaseolus vulgaris* L.)	Field experiment done in clayey soil with electrical conductivity of 0.49 dS/m and pH of 7.41.	A dosage of 40 mg L^{-1} of MN-NPs improved vegetative growth, flowering, and yield of common beans.	Egypt	Salama *et al*, 2022
NPK nanofertilizers	Foliar	Potato	The soil has a clay texture, with a pH of 7.7, an electrical conductivity (EC) of 1.35 dS m^{-1}, a cation exchange capacity (CEC) of 37.87 cmol Kg^{-1}, and a soil organic carbon content of 18.48 g Kg^{-1}.	Economic yield (23.59 T ha^{-1}), NPK nutrient use efficiency (67.74, 278.92, 118.54 Kg of potato/Kg of nutrient), starch rates (79.62%), harvest index (59.24%), and lower potato nitrate content (1.15 g Kg^{-1}) were observed in plots receiving foliar application of NPK nanofertilizers at 50% or 25% of recommended level.	Egypt	Abd El-Azeim *et al*, 2020

Chitosan-based sustained release nanofertilizer with incorporated potassium (CNK)	Soil application (mixed with soil pre-sowing)	*Zea mays* L. (Maize, fodder variety)	Field pot experiment executed in Bhavnagar, Gujarat, using bird net protection. The soil included sandy loam with deficient nitrogen and phosphorus, and moderate potassium levels. The experiment used a randomized complete block design with eight treatments and a growth duration of sixty days, including three replications.	Enhanced soil porosity, water conductivity, and friability Minimized potassium leaching Increased biomass by 51% (fresh) and 41.75% (dry) at a 75% CNK dose Doubled root biomass in comparison to conventional fertilizer Higher microbial and enzyme activity (soil health)	India	Kubavat, D. *et al*, 2020
PVA–starch supported Cu–Zn/CNF nanofertilizer (PBMC)	Mixed with soil (pot experiment)	*Cicer arietinum* (chickpea)	When compared to the Cu-only, Zn-only, and control groups, the garden soil at IIT Kanpur had a pH of around 7.6 and a moisture content of approximately 15%. The dose ranged from 0.25 to 4.0 grams of PBMC per kilogram of soil. The growth period lasted for thirty days.	A higher percentage of seeds germinating (up to 96%)! Plant height rose from 18 centimetres (the control) to 33 centimetres. Chlorophyll and protein levels that are both higher. A more robust root-shoot development and increased water intake. Reactive oxygen species (ROS) in plants were scavenged by zinc exposure.	India	Kumar, R. *et al*, 2018
Zinc-loaded manganese hollow core shell nanofertilizer	Soil application (pot culture)	*Oryza sativa* L. (Rice)	The controlled pot trials were conducted under two different conditions: aerobic and submerged. The black dirt used for experimentation (Inceptisol). Percolation reactors were used to conduct slow-release tests, and the nutrient release was monitored for a period of 29 days.	Enhanced zinc release for up to 696 hours, in contrast to the 408 hours for zinc SO4-. There was a 17–36% rise in grain production. Increased zinc absorption (5.66 mg/hill in submerged conditions and 3.47 mg/hill in aerobic conditions). The Zn content of the shoots and yield metrics were improved. Zinc loss in the environment was reduced.	India	Yuvaraj, M. *et al*, 2015
Iron Oxide Nanoparticles (Fe_3O_4 NPs)	Soil application	Rice (*Oryza sativa*)	Experiments conducted in the laboratory to evaluate the germination of seeds, the growth of shoots and roots, and the chlorophyll content.	When compared to conventional iron supplements, this product has superior iron bioavailability, enhanced seed germination, improved shoot and root growth, and higher chlorophyll content.	United States	Afzal *et al*. 2021
Zinc Oxide Nanoparticles (ZnO NPs)	Foliar spray	Maize (*Zea mays*)	Experiments conducted in the field to determine the rate of photosynthesis, the concentration of soluble carbohydrates, and the chlorophyll content.	The rate of photosynthesis was raised, the concentration of soluble carbohydrates was increased, and the chlorophyll content was boosted, all of which led to improved growth and production.	United Kingdom	Saurabh *et al*. 2024
Urea-functionalized Amorphous Calcium Phosphate Nanofertilizers	Soil application	Various crops	Laboratory synthesis maximizing production costs and environmental sustainability, then greenhouse tests of nutrient release and plant development.	Cost-effective production techniques, better environmental sustainability, and optimized nutrient release profiles all contribute to higher plant growth and output.	Germany	Carmona *et al*. 2021
Chitosan-coated Zinc Nanoparticles	Soil application	Potato (*Solanum tuberosum*)	Greenhouse studies on zinc buildup in plants, soil toxicity, and nutrient release.	Longer zinc release time, less soil toxicity, and avoidance of zinc over-accumulation in plants help to promote better development.	Netherlands	Mukhopadhyay, 2014
Silica Nanoparticles (SiO_2 NPs)	Soil application	Wheat (*Triticum aestivum*)	Field studies evaluating general plant health under different soil conditions, water retention, and nutrient retention.	Better retention of necessary macronutrients (N, P, K), improved soil water retention, and more plant stress condition resistance.	Canada	Mukhopadhya, 2014

10. Future Perspectives and Research Directions

Advancement of nanofertilizers requires interdisciplinary efforts to address issues of safety, environmental impact, efficiency, and scalability. Although they enhance nutrient use efficiency, excessive application may inhibit plant growth, emphasizing the need for crop-specific optimization and standardized formulations.

Future research should focus on long-term environmental fate, including nanoparticle persistence, transformation, and accumulation, along with impacts on soil microbiota, food chains, and human health through multiple exposure pathways. Equally important are harmonized regulatory frameworks, safety thresholds, and standardized testing protocols.

Development should prioritize smart, biodegradable, and stimuli-responsive nanofertilizers integrated with sensors for real-time nutrient monitoring, along with cost-effective green synthesis and scalable production. Further studies are needed on nanoparticle interactions with soils, plants, and degradation pathways, as well as reliable detection methods in plant tissues. Integration with precision agriculture—using AI, IoT, GPS-guided application, drones, and sensor-based systems—can significantly improve efficiency and reduce losses (Zulfiqar *et al*., 2019). Strong regulatory systems must ensure risk assessment, exposure monitoring, labeling, and international harmonization, supported by continuous toxicity evaluation across ecosystems.

Finally, farmer training, extension programs, and stakeholder engagement are essential for adoption and safe use (Lombi *et al*., 2019; Rao *et al*., 2021). Overall, nanofertilizers offer a promising pathway for sustainable agriculture by enhancing productivity while reducing environmental impacts (Prasad *et al*., 2017).

11. Conclusions

A revolutionary shift toward more ecologically conscious, efficient, and sustainable farming practices has been brought about by the development and use of nanotechnology in agriculture through the creation and use of nanofertilizers. This review highlights that nanofertilizers are a better alternative to conventional fertilizers in many ways. They improve nutrient use efficiency (NUE), enable controlled and targeted nutrient release, reduce nutrient losses through leaching or volatilization, and enhance crop performance in both normal and stress conditions. With these qualities, nanofertilizers may be a game-changer for future agricultural advances that tackle both the problem of boosting food production and the problem of reducing environmental deterioration.

Nanofertilizers have the potential to boost soil microbial activity, decrease greenhouse gas emissions, and lessen the impact of biotic and abiotic stressors. Their nano-size allows greater penetration into plant tissues, thereby enhancing nutrient uptake and reducing waste. Furthermore, nano-biofertilizers, which are a combination of nanocarriers and biofertilizers or microbial agents, further improve soil fertility and plant development while also encouraging ecological sustainability.

The widespread adoption of nanofertilizers is a big faces significant challenges, despite their potential. Scientific rigor is required to address issues including phytotoxicity, bioaccumulation in aquatic and plant systems, potential risks to human health, uncertain long-term ecological impacts, and a lack of defined regulatory frameworks. Moreover, high manufacturing costs, inconsistent particle behavior in complex soil-plant systems, and low public awareness further complicate the deployment.

Future research must prioritize the development of safe, standardized formulations, comprehensive field-based toxicity and efficacy assessments, cost-effective production methods, and clear regulatory frameworks. Nanofertilizers promise. The promise of nanofertilizers in advancing sustainable agriculture~~, but their successful adoption~~ can only be realized through a multidisciplinary, precautionary, and inclusive approach to address both the challenges of global food security as well as environmental sustainability. The integration of nanofertilizers with precision agriculture technologies, the development of smart responsive systems, and the establishment of robust safety protocols will be critical for transforming this promising technology into a mainstream agricultural practice that benefits farmers, consumers, and the environment.

Funding Declaration

Any agency provides no funding or financial help for drafting and writing this article.

Conflicts of interest/Competing interests- The authors declare no competing interests.

References

1. Aamir Iqbal M. Nano-fertilizers for sustainable crop production under changing climate: A global perspective. In: *Sustainable Crop Production*. IntechOpen; 2020.
2. Abd El-Azeim MM, Sherif MA, Hussien MS, Haddad SA. Temporal impacts of different fertilization systems on soil health under arid conditions of potato monocropping. *Journal of Soil Science and Plant Nutrition*. 2020;20(2):322–334. Available from: https://doi.org/10.1007/s42729-019-00110-2
3. Abdel-Aziz HMM, Hasaneen MNA, Omer AM. Nano chitosan-NPK fertilizer enhances the growth and productivity of wheat plants grown in sandy soil. *Revista de Investigacion Agraria [Spanish Journal of Agricultural Research]*. 2016;14(1):e0902. Available from: https://doi.org/10.5424/sjar/2016141-8205
4. Achari GA, Kowshik M. Recent developments on nanotechnology in agriculture: Plant mineral nutrition, health, and interactions with soil microflora. *Journal of Agricultural and Food Chemistry*. 2018;66(33):8647–8661. Available from: https://doi.org/10.1021/acs.jafc.8b00691
5. Adhikari T, Kundu, S, Biswas AK, Tarafdar JC, Rao AS. Effect of copper oxide nanoparticle on seed germination of selected crops. *Journal of Agricultural Science and Technology*. 2021;23:123–132.
6. Adil M, Bashir S, Bashir S, Aslam Z, Ahmad N, Younas T, Asghar RMA, Alkahtani J, Dwiningsih Y, Elshikh MS. Zinc oxide nanoparticles improved chlorophyll contents, physical parameters, and wheat yield under salt stress. *Frontiers in Plant Science*. 2022;13:932861. Available from: https://doi.org/10.3389/fpls.2022.932861
7. Afzal S, Sharma D, Singh NK. Eco-friendly synthesis of phytochemical-capped iron oxide nanoparticles as nano-priming agent for boosting seed germination in rice (*Oryza sativa* L.). *Environmental Science and Pollution Research International*. 2021;28(30):40275–40287. Available from: https://doi.org/10.1007/s11356-020-12056-5
8. Ahamed N A, Sachin Sadavarte P. Chemical farming, emerging issues of chemical farming. *International Journal of Innovative Science and Research Technology*. 2024:2502–2508. Available from: https://doi.org/10.38124/ijisrt/ijisrt24mar2197

9. Ahamed N, *et al*. Environmental impact of synthetic fertilizers: Risks and alternatives. *Journal of Agricultural Sciences*. 2024;32(1):45-60.
10. Akhtar N, Ilyas N, Meraj TA, Pour-Aboughadareh A, Sayyed RZ, Mashwani ZU, Poczai P. Improvement of Plant Responses by Nanobiofertilizer: A Step towards Sustainable Agriculture. *Nanomaterials*. 2022.
11. Alejandro S, Höller S, Meier B, Peiter E. Manganese in plants: From acquisition to subcellular allocation. *Frontiers in Plant Science*. 2020;11:300. Available from: https://doi.org/10.3389/fpls.2020.00300
12. Ali S, Mehmood A, Khan N. Uptake, translocation, and con sequences of nanomaterials on plant growth and stress adaptation. *J Nanomater*. 2021.
13. Al-Juthery HW, Lahmoud NR, Alhasan A, Al-Jassani N, Houria A. NanoFertilizers as a Novel Technique for Maximum Yield in Wheat Biofortification (Article Review). *IOP Conf. Ser. Earth Environ. Sci*. 2022.
14. Alkhader AMF, National Agricultural Research Center. Nanofertilizers as an alternative to inorganic fertilizers: A review. *African Journal of Food Agriculture Nutrition and Development*. 2023;23(122):23956–23974. Available from: https://doi.org/10.18697/ajfand.122.23145
15. Altammar KA. A review on nanoparticles: characteristics, synthesis, applications, and challenges. *Frontiers in Microbiology*. 2023;14:1155622. Available from: https://doi.org/10.3389/fmicb.2023.1155622
16. Ameen A, *et al*. Nanofertilizers: A sustainable approach for enhancing crop yield. *International Journal of Agricultural Nanotechnology*. 2018;5(2):98-115.
17. Ashkavand P, Tabari M, Zarafshar M, Tomášková I, Struve DK. Effect of SiO2 nanoparticles on drought resistance in hawthorn seedlings. *Forest Research Papers*. 2015;76:350-359.
18. Aubert T, Burel A, Esnault M-A, Cordier S, Grasset F, Cabello-Hurtado F. Root uptake and phytotoxicity of nanosized molybdenum octahedral clusters. *Journal of Hazardous Materials*. 2012;219–220:111–118. Available from: https://doi.org/10.1016/j.jhazmat.2012.03.058
19. Avila-Quezada GD, Ingle AP, Golińska P, Rai M. Strategic applications of nano-fertilizers for sustainable agriculture: Benefits and bottlenecks. *Nanotechnology Reviews*. 2022;11(1):2123–2140. Available from: https://doi.org/10.1515/ntrev-2022-0126
20. Babu S, Singh RP, Yadav D, Rathore SS, Raj R, Avasthe R, Yadav SK, Das A, Yadav V, Yadav B. Nanofertilizers for agricultural and environmental sustainability. *Chemosphere*. 2021.
21. Bairwa P, Kumar N, Devra V, Abd-Elsalam K. Nano-biofertilizers synthesis and applications in agroecosystems. *Agrochemicals*. 2023;2(1):118–134. Available from: https://doi.org/10.3390/agrochemicals2010009
22. Baker TJ, Tyler CR, Galloway TS. Impacts of metal and metal oxide nanoparticles on marine organisms. *Environmental Pollution (Barking, Essex: 1987)*. 2014;186:257–271. Available from: https://doi.org/10.1016/j.envpol.2013.11.014
23. Bayat M, Zargar M, Chudinova E, Astarkhanova T, Pakina E. *In vitro* evaluation of antibacterial and antifungal activity of biogenic silver and copper nanoparticles: The first report of applying biogenic nanoparticles against *Pilidium concavum* and *Pestalotia* sp. Fungi. *Molecules (Basel, Switzerland)*. 2021;26(17):5402. Available from: https://doi.org/10.3390/molecules26175402
24. Bernela M, Rani R, Malik P, Mukherjee TK. Nanofertilizers: applications and future prospects. In: Sindhu RK, Chitkara M, Singh IS, editors. *Nanotechnology principles and applica tions*. 1st edn. Jenny Stanford Publishing; 2021. p. 289–332.
25. Bhardwaj AK, Arya G, Kumar R, Hamed L, Pirasteh-Anosheh H, Jasrotia P, Kashyap PL, Singh GP. Switching to nanonutrients for sustaining agroecosystems and environment: the challenges and benefits in moving up from ionic to particle feeding. *Journal of Nanobiotechnology*. 2022;20(1):19. Available from: https://doi.org/10.1186/s12951-021-01177-9
26. Broadley M, Brown P, Cakmak I, Rengel Z, Zhao F. Chapter 7- function of nutrients: micronutrients. In: Marschner P, editor. *Marschner's Mineral Nutrition of Higher Plants*. Academic Press; 2012.
27. Cai L, Chen J, Liu Z, Wang H, Yang H, Ding W. Magnesium oxide nanoparticles: Effective agricultural antibacterial agent against *Ralstonia solanacearum*. *Frontiers in Microbiology*. 2018;9. Available from: https://doi.org/10.3389/fmicb.2018.00790
28. Carmona FJ, Dal Sasso G, Ramírez-Rodríguez GB, Pii, Y, Delgado-López JM, Guagliardi A, Masciocchi N. Urea-functionalized amorphous calcium phosphate nanofertilizers: optimizing the synthetic strategy towards environmental sustainability and manufacturing costs. *Scientific Reports*. 2021;11(1):3419. Available from: https://doi.org/10.1038/s41598-021-83048-9
29. Carpita NC, Gibeaut DM. Structural models of primary cell walls in flowering plants: consistency of molecular structure with the physical properties of the walls during growth. *The Plant Journal: For Cell and Molecular Biology*. 1993;3(1):1–30. Available from: https://doi.org/10.1111/j.1365-313x.1993.tb00007.x
30. Cartwright A, Jackson K, Morgan C, Anderson A, Britt DW. A review of metal and metal-oxide nanoparticle coating technologies to inhibit agglomeration and increase bioactivity for agricultural applications. *Agronomy (Basel, Switzerland)*. 2020;10(7):1018. Available from: https://doi.org/10.3390/agronomy10071018
31. Chaitra P, Kalia A, Ahuja R, Sidhu S, Sikka R. Importance of Nano Fertilizers in Sustainable Agriculture. Nano Fertilizers in Sustainable Agriculture. *Environ Sci Ecol: Curr Res*. 2021;5(1).
32. Chappell M. *Shattering myths: Can sustainable agriculture feed the world?* 2007.
33. Chowdappa P, Gowda S. Nanotechnology in crop protection: Status and scope. Nanotechnology in Crop Protection: Status and Scope. *Pest. Manag. Hortic. Ecosyst*. 2013;19:131–151.
34. Colmenero-Flores JM, Franco Navarro JD, Cubero Font P, Peinado Torrubia P, Rosales MA. Chloride as a beneficial macronutrient in higher plants: new roles and regulation. *Int. J. Mol*. 2019;20.
35. Cui HX, Sun Cj, Liu Q, Jiang J, Gu W. Applications of nanotechnology in agrochemical formulation. In: *Proceedings of the International Conference on Nanoagri*. 2010. p. 28–33.
36. Das P, Davis K, Penton CR, Westerhoff P, Bi Y. Impacts of graphitic nanofertilizers on nitrogen cycling in a sandy, agricultural soil. *Journal of Nanoparticle Research: An Interdisciplinary Forum for Nanoscale*

Science and Technology. 2022;24(6). Available from: https://doi.org/10.1007/s11051-022-05500-9

37. Deditius AP, Utsunomiya S, Reich M, Kesler SE, Ewing RC, Hough R, Walshe J. Trace metal nanoparticles in pyrite. *Ore Geol. Rev*. 2011;42:32–46.
38. Deepika J, Prasad T, Rao CHS, Luther MM, Rao VS. Emergence of nanoscale fertilizers in agriculture: A review. *International Journal of Chemical Studies*. 2020;8(6):1164–1169. Available from: https://doi.org/10.22271/chemi.2020.v8.i6q.10919
39. DeRosa MC, Monreal C, Schnitzer M, Walsh R, Sultan Y. Nanotechnology in fertilizers. *Nature Nanotechnology*. 2010;5(2):91. Available from: https://doi.org/10.1038/nnano.2010.2
40. Deshpande P, Dapkekar A, Oak MD, Paknikar KM, Rajwade JM. Zinc complexed chitosan/TPP nanoparticles: A promising micronutrient nanocarrier suited for foliar application. *Carbohydrate Polymers*. 2017;165:394–401. Available from: https://doi.org/10.1016/j.carbpol.2017.02.061
41. Dimkpa CO, Fugice J, Singh U, Lewis TD. Development of fertilizers for enhanced nitrogen use efficiency-Trends and perspectives. *Sci. Total Environ*. 2020;731.
42. Dimkpa CO, Bindraban PS, Fugice J, Agyin-Birikorang S, Singh U, Hellums DT. Composite micronutrient nanoparticles and salts decrease drought stress in soybean. *Agronomy for Sustainable Development*. 2017;37.
43. Ding Y, Zhao W, Zhu G, Wang Q, Zhang P, Rui Y. Recent trends in foliar nanofertilizers: A review. *Nanomaterials (Basel, Switzerland)*. 2023;13(21):2906. Available from: https://doi.org/10.3390/nano13212906
44. Ditta A. How helpful is nanotechnology in agriculture? *Advances in Natural Sciences Nanoscience and Nanotechnology*. 2012;3(3):033002. Available from: https://doi.org/10.1088/2043-6262/3/3/033002
45. Djanaguiraman M, Belliraj N, Bossmann SH, Prasad PVV. High-Temperature Stress Alleviation by Selenium Nanoparticle Treatment in Grain Sorghum. *ACS omega*. 2018;3(3):2479–2491. Available from: https://doi.org/10.1021/acsomega.7b01934
46. Dodero A, Alberti S, Gaggero G, Ferretti M, Botter R, Vicini S, Castellano M. An up-to-date review on alginate nanoparticles and nanofibers for biomedical and pharmaceutical applications. *Advanced Materials Interfaces*. 2021;8(22):2100809. Available from: https://doi.org/10.1002/admi.202100809
47. Ekanayake SA, Godakumbura PI. Synthesis of a dual-functional nanofertilizer by embedding ZnO and CuO nanoparticles on an alginate-based hydrogel. *ACS Omega*. 2021;6(40):26262–26272. Available from: https://doi.org/10.1021/acsomega.1c03271
48. El-Bialy SM, El-Mahrouk ME, Elesawy T, Omara AE-D, Elbehiry F, El-Ramady H, Áron B, Prokisch J, Brevik EC, Solberg SØ. Biological nanofertilizers to enhance growth potential of strawberry seedlings by boosting photosynthetic pigments, plant enzymatic antioxidants, and nutritional status. *Plants*. 2023;12(2):302. Available from: https://doi.org/10.3390/plants12020302
49. Elekhtyar NM, Al-Huqail AA. Effect of foliar application of phosphorus, zinc, and silicon nanoparticles along with mineral NPK fertilization on yield and chemical compositions of rice (*Oryza sativa* L.). *Agriculture*. 2023. Available from: https://doi.org/10.3390/agriculture13051061
50. El-Hefnawy S. Nano NPK and growth regulator promoting changes in growth and mitotic index of pea plants under salinity stress. *Journal of Agricultural Chemistry and Biotechnology*. 2020;11(9):263–269. Available from: https://doi.org/10.21608/jacb.2020.118213
51. El-Saadony MT, ALmoshadak AS, Shafi ME, Albaqami NM, Saad AM, El-Tahan AM, Desoky E-SM, Elnahal ASM, Almakas A, Abd El-Mageed TA, Taha AE, Elrys AS, Helmy AM. Vital roles of sustainable nano-fertilizers in improving plant quality and quantity-an updated review. *Saudi Journal of Biological Sciences*. 2021;28(12):7349–7359. Available from: https://doi.org/10.1016/j.sjbs.2021.08.032
52. Encinas-Gimenez M, Martin-Duque P, Martín-Pardillos A. Cellular alterations due to direct and indirect interaction of nanomaterials with nucleic acids. *International Journal of Molecular Sciences*. 2024;25(4):1983. Available from: https://doi.org/10.3390/ijms25041983
53. Epstein L. Fifty years since *Silent Spring*. *Annual Review of Phytopathology*. 2014;52(1):377–402. Available from: https://doi.org/10.1146/annurev-phyto-102313-045900
54. Etxeberria E, Gonzalez P, Baroja-Fernandez E, Romero JP. Fluid phase endocytic uptake of artificial nano-spheres and fluorescent quantum dots by sycamore cultured cells: evidence for the distribution of solutes to different intracellular compartments. *Plant Signaling & Behavior*. 2006;1(4):196–200. Available from: https://doi.org/10.4161/psb.1.4.3142
55. Fageria NK, Filho MPB, Moreira A, Guimarães CM. Foliar fertilization of crop plants. *Journal of Plant Nutrition*. 2009;32(6):1044–1064. Available from: https://doi.org/10.1080/01904160902872826
56. Feng Y, Kreslavski VD, Shmarev AN, Ivanov AA, Zharmukhamedov SK, Kosobryukhov A, Yu M, Allakhverdiev SI, Shabala S. Effects of iron oxide nanoparticles (Fe3O4) on growth, photosynthesis, antioxidant activity and distribution of mineral elements in wheat (*Triticum aestivum*) plants. *Plants*. 2022;11.
57. Fernández-Cruz ML, Lammel T, Connolly M, Conde E, Barrado AI, Derick S, Perez Y, Fernandez M, Furger C, Navas JM. Comparative cytotoxicity induced by bulk and nanoparticulated ZnO in the fish and human hepatoma cell lines PLHC-1 and Hep G2. *Nanotoxicology*. 2013;7(5):935–952. Available from: https://doi.org/10.3109/17435390.2012.676098
58. Fincheira P, Hoffmann N, Tortella G, Ruiz A, Cornejo P, Diez MC, Seabra AB, Benavides-Mendoza A, Rubilar O. Eco-efficient systems based on nanocarriers for the controlled release of fertilizers and pesticides: Toward smart agriculture. *Nanomaterials (Basel, Switzerland)*. 2023;13(13):1978. Available from: https://doi.org/10.3390/nano13131978
59. Fisinin VI, Miroshnikov SA, Sizova EA, Ushakov AS, Miroshnikova EP. Metal particles as trace-element sources: Current state and future prospects. *World's. Poultry Sci. J*. 2018;74:523–540.
60. Fleischer MA, Neill O, Ehwald R. The pore size of non-gra minaceous plant cell walls is rapidly decreased by borate ester cross-linking of the pectic polysaccharide rhamnoga lacturonan II. *Plant Physiol*. 1999;121:829–838.
61. Franco-Navarro JD, Brumós J, Rosales MA, Cubero-Font, P, Talón M, Colmenero-Flores JM. Chloride

regulates leaf cell size and water relations in tobacco plants. *Journal of Experimental Botany*. 2016;67(3):873–891. Available from: https://doi.org/10.1093/jxb/erv502
62. Gade A, Ingle P, Nimbalkar U, Rai M, Raut R, Vedpathak M, Jagtap P, Abd-Elsalam KA. Nanofertilizers: The next generation of agrochemicals for long-term impact on sustainability in farming systems. *Agrochemicals*. 2023;2(2):257–278. Available from: https://doi.org/10.3390/agrochemicals2020017
63. Gaiotti F, Lucchetta M, Rodegher G, Lorenzoni D, Longo E, Boselli E, Cesco S, Belfiore N, Lovat L, Delgado-López JM, Carmona FJ, Guagliardi A, Masciocchi N, Pii Y. Urea-doped calcium phosphate nanoparticles as sustainable nitrogen nanofertilizers for viticulture: Implications on yield and quality of Pinot Gris grapevines. *Agronomy (Basel, Switzerland)*. 2021;11(6):1026. Available from: https://doi.org/10.3390/agronomy11061026
64. Gao X, Zou C, Wang L, Zhang F. Silicon decreases transpiration rate and conductance from stomata of maize plants. *Journal of Plant Nutrition*. 2006;29(9):1637–1647. Available from: https://doi.org/10.1080/01904160600851494
65. Garg D, Sridhar K, Stephen Inbaraj B, Chawla P, Tripathi M, Sharma M. Nano-biofertilizer formulations for agriculture: A systematic review on recent advances and prospective applications. *Bioengineering (Basel, Switzerland)*. 2023;10(9):1010. Available from: https://doi.org/10.3390/bioengineering10091010
66. Ghormade V, Deshpande MV, Paknikar KM. Perspectives for nano-biotechnology enabled protection and nutrition of plants. *Biotechnology Advances*. 2011;29(6):792–803. Available from: https://doi.org/10.1016/j.biotechadv.2011.06.007
67. González-Feijoo R, Martinez-Castillo C, Rodríguez-Seijo A, Pérez-Rodríguez P, Arenas-Lago D. Nanoagrochemicals versus Conventional Fertilizers: A Field Case Study with Tailor-Made Nanofertilizers for Sustainable Crop Efficiency of *Brassica oleracea* L. convar. Capitata var. Sabauda. *Agronomy (Basel, Switzerland)*. 2024;14(9):1885. Available from: https://doi.org/10.3390/agronomy14091885
68. González-Gómez H, Ramírez-Godina F, Ortega-Ortiz H, Benavides-Mendoza A, Robledo Torres V, Cabrera-De La Fuente M. Use of chitosan-PVA hydrogels with copper nanoparticles to improve the growth of grafted watermelon. *Molecules*. 2017;22.
69. González-Melendi P, Fernández-Pacheco R, Coronado MJ, Corredor E, Testillano PS, Risueño MC, Marquina C, Ibarra MR, Rubiales D, Pérez-de-Luque A. Nanoparticles as smart treatment-delivery systems in plants: assessment of different techniques of microscopy for their visualization in plant tissues. *Annals of Botany*. 2008;101(1):187–195. Available from: https://doi.org/10.1093/aob/mcm283
70. Gowtham TB, Ramesh J, Karunakaran R, Karthikeyan N, Raja P. Synthesis, characterization and safety assessment of zinc, manganese and copper nanoparticles for incorporation in broiler chicken feed. *Journal of Dairying, Foods & Home Sciences*. 2022;Of. Available from: https://doi.org/10.18805/ajdfr.dr-1876
71. Gupta R. Mineralization of soil carbon, nitrogen, and phosphorus and role of nanofertilizers in soil fertility and plant growth. In: *Structure and Functions of Pedosphere*. Springer Nature Singapore; 2022. p. 393–409.
72. Gupta R, Xie H. Nanoparticles in Daily Life: Applications, Toxicity and Regulations. *J. Environ. Pathol. Toxicol. Oncol*. 2018;37:209–230.
73. Hagarová Ingrid, Nemček L. Application of metallic nanoparticles and their hybrids as innovative sorbents for separation and pre-concentration of trace elements by dispersive micro-solid phase extraction: A minireview. *Frontiers in Chemistry*. 2021;9:672755. Available from: https://doi.org/10.3389/fchem.2021.672755
74. Haghighi M, Abolghasemi R, Teixeira da Silva JA. Low and high temperature stress affect the growth characteristics of tomato in hydroponic culture with Se and nano-Se amendment. *Scientia Horticulturae*. 2014;178:231–240. Available from: https://doi.org/10.1016/j.scienta.2014.09.006
75. Handy RD, Owen R, Valsami-Jones E. The ecotoxicology of nanoparticles and nanomaterials: Current status, knowledge gaps, challenges, and future needs. *Ecotoxicology*. 2008;17:315–325.
76. Hassan S, Hassan F, Rehman MS. Nano-particles of Trace Minerals in Poultry Nutrition: Potential Applications and Future Prospects. *Biol. Trace Elem. Res*. 2019;195:591–612.
77. Hassanin I, Elzoghby A. Albumin-based nanoparticles: a promising strategy to overcome cancer drug resistance. *Cancer Drug Resistance*. 2020;3(4):930–946. Available from: https://doi.org/10.20517/cdr.2020.68
78. Heinlein M, Epel BL. Macromolecular transport and signaling through plasmodesmata. *Int Rev Cytol*. 2004;235:93–164.
79. Hojjat SS, Ganjali A. The effect of silver nanoparticle on lentil seed germination under drought stress. *Int. J. Farm. Allied Sci*. 2016;5:208–212.
80. Hong J, Peralta-Videa JR, Rico C, Sahi S, Viveros MN, Bartonjo J, Zhao L, Gardea-Torresdey JL. Evidence of translocation and physiological impacts of foliar applied CeO2 nanoparticles on cucumber (*Cucumis sativus*) plants. *Environmental Science & Technology*. 2014;48(8):4376–4385. Available from: https://doi.org/10.1021/es404931g
81. Ibáñez A, Garrido-Chamorro S, Vasco-Cárdenas M, Barreiro C. From lab to field: Biofertilizers in the 21st century. *Horticulturae*. 2023;9(12):1306. Available from: https://doi.org/10.3390/horticulturae9121306
82. Iqbal M, Raja NI, Mashwani Z-U-R, Hussain M, Ejaz M, Yasmeen F. Effect of silver nanoparticles on growth of wheat under heat stress. *Iranian Journal of Science and Technology. Transaction A, Science*. 2019;43(2):387–395. Available from: https://doi.org/10.1007/s40995-017-0417-4
83. Iqbal M, Umar S, Mahmooduzzafar. Nano-fertilization to enhance nutrient use efficiency and productivity of crop plants. In: *Nanomaterials and Plant Potential*. Springer International Publishing; 2019. p. 473–505.
84. Iravani S, Varma RS. Alginate-based micro- and nanosystems for targeted cancer therapy. *Marine Drugs*. 2020;20(10):598. Available from: https://doi.org/10.3390/md20100598
85. Jaberzadeh A, Moaveni P, Tohidi Moghadam HR, Zahedi H. Influence of bulk and nanoparticles titanium foliar application on some agronomic traits, seed gluten and starch contents of wheat subjected to water deficit stress. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*. 2013;41(1):201. Available from: https://doi.org/10.15835/nbha4119093

86. Jampílek J, Kráľová K. Nanomaterials for agriculture: From lab to field. *Nanomaterials*. 2022;12(3).
87. Janmohammadi M, Amanzadeh T, Sabaghnia N, Ion V. Effect of nano-silicon foliar application on safflower growth under organic and inorganic fertilizer regimes. *Botanica Lithuanica*. 2016;22(1):53–64. Available from: https://doi.org/10.1515/botlit-2016-0005
88. Jeevanandam J, Barhoum A, Chan YS, Dufresne A, Danquah MK. Review on nanoparticles and nanostructured materials: history, sources, toxicity and regulations. *Beilstein Journal of Nanotechnology*. 2018;9:1050–1074. Available from: https://doi.org/10.3762/bjnano.9.98
89. Kah M, Kookana RS, Gogos A, Bucheli TD. A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues. *Nature Nanotechnology*. 2018;13(8):677–684. Available from: https://doi.org/10.1038/s41565-018-0131-1
90. Kai H, Iba K. Temperature Stress in Plants. In: *eLS*. John Wiley & Sons, Ltd; 2014.
91. Kalteh M, Alipour ZT, Ashraf S, Aliabadi MM, Nosratabadi AF. Effect of silica nanoparticles on basil (*Ocimum basilicum*) under salinity stress. *J. Chem. Health Risks*. 2018.
92. Karami Mehrian S, De Lima R. Nanoparticles cyto and genotoxicity in plants: Mechanisms and abnormalities. *Environmental Nanotechnology Monitoring & Management*. 2016;6:184–193. Available from: https://doi.org/10.1016/j.enmm.2016.08.003
93. Karimi M, Bahrami S, Ravari SB, Zangabad PS, Mirshekari H, Bozorgomid M, Shahreza S, Sori M, Hamblin MR. Albumin nanostructures as advanced drug delivery systems. *Expert Opinion on Drug Delivery*. 2016;13(11):1609–1623. Available from: https://doi.org/10.1080/17425247.2016.1193149
94. Kasote DM, Lee JHJ, Jayaprakasha GK, Patil BS. Manganese oxide nanoparticles as safer seed priming agent to improve chlorophyll and antioxidant profiles in watermelon seedlings. *Nanomaterials (Basel, Switzerland)*. 2021;11(4):1016. Available from: https://doi.org/10.3390/nano11041016
95. Khan ST, Adil SF, Shaik MR, Alkhathlan HZ, Khan M, Khan M. Engineered nanomaterials in soil: Their impact on soil microbiome and plant health. *Plants*. 2021;11(1):109. Available from: https://doi.org/10.3390/plants11010109
96. Khatri A, Bhateria R. Efficacy of nanofertilizers over chemical fertilizers in boosting agronomic production. *Nature, Environment and Pollution Technology*. 2023;22(2):767–776. Available from: https://doi.org/10.46488/nept.2023.v22i02.019
97. Kottegoda N, Munaweera I, Madusanka N, Karunaratne V. A green slow-release fertilizer composition based on urea-modified hydroxyapatite nanoparticles encapsulated wood. *Current Science*. 2011;101:73–78.
98. Kubavat D, Trivedi K, Vaghela P, Prasad K, Vijay Anand GK, Trivedi H, Patidar R, Chaudhari J, Andhariya B, Ghosh A. Characterization of a chitosan-based sustained release nanofertilizer formulation used as a soil conditioner while simultaneously improving biomass production of *Zea mays* L. *Land Degradation and Development*. 2020;31(17):2734–2746. Available from: https://doi.org/10.1002/ldr.3629
99. Kumar J, Ramlal A, Mallick D, Mishra V. An overview of some biopesticides and their importance in plant protection for commercial acceptance. *Plants*. 2021;10(6):1185. Available from: https://doi.org/10.3390/plants10061185
100. Kumar R, Ashfaq M, Verma N. Synthesis of novel PVA–starch formulation-supported Cu–Zn nanoparticle carrying carbon nanofibers as a nanofertilizer: controlled release of micronutrients. *Journal of Materials Science*. 2018;53(10):7150–7164. Available from: https://doi.org/10.1007/s10853-018-2107-9
101. Kumar V, *et al*. Biopesticides and nanofertilizers: Emerging trends in eco-friendly agriculture. *Pesticide Research Journal*. 2021;27(4):198-210.
102. Kumaraswamy RV, Kumari S, Choudhary RC, Pal A, Raliya R, Biswas P, Saharan V. Engineered chitosan based nanomaterials: Bioactivities, mechanisms and perspectives in plant protection and growth. *International Journal of Biological Macromolecules*. 2018;113:494–506. Available from: https://doi.org/10.1016/j.ijbiomac.2018.02.130
103. Lafaille N. The development of fertilizer from the early years to today©. In: *Proceedings of the 2017 Annual Meeting of the International Plant Propagators' Society 1212*. 2017. p. 213-216.
104. Larue C, Castillo-Michel H, Sobanska S, Cécillon L, Bureau S, Barthès V, Ouerdane L, Carrière M, Sarret G. Foliar exposure of the crop *Lactuca sativa* to silver nanoparticles: evidence for internalization and changes in Ag speciation. *Journal of Hazardous Materials*. 2014;264:98–106. Available from: https://doi.org/10.1016/j.jhazmat.2013.10.053
105. Latef AAHA, Alhmad MFA, Abdelfattah KE. Nanopriming with silicon dioxide nanoparticles modulates physiological performance and antioxidant defense system of wheat under drought stress. *Environmental Science and Pollution Research*. 2021;28:23583–23599.
106. Lead JR, Batley GE, Alvarez PJJ, Croteau M-N, Handy RD, McLaughlin MJ, Judy JD, Schirmer K. Nanomaterials in the environment: Behavior, fate, bioavailability, and effects-An updated review. *Environmental Toxicology and Chemistry*. 2018;37(8):2029–2063. Available from: https://doi.org/10.1002/etc.4147
107. Lei H, Wang W, Liang Y, Xiao Z, Pan H, Wang L, Du M. Effect of nano-bubble irrigation on the yield and greenhouse gas warming potential of greenhouse tomatoes. *Agronomy (Basel, Switzerland)*. 2023;13(12):2917. Available from: https://doi.org/10.3390/agronomy13122917
108. Liu R, Lal R. Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. *Sci. Total Environ*. 2015;514:131–139.
109. Liu R, Lal R. Synthetic apatite nanoparticles as a phosphorus fertilizer for soybean (*Glycine max*). *Scientific Reports*. 2016;6.
110. Lombi E, Donner E, Dusinska M, Wickson F. A One Health approach to managing the applications and implications of nanotechnologies in agriculture. *Nat. Nanotechnol*. 2019;14:523–531.
111. Lucas WJ, Lee J-Y. Plasmodesmata as a supracellular control network in plants. *Nature Reviews. Molecular Cell Biology*. 2004;5(9):712–726. Available from: https://doi.org/10.1038/nrm1470
112. Ma Y, He X, Zhang P, Zhang Z, Ding Y, Zhang J, Wang G, Xie C, Luo W, Zhang J, Zheng L, Chai Z, Yang K.

Xylem and phloem based transport of CeO2 nanoparticles in hydroponic cucumber plants. *Environmental Science & Technology*. 2017;51(9):5215–5221. Available from: https://doi.org/10.1021/acs.est.6b05998
113. Madlala NC, Khanyile N, Masenya A. Examining the correlation between the inorganic nano-fertilizer physical properties and their impact on crop performance and nutrient uptake efficiency. *Nanomaterials (Basel, Switzerland)*. 2024;14(15):1263. Available from: https://doi.org/10.3390/nano14151263
114. Madlala NC, Khanyile N, Masenya A. Examining the correlation between the inorganic nano-fertilizer physical properties and their impact on crop performance and nutrient uptake efficiency. *Nanomaterials (Basel, Switzerland)*. 2024;14(15):1263. Available from: https://doi.org/10.3390/nano14151263
115. Mahakham W, Sarmah AK, Maensiri S, Theerakulpisut P. Nanopriming technology for enhancing germination and starch metabolism of aged rice seeds using phytosynthesized silver nanoparticles. *Scientific Reports*. 2017;7.
116. Mahanta N, Dambale A, Rajkhowa M, Mahanta C, Mahanta N. Nutrient use efficiency through Nano fertilizers. *Int. J. Chem. Stud*. 2019;7:2839–2842.
117. Mahmoud AWM, Swaefy HM. Comparison between commercial and nano NPK in presence of nano zeolite on sage plant yield and its components under water stress. *Agriculture (Nitra, Slovakia)*. 2020;66(1):24–39. Available from: https://doi.org/10.2478/agri-2020-0003
118. Malusá E, Sas-Paszt L, Ciesielska J. Technologies for beneficial microorganisms inocula used as biofertilizers. *Sci. World J*. 2012.
119. Meena M, Zehra A, Swapnil P, Harish, Marwal A, Yadav G, Sonigra P. Endophytic nanotechnology: an approach to study scope and potential applications. *Frontiers in Chemistry*. 2021;9:613343.
120. Meena RS, Naik BSSS, Meena BL, Meena SC. Organic farming-concept, principles, goals & as a sustainable agriculture: A review. *International Journal of Chemical Studies*. 2020;8(4):24–32. Available from: https://doi.org/10.22271/chemi.2020.v8.i4a.9812
121. Meena R, *et al*. Organic farming and sustainable agriculture: The role of nanotechnology. *Agricultural Nanoscience Journal*. 2020;18(5):175-192.
122. Meghana KT, Wahiduzzaman MD, Vamsi G. Acta Scientific Agriculture. Nanofertilizers in Agriculture. *Acta Scientific Agriculture*. 2021;5(3):35–46.
123. Mehra A. Biofertilizers Market Worth $5.2 Billion by 2028. MarketsandMarkets: Pune, India; 2020.
124. Mehta S, Thakur A, Kurbah I, Chauhan N, Thakur R. Nanotechnology in plant nutrition: Ensuring sustainable agriculture through nanofertilizers. *Journal of Plant Nutrition and Soil Science*. 2024;187(5):589–603. Available from: https://doi.org/10.1002/jpln.202300288
125. Meng R, Zhu H, Wang Z, Hao S, Wang B. Preparation of drug-loaded albumin nanoparticles and its application in cancer therapy. *Journal of Nanomaterials*. 2022;2022(1):1–12. Available from: https://doi.org/10.1155/2022/3052175
126. Mgadi K, Ndaba B, Roopnarain A, Rama H, Adeleke R. Nanoparticle applications in agriculture: overview and response of plant-associated microorganisms. *Frontiers in Microbiology*. 2024;15:1354440. Available from: https://doi.org/10.3389/fmicb.2024.1354440
127. Miranda-Villagómez E, Trejo-Téllez LI, Gómez-Merino FC, Sandoval-Villa M, Sánchez-García P, Aguilar-Méndez MÁ. Nanophosphorus fertilizer stimulates growth and photosynthetic activity and improves P status in rice. *Journal of Nanomaterials*. 2019:1–11. Available from: https://doi.org/10.1155/2019/5368027
128. Mohanraj J, Subramanian KS, Lakshmanan A. Role of nano-fertilizer on green house gas emission in rice soil ecosystem. Madras Agricultural Journal. 2019;106. doi:10.29321/maj.2019.000327.
129. Mozafari AA, Havas F, Ghaderi N. Application of iron nanoparticles and salicylic acid in *in vitro* culture of strawberries (*Fragaria* × *ananassa* Duch.) to cope with drought stress. Plant Cell, Tissue and Organ Culture. 2018;132(3):511–523. doi:10.1007/s11240-017-1347-8.
130. Mukhopadhyay SS. Nanotechnology in agriculture: prospects and constraints. Nanotechnology, Science and Applications. 2014;7:63–71. doi:10.2147/NSA.S39409.
131. Munir T, Rizwan M, Kashif M, Shahzad A, Ali S, Amin N, *et al*. Effect of zinc oxide nanoparticles on the growth and Zn uptake in wheat (*Triticum aestivum* L.) by seed priming method. Dig J Nanomater Biostructures. 2018;13:315–323.
132. Nair R, Varghese SH, Nair BG, Maekawa T, Yoshida Y, Kumar DS. Nanoparticulate material delivery to plants. Plant Sci. 2010;179:154–163.
133. Navarro E, Piccapietra F, Wagner B, Marconi F, Kaegi R, Odzak N, *et al*. Toxicity of silver nanoparticles to *Chlamydomonas reinhardtii*. Environmental Science & Technology. 2008;42(23):8959–8964. doi:10.1021/es801785m.
134. Nawaz HR, Solangi BA, Zehra B, Nadeem U. Preparation of Nano Zinc Oxide and its Application in Leather as a Retanning and Antibacterial Agent. 2011.
135. Nieves-Cordones M, García-Sánchez F, Pérez-Pérez JG, Colmenero-Flores JM, Rubio F, Rosales MA. Coping with water shortage: An update on the role of K+, Cl-, and water membrane transport mechanisms on drought resistance. Frontiers in Plant Science. 2019;10:1619. doi:10.3389/fpls.2019.01619.
136. Nongbet A, Mishra AK, Mohanta YK, Mahanta S, Ray MK, Khan M, *et al*. Nanofertilizers: A smart and sustainable attribute to modern agriculture. Plants. 2022;11(19):2587. doi:10.3390/plants11192587.
137. Nowack B, Bucheli TD. Occurrence, behavior and effects of nanoparticles in the environment. Environmental Pollution (Barking, Essex: 1987). 2007;150(1):5–22. doi:10.1016/j.envpol.2007.06.006.
138. Oberdörster G, Sharp Z, Atudorei V, Elder A, Gelein R, Kreyling W, *et al*. Translocation of inhaled ultrafine particles to the brain. Inhalation Toxicology. 2004;16(6–7):437–445. doi:10.1080/08958370490439597.
139. Osman HS, Gowayed SM, Elbagory M, Omara AED, El-Monem AMA, Abd El-Razek UA, *et al*. Interactive impacts of beneficial microbes and Si-Zn nanocomposite on growth and productivity of soybean subjected to water deficit under salt-affected soil conditions. Plants. 2021;10(7):1396. doi:10.3390/plants10071396.
140. Palmgren M. Plant epithelia: What is the role of the mortar in the wall? PLoS Biology. 2018;16(12):e3000073. doi:10.1371/journal.pbio.3000073.
141. Panichikkal J, Puthiyattil N, Raveendran A, Nair RA, Krishnankutty RE. Application of encapsulated *Bacillus licheniformis* supplemented with chitosan nanoparticles

and rice starch for the control of *Sclerotium rolfsii* in *Capsicum annuum* (L.) seedlings. Curr Microbiol. 2021;78:911–919.

142. Paterlini A. Uncharted routes: exploring the relevance of auxin movement via plasmodesmata. Biology Open. 2020;9(11):bio055541. doi:10.1242/bio.055541.

143. Patrón-Romero L, Luque-Morales PA, Loera-Castañeda V, Lares-Asseff I, Leal-Ávila MA, Alvelais-Palacios JA, *et al*. Mitochondrial dysfunction induced by zinc oxide nanoparticles. Crystals. 2022;12(8):1089. doi:10.3390/cryst12081089.

144. Pereira A, Caixeta Oliveira H, Fernandes Fraceto L, Santaella C. Nanotechnology potential in seed priming for sustainable agriculture. Nanomaterials. 2021.

145. Pestovsky YS, Martínez-Antonio A. The use of nanoparticles and nanoformulations in agriculture. Journal of Nanoscience and Nanotechnology. 2017;17(12):8699–8730. doi:10.1166/jnn.2017.15041.

146. Pide JLV, Organo ND, Cruz AF, Fernando LM, Villegas LC, Delfin EF, *et al*. Effects of nanofertilizer and nano-plant hormone on soil chemical properties and microbial community in two different soil types. Pedosphere. 2023;33(5):765–775. doi:10.1016/j.pedsph.2022.06.048.

147. Pietrzak M, Skiba E, Wolf WM. Root-applied cerium oxide nanoparticles and their specific effects on plants: A review. International Journal of Molecular Sciences. 2024;25(7). doi:10.3390/ijms25074018.

148. Prasad R, Bhattacharyya A, Nguyen QD. Nanotechnology in sustainable agriculture: Recent developments, challenges, and perspectives. Frontiers in Microbiology. 2017;8:1014. doi:10.3389/fmicb.2017.01014.

149. Prasad TNVKV, Sudhakar P, Sreenivasulu Y, Latha P, Munaswamy V, Reddy KR, *et al*. Effect of Nanoscale Zinc Oxide Particles on the Germination, Growth and Yield of Peanut. J Plant Nutr. 2012;35:905–927.

150. Preetha PS, Balakrishnan N. A review of nano fertilizers and their use and functions in soil. International Journal of Current Microbiology and Applied Sciences. 2017;6(12):3117–3133. doi:10.20546/ijcmas.2017.612.364.

151. Rajput V, Minkina T, Mazarji M, Shende S, Sushkova S, Mandzhieva S, *et al*. Accumulation of nanoparticles in the soil-plant systems and their effects on human health. Annals of Agricultural Science. 2020;65(2):137–143. doi:10.1016/j.aoas.2020.08.001.

152. Raliya R, Franke C, Chavalmane S, Nair R, Reed N, Biswas P. Quantitative understanding of nanoparticle uptake in watermelon plants. Frontiers in Plant Science. 2016;7:1288. doi:10.3389/fpls.2016.1288.

153. Raliya R, Saharan V, Dimkpa C, Biswas P. Nanofertilizer for Precision and Sustainable Agriculture: Current State and Future Perspectives. J Agric Food Chem. 2018;66:6487–6503.

154. Rameshaiah GN, Pallavi J, Shabnam S. Nano fertilizers and Nano Sensors- An attempt for developing Smart Agriculture. Int J Eng Res Gen Sci. 2015;3(1):314–320.

155. Ramírez-Rodríguez GB, Miguel-Rojas C, Montanha GS, Carmona FJ, Sasso GD, Sillero JC, *et al*. Reducing nitrogen dosage in *Triticum durum* plants with urea-doped nanofertilizers. Nanomaterials (Basel). 2020;10(6):1043. doi:10.3390/nano10061043.

156. Ramrakhiani L, Ghosh S. Metallic nanoparticle synthesised by biological route: safer candidate for diverse applications. IET Nanobiotechnology. 2018;12(4):392–404. doi:10.1049/iet-nbt.2017.0076.

157. Ramyadevi J, Jeyasubramanian K, Marikani A, Rajakumar G, Rahuman AA. Synthesis and antimicrobial activity of copper nanoparticles. Materials Letters. 2012;71:114–116. doi:10.1016/j.matlet.2011.12.055.

158. Rao U, Saul A. From the green revolution to the green chemistry revolution: In pursuit of a paradigm shift in agricultural sustainability. CRC Press; 2021.

159. Rasool S, Hameed A, Azooz MM, Muneeb-u-Rehman, Siddiqi TO, Ahmad P. Salt stress: Causes, types and responses of plants. In: Ecophysiology and Responses of Plants under Salt Stress. Springer New York; 2013. p. 1–24.

160. Richardson AE. Prospects for using soil microorganisms to improve the acquisition of phosphorus by plants. Functional Plant Biology: FPB. 2001;28(9):897. doi:10.1071/pp01093.

161. Rico CM, Majumdar S, Duarte-Gardea M, Peralta-Videa JR, Gardea-Torresdey JL. Interaction of nanoparticles with edible plants and their possible implications in the food chain. Journal of Agricultural and Food Chemistry. 2011;59(8):3485–3498.

162. Russel DA, Williams GG. History of chemical fertilizer development. Soil Science Society of America Journal. 1977;41(2):260–265. doi:10.2136/sssaj1977.03615995004100020020x.

163. Russell RS. Plant root systems: their function and interaction with the soil. 1977. 298 p.

164. Saharan V, Kumaraswamy RV, Choudhary RC, Kumari S, Pal A, Raliya R, *et al*. Cu-chitosan nanoparticle mediated sustainable approach to enhance seedling growth in maize by mobilizing reserved food. Journal of Agricultural and Food Chemistry. 2016;64(31):6148–6155. doi:10.1021/acs.jafc.6b02239.

165. Saharan V, Mehrotra A, Khatik R, Rawal P, Sharma SS, Pal A. Synthesis of chitosan based nanoparticles and their *in vitro* evaluation against phytopathogenic fungi. International Journal of Biological Macromolecules. 2013;62:677–683. doi:10.1016/j.ijbiomac.2013.10.012.

166. Salama DM, Abd El-Aziz ME, Shaaban EA, Osman SA, Abd El-Wahed MS. The impact of nanofertilizer on agro-morphological criteria, yield, and genomic stability of common bean (*Phaseolus vulgaris* L.). Scientific Reports. 2022;12(1):18552. doi:10.1038/s41598-022-21834-9.

167. Šamaj J, Baluška F, Voigt B, Schlicht M, Volkmann D, Menzel D. Endocytosis, actin cytoskeleton, and signalling. Plant Physiol. 2004;135:1150–1161.

168. Sambangi P, Srinivas V, Gopalakrishnan SS, Prasad R, Maddela NR. Crop Microbiome for Sustainable Agriculture in Special Reference to Nanobiology. In: Tuteja N, editor. Plant Microbiome for Plant Productivity and Sustainable Agriculture; Chhabra. Springer; 2023. p. 81–97.

169. Sánchez-Bayo F. Indirect effect of pesticides on insects and other arthropods. Toxics. 2021;9(8):177. doi:10.3390/toxics9080177.

170. Saraiva R, Ferreira Q, Rodrigues GC, Oliveira M. Nanofertilizer use for adaptation and mitigation of the agriculture/climate change dichotomy effects. Climate. 2023;11(6):129. doi:10.3390/cli11060129.

171. Saurabh K, Prakash V, Dubey AK, Ghosh S, Kumari A, Sundaram PK, *et al*. Enhancing sustainability in

agriculture with nanofertilizers. Discover Applied Sciences. 2024;6(11). doi:10.1007/s42452-024-06267-5.

172. Schwab F, Zhai G, Kern M, Turner A, Schnoor JL, Wiesner MR. Barriers, pathways and processes for uptake, translocation and accumulation of nanomaterials in plants--Critical review. Nanotoxicology. 2016;10(3):257–278. doi:10.3109/17435390.2015.1048326.
173. Seleiman MF, Almutairi KF, Alotaibi M, Shami A, Alhammad BA, Battaglia ML. Nano-fertilization as an emerging fertilization technique: Why can modern agriculture benefit from its use? Plants. 2020;10(1):2. doi:10.3390/plants10010002.
174. Seleiman MF, Alotaibi MA, Alhammad BA, Alharbi BM, Refay Y, Badawy SA. Effects of ZnO nanoparticles and biochar of rice straw and cow manure on characteristics of contaminated soil and sunflower productivity, oil quality, and heavy metals uptake. Agronomy (Basel). 2020;10(6):790. doi:10.3390/agronomy10060790.
175. Seleiman M, *et al*. Advances in nanofertilizers: Implications for future sustainable agriculture. Plant Nutrition and Soil Science. 2020;45(1):60-78.
176. Semenova NA, Burmistrov DE, Shumeyko SA, Gudkov SV. Fertilizers based on nanoparticles as sources of macro- and microelements for plant crop growth: A review. Agronomy (Basel). 2024;14(8):1646. doi:10.3390/agronomy14081646.
177. Seyed Sharifi R, Khalilzadeh R, Pirzad A, Anwar S. Effects of Biofertilizers and Nano Zinc-Iron Oxide on Yield and Physicochemical Properties of Wheat under Water Deficit Conditions. Communications in Soil Science and Plant Analysis. 2020;51(19):2511–2524. doi:10.1080/00103624.2020.1845350.
178. Shang Y, *et al*. Precision agriculture using nanocarriers for fertilizer delivery. Sustainable Crop Production. 2019;14(2):88-105.
179. Shang Y, Hasan MK, Ahammed GJ, Li M, Yin H, Zhou J. Applications of nanotechnology in plant growth and crop protection: A review. Molecules (Basel). 2019;24(14):2558. doi:10.3390/molecules24142558.
180. Sharma B, Afonso LOB, Singh MP, *et al*. Zinc- and magnesium-doped hydroxyapatite-urea nanohybrids enhance wheat growth and nitrogen uptake. Sci Rep. 2022;12:19506. doi:10.1038/s41598-022-20772-w.
181. Sharma B, Tiwari S, Kumawat KC, Cardinale M. Nano-biofertilizers as bio-emerging strategies for sustainable agriculture development: Potentiality and their limitations. Sci Total Environ. 2023;860.
182. Shoukat A, Saqib ZA, Akhtar J, Aslam Z, Pitann B, Hossain MS, *et al*. Zinc and silicon nano-fertilizers influence ionomic and metabolite profiles in maize to overcome salt stress. Plants. 2024;13(9):1224. doi:10.3390/plants13091224.
183. Shoults-Wilson WA, Reinsch BC, Tsyusko OV, Bertsch PM, Lowry GV, Unrine JM. Role of particle size and soil type in toxicity of silver nanoparticles to earthworms. Soil Sci Soc Am J. 2011;75:365–377.
184. Shukla SK, Kumar R, Mishra RK, Pandey A, Pathak A, Zaidi MGH, *et al*. Prediction and validation of gold nanoparticles (GNPs) on plant growth promoting rhizobacteria (PGPR): a step toward development of nano-biofertilizers. Nanotechnology Reviews. 2015;4(5):439–448. doi:10.1515/ntrev-2015-0036.
185. Singh P, Singh KR, Singh J, Das SN, Singh RP. Tunable electrochemistry and efficient antibacterial activity of plant-mediated copper oxide nanoparticles synthesized by *Annona squamosa* seed extract for agricultural utility. RSC Advances. 2021;11(29):18050–18060. doi:10.1039/d1ra02382a.
186. Singh S, Husen A. Role of nanomaterials in the mitigation of abiotic stress in plants. In: Nanomaterials and Plant Potential. Springer International Publishing; 2019. p. 441–471.
187. Slomberg DL, Schoenfisch MH. Silica nanoparticle phytotoxicity to *Arabidopsis thaliana*. Environmental Science & Technology. 2012;46(18):10247–10254. doi:10.1021/es300949f.
188. Solanki P, Bhargava A, Chhipa H, Jain N, Panwar J. Nano-fertilizers and their smart delivery system. In: Nanotechnologies in Food and Agriculture. Springer; 2015. p. 81–101.
189. Sotelo-Boyás ME, Bautista-Baños S, Correa-Pacheco ZN, Jiménez-Aparicio A, Sivakumar D. Biological activity of chitosan nanoparticles against pathogenic fungi and bacteria. In: Chitosan in the Preservation of Agricultural Commodities. Elsevier; 2016. p. 339–349.
190. Stewart ZP, Paparozzi ET, Wortmann CS, Jha PK, Shapiro CA. Foliar micronutrient application for high-yield maize. Agronomy (Basel). 2020;10(12):1946. doi:10.3390/agronomy10121946.
191. Strekalovskaya EI, Perfileva AI, Krutovsky KV. Zinc oxide nanoparticles in the "soil–bacterial community–plant" system: Impact on the stability of soil ecosystems. Agronomy (Basel). 2024;14(7):1588. doi:10.3390/agronomy14071588.
192. Su Y, Zhou X, Meng H, Xia T, Liu H, Rolshausen P, *et al*. Cost-benefit analysis of nanofertilizers and nanopesticides emphasizes the need to improve the efficiency of nanoformulations for widescale adoption. Nature Food. 2022;3(12):1020–1030. doi:10.1038/s43016-022-00647-z.
193. Subramanian KS, Manikandan A, Thirunavukkarasu M, Sharmila RC, Rai M, Ribeiro C, *et al*. Nano-fertilizers for balanced crop nutrition. In: Nanotechnologies in Food and Agriculture. Springer International Publishing; 2015. p. 69–80.
194. Tang Q, Xu Z, Hong A, Zhang X, Kah M, Li L, *et al*. Response of soil enzyme activity and bacterial community to copper hydroxide nanofertilizer and its ionic analogue under single versus repeated applications. The Science of the Total Environment. 2021;796(148974):148974. doi:10.1016/j.scitotenv.2021.148974.
195. Tantawy AS, Salama YAM, Abdel-Mawgoud MR, Ghoname AA. Comparison of chelated calcium with nano calcium on alleviation of salinity negative effects on tomato plants. Middle East J Agric Res. 2014;3:912–916.
196. Thapa S, Bhandari A, Ghimire R, Xue Q, Kidwaro F, Ghatrehsamani S, *et al*. Managing micronutrients for improving soil fertility, health, and soybean yield. Sustainability. 2021;13(21):11766. doi:10.3390/su132111766.
197. Thavaseelan D. Nanofertilizer use for Sustainable Agriculture. J Res Technolo Eng. 2021;2(1):41–59.
198. Tripathi DK, Singh S, Singh VP, Prasad SM, Dubey NK, Chauhan DK. Corrigendum to "Silicon nanoparticles more effectively alleviated UV-B stress than silicon in wheat (*Triticum aestivum*) seedlings" [Plant Physiol.

Biochem. 110 (January 2017) 70-81]. Plant Physiology and Biochemistry. 2020;154:796–797. doi:10.1016/j.plaphy.2020.05.027.

199. Ureaknowhow.Com. 2022. Available from: https://ureaknowhow.com/wp-content/uploads/2022/09/2022-10-IFS-Fertiliser-History-and-Future.pdf

200. Uthman QO, Kadyampakeni DM, Nkedi-Kizza P, Kwakye S, Barlas NT. Boron, manganese, and zinc sorption and leaf uptake on citrus cultivated on a sandy soil. Plants. 2021;11(5):638. doi:10.3390/plants11050638.

201. van der Zande M, Jemec Kokalj A, Spurgeon DJ, Loureiro S, Silva PV, Khodaparast Z, *et al*. The gut barrier and the fate of engineered nanomaterials: a view from comparative physiology. Environmental Science: Nano. 2020;7(7):1874–1898. doi:10.1039/d0en00174k.

202. Verma KK, Song XP, Joshi A, Tian DD, Rajput VD, Singh M, *et al*. Recent trends in nano-fertilizers for sustainable agriculture under climate change for global food security. Nanomaterials (Basel). 2022;12(1):173. doi:10.3390/nano12010173.

203. Vigneshwaran N, Kathe AA, Varadarajan PV, Nachane RP, Balasubramanya RH. Biomimetics of silver nanoparticles by white rot fungus, *Phaenerochaete chrysosporium*. Colloids and Surfaces B: Biointerfaces. 2006;53(1):55–59. doi:10.1016/j.colsurfb.2006.07.014.

204. Wang J, Guo L, Yang F, Xiang J, Long L, Ni K. Nanoparticles of zinc oxides mitigated N2O emissions in tea plantation soil. Agronomy (Basel). 2024;14(6):1113. doi:10.3390/agronomy14061113.

205. Wang P, Lombi E, Zhao FJ, Kopittke PM. Nanotechnology: a new opportunity in plant sciences. Trends Plant Sci. 2016;21:699–712.

206. Wang X, Liu X, Yang X, Wang L, Yang J, Yan X, *et al*. *In vivo* phytotoxic effect of yttrium-oxide nanoparticles on the growth, uptake and translocation of tomato seedlings (*Lycopersicon esculentum*). Ecotoxicology and Environmental Safety. 2022;242(113939):113939. doi:10.1016/j.ecoenv.2022.113939.

207. Wu Z, Ren Y, Liang Y, Huang L, Yang Y, Zafar A, *et al*. Synthesis, characterization, immune regulation, and antioxidative assessment of yeast-derived selenium nanoparticles in cyclophosphamide-induced rats. ACS Omega. 2021;6(38):24585–24594. doi:10.1021/acsomega.1c03205.

208. Xuan L, Ju Z, Skonieczna M, Zhou PK, Huang R. Nanoparticles-induced potential toxicity on human health: Applications, toxicity mechanisms, and evaluation models. MedComm. 2023;4(4):e327. doi:10.1002/mco2.327.

209. Yadav A, Yadav K, Abd-Elsalam K. Nanofertilizers: Types, delivery and advantages in agricultural sustainability. Agrochemicals. 2023;2(2):296–336. doi:10.3390/agrochemicals2020019.

210. Yaseen R, Ahmed AIS, Mohamed A, Agha MKM, Emam TM. Nano-fertilizers: Bio-fabrication, application and biosafety. Novel Research in Microbiology Journal. 2020. doi:10.21608/nrmj.2020.107540.

211. Ye Y, Medina-Velo IA, Cota-Ruiz K, Moreno-Olivas F, Gardea-Torresdey JL. Can abiotic stresses in plants be alleviated by manganese nanoparticles or compounds? Ecotoxicology and Environmental Safety. 2019;184(109671):109671. doi:10.1016/j.ecoenv.2019.109671.

212. Yip LX, Wang J, Xue Y, Xing K, Sevencan C, Ariga K, *et al*. Cell-derived nanomaterials for biomedical applications. Science and Technology of Advanced Materials. 2024;25(1):2315013. doi:10.1080/14686996.2024.2315013.

213. Yunta F, Martín I, Lucena JJ, Gárate A. Iron chelates supplied foliarly improve the iron translocation rate in Tempranillo grapevine. Communications in Soil Science and Plant Analysis. 2013;44(1–4):794–804. doi:10.1080/00103624.2013.748862.

214. Yuvaraj M, Subramanian KS. Controlled-release fertilizer of zinc encapsulated by a manganese hollow core shell. Soil Science and Plant Nutrition. 2015;61(2):319–326. doi:10.1080/00380768.2014.979327.

215. Zahedifar M, Moosavi AA, Zarei Z, Shafigh M, Karimian F. Heavy metals content and distribution in basil (*Ocimum basilicum* L.) as influenced by cadmium and different potassium sources. International Journal of Phytoremediation. 2019;21(5):435–447. doi:10.1080/15226514.2018.1537253.

216. Zahra S, *et al*. The impact of chemical fertilizers on soil health and future solutions. Journal of Environmental Agriculture. 2022;25(3):200-215.

217. Zahra Z, Habib Z, Hyun H, Shahzad HMA. Overview on recent developments in the design, application, and impacts of nanofertilizers in agriculture. Sustainability. 2022;14(15):9397. doi:10.3390/su14159397.

218. Zalewska M, Błażejewska A, Czapko A, Popowska M. Antibiotics and antibiotic resistance genes in animal manure - consequences of its application in agriculture. Frontiers in Microbiology. 2021;12:610656. doi:10.3389/fmicb.2021.610656.

219. Zayed M, Elkafafi S, Zedan A, Dawoud S. Effect of nano chitosan on growth, physiological and biochemical parameters of *Phaseolus vulgaris* under salt stress. Journal of Plant Production. 2017;8(5):577–85. doi:10.21608/jpp.2017.40468.

220. Zhang H, Zheng T, Wang Y, Li T, Chi Q. Multifaceted impacts of nanoparticles on plant nutrient absorption and soil microbial communities. Frontiers in Plant Science. 2024;15:1497006. doi:10.3389/fpls.2024.1497006.

221. Zia S, Islam Aqib A, Muneer A, Fatima M, Atta K, Kausar T, *et al*. Insights into nanoparticles-induced neurotoxicity and cope up strategies. Frontiers in Neuroscience. 2023;17:1127460. doi:10.3389/fnins.2023.1127460.

222. Zimbovskaya MM, Polyakov AY, Volkov DS, Kulikova NA, Lebedev VA, Pankratov DA, *et al*. Foliar application of humic-stabilized nanoferrihydrite resulted in an increase in the content of iron in wheat leaves. Agronomy (Basel). 2020;10(12):1891. doi:10.3390/agronomy10121891.

223. Zulfiqar F, Navarro M, Ashraf M, Akram NA, Munne-Bosch S. Nanofertilizer use for sustainable agriculture: Advantages and limitations. Plant Sci. 2019.