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NANOFERTILIZERS AND STRESS MANAGEMENT: EMERGING OPPORTUNITIES FOR CLIMATE-RESILIENT FARMING

Abbas Shoukat*

Institute of Plant Nutrition and Soil Science, Kiel University, Hermann-Rodewald-Str. 2, 24118 Kiel, Germany

**Corresponding author*: ashoukat@plantnutrition.uni-kiel.de

ABSTRACT

Nanofertilizers (NFs) represent a transformative approach in sustainable agriculture by integrating nanoscale carriers and smart delivery systems into plant nutrition. This review synthesizes recent advances in four major categories of NFs: macro-nanofertilizers (N, P, K), micro-nanofertilizers (Zn, Fe, Mn, Cu, B, Mo), nano-biofertilizers (microbial and polysaccharide-based), and smart nanofertilizers (controlled-release and stimuli-responsive). We highlight their unique mechanisms of action, including multiple uptake pathways (root, foliar, and stomatal), controlled nutrient release, improved bioavailability, and modulation of plant physiology at molecular and metabolic levels. A particular focus is given to their role in mitigating abiotic stresses salinity, drought, heat, and nutrient deficiencies through regulation of ion homeostasis, antioxidant defense, osmolyte accumulation, and photosynthetic stability. Evidence from cereals, horticultural crops, and biofortification programs indicates that NFs not only enhance nutrient-use efficiency (NUE) and yields but also improve nutritional quality of grains, thereby addressing both food security and hidden hunger. Environmental assessments reveal that, compared with conventional fertilizers, NFs substantially reduce leaching, volatilization, and greenhouse gas emissions, while potential ecological risks remain associated with nanoparticle persistence, transformation, and impacts on soil microbial diversity. Despite these advantages, limitations such as nanotoxicity, high production costs, and insufficient multi-year field validations pose challenges to widescale adoption. Emerging opportunities lie in safe-by-design formulations using biodegradable carriers, stress-specific nanoformulations, and integration with precision agriculture and digital farming. Overall, NFs offer a paradigm shift toward climate-smart and resource-efficient agriculture, but responsible innovation, regulatory frameworks, and farmer-oriented validation are essential for realizing their global potential.

Keywords: Nano-biofertilizers, Nutrient-use efficiency (NUE), Biofortification, Abiotic stress tolerance (salinity, drought, heat), Ion homeostasis

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1. INTRODUCTION

1.1. Global Food and Climate Challenges

Food security has emerged as one of the most critical global concerns of the twenty-first century (Leisinger et al., 2002). According to the Food and Agriculture Organization (FAO), the world will need to produce nearly 70% more food by 2050 to meet the demands of a projected 9.7 billion people (Hussain et al., 2025). This increase must be achieved against the backdrop of shrinking arable land, soil degradation and limited water resources**.** Currently, approximately 33% of the world's soils are degraded due to erosion, nutrient depletion, and salinization, while irrigation already consumes about 70% of global freshwater resources (Khondoker et al., 2023). These figures illustrate the pressing reality that our natural resource base is under severe strain.

Compounding these challenges is the intensifying impact of climate change. Global average temperatures have already risen by 1.1°C above pre-industrial levels, and are projected to increase by at least 2 °C by the end of the century if greenhouse gas emissions continue unchecked (Adak et al., 2023). Shifts in precipitation patterns, coupled with the increased frequency of extreme weather events, are disrupting agricultural calendars, shortening growing seasons, and threatening crop yields. For instance, climate models estimate that wheat yields may decline by 6% for every 1°C rise in global temperature, while rice and maize production could fall by 10–20% in vulnerable regions (Asseng et al., 2017). Droughts in sub-Saharan Africa, salinity intrusion in South Asia, and heat waves in Europe and North America all demonstrate that no region is immune to these disruptions.

The consequences extend beyond mere yield reduction. Climate change also affects nutritional quality (Agrimonti et al., 2021). Elevated atmospheric CO_2 has been shown to reduce the protein, iron, and zinc content of

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staple cereals, exacerbating hidden hunger in vulnerable populations. Moreover, climate-related disasters such as floods, cyclones, and wildfires disrupt not only on-farm production but also supply chains, transport networks, and storage systems, thereby magnifying the risks of food insecurity (Clement, 2025). Smallholder farmers who form the backbone of food production in many developing countries are particularly vulnerable because they rely heavily on rain-fed systems and often lack access to financial, technical, and institutional support (Kapari et al., 2023). Thus, global food and climate challenges present a dual crisis: the need to increase productivity while simultaneously reducing agriculture's environmental footprint.

1.2. Inefficiency of Conventional Fertilizers

Since the Green Revolution, fertilizers have played an indispensable role in boosting crop productivity and ensuring food security. The widespread use of nitrogen, phosphorus, and potassium fertilizers contributed significantly to yield improvements in rice, wheat, and maize, lifting millions out of hunger (Sinha & Tandon, 2020). However, the efficiency of conventional fertilizers is alarmingly low. Studies indicate that crops typically use only 30–40% of applied nitrogen, 15–20% of phosphorus, and 35–50% of potassium; the remainder is lost through leaching, runoff, volatilization, or fixation in the soil (Sinha & Tandon, 2020). These inefficiencies not only undermine farmer profitability but also impose high ecological costs.

The environmental consequences of fertilizer mismanagement are profound. Nitrogen fertilizers are the largest source of nitrous oxide (N_2O) emissions, a greenhouse gas with a global warming potential nearly 300 times that of CO_2 (Filonchyk et al., 2024). Excess phosphorus contributes to eutrophication of water bodies, creating harmful algal blooms, oxygen depletion, and biodiversity loss (Wurtsbaugh et al., 2019). Potassium imbalances, though less publicly visible, can disturb soil health and crop resilience (Khan et al., 2014). In South Asia, for example, excessive urea application coupled with declining use of balanced fertilizers has degraded soil structure and caused long-term declines in productivity (Geng et al., 2015). Similarly, in China, the over-application of fertilizers has led to groundwater contamination, nitrate pollution, and acidification of nearly 20% of agricultural soils (Ju et al., 2004).

Economically, inefficient fertilizers also represent massive losses. It is estimated that globally, farmers waste billions of dollars annually on fertilizer that never reaches crops (Sheriff, 2005). This inefficiency is unsustainable in both developed and developing nations. For smallholder farmers, fertilizer losses exacerbate poverty and deepen dependence on subsidies. For industrial agriculture, they contribute to the carbon footprint of global food systems, making agriculture one of the major contributors to climate change (Lal, 2022). Therefore, while conventional fertilizers have undeniably boosted global food production, their inefficiency and ecological impact underline the need for smarter, more sustainable alternatives.

1.3. Emergence of Nanotechnology for Sustainable Crop Nutrition

Nanotechnology has emerged as a transformative tool in addressing the shortcomings of conventional fertilizers and in meeting future food and climate challenges (Rana et al., 2024). Nanofertilizers are fertilizers engineered at the nanoscale (1–100 nm) that leverage unique properties, such as high surface area-to-volume ratios, enhanced reactivity, and controlled-release mechanisms (Shabiya et al., 2025). These properties make nanofertilizers fundamentally different from traditional bulk fertilizers in terms of nutrient delivery, uptake, and efficiency.

One of the most promising features of nanofertilizers is their ability to deliver nutrients in a controlled and targeted manner. Nutrients encapsulated in nanomaterials such as nanoclays, polymeric nanoparticles, carbon nanotubes, and hydroxyapatite can be released slowly and in synchrony with plant growth stages (Takkar & Gumber, 2024). This reduces losses due to leaching or volatilization, ensures continuous nutrient availability, and minimizes the need for repeated applications. Moreover, nanofertilizers can be designed as stimuli-responsive systems that trigger nutrient release in response to environmental factors such as soil pH, moisture, or root exudates (Azeem, 2025).

Uptake mechanisms of nanofertilizers also enhance their effectiveness. Due to their small size, nanoparticles can enter plant systems through stomata, cuticular pores, and root apoplasts, and then move systemically through xylem and phloem pathways (Avellan et al., 2021). This targeted delivery ensures higher nutrient-use efficiency compared to conventional fertilizers. For instance, zinc oxide nanoparticles have been shown to increase grain zinc content in wheat while simultaneously improving plant antioxidant defenses under salinity stress (Mishra et al., 2025). Similarly, nitrogen nanofertilizers enhance chlorophyll content and photosynthetic efficiency in maize, resulting in higher biomass and grain yields with reduced input quantities (Azam et al., 2022).

Beyond nutrient delivery, nanofertilizers hold promise in stress alleviation a dimension critical in the era of climate change (Shoukat et al., 2024). They can mitigate salinity stress by regulating Na^+/K^+ balance, improve drought tolerance by enhancing relative water content and osmolyte accumulation, and alleviate heat stress by stabilizing photosynthetic machinery and reducing oxidative damage (Ahmed & Mohamed, 2025). In this way, nanofertilizers not only act as nutrient suppliers but also as protective agents, equipping plants to withstand environmental fluctuations.

The broader sustainability benefits are equally compelling. By reducing input requirements, nanofertilizers contribute to lower greenhouse gas emissions, improved soil health, and reduced water contamination (Mohanraj et al., 2019). They also align with global calls for climate-smart agriculture and the Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). As highlighted in recent studies and reviews, the integration of nanotechnology into agriculture represents a paradigm shift, moving from the high-input, environmentally costly systems of the Green Revolution to a new model of precision, efficiency, and resilience (Wei et al., 2025).

2. CONCEPT AND CLASSIFICATION OF NANOFERTILIZERS

The term nanofertilizer refers broadly to the application of nanotechnology in plant nutrition, where nutrients are either engineered at the nanoscale or delivered using nano-enabled carriers (Xin et al., 2022). The idea behind nanofertilizers is not simply to make fertilizers smaller, but to fundamentally redesign the way nutrients are supplied to plants (Kalia & Kaur, 2018). By leveraging the high surface area, tunable porosity, and functional surface chemistry of nanomaterials, nanofertilizers aim to increase nutrient-use efficiency (NUE), reduce losses, synchronize nutrient release with plant demand, and lower environmental impacts. This makes them distinct from conventional fertilizers, which often act as blunt inputs, releasing nutrients rapidly into the soil regardless of crop needs or environmental conditions.

From a conceptual standpoint, nanofertilizers can be grouped into four major categories: (i) macro-nanofertilizers delivering bulk nutrients such as nitrogen, phosphorus, and potassium; (ii) micro-nanofertilizers supplying essential trace elements like zinc, iron, manganese, copper, boron, and molybdenum; (iii) nano-biofertilizers, which integrate beneficial microbes or organic compounds with nanoscale carriers; and (iv) smart nanofertilizers, which are engineered to release nutrients in response to specific environmental or biological triggers. Together, these categories form a comprehensive framework for understanding how nanotechnology is being applied to plant nutrition.

2.1. Macro-nanofertilizers (N, P, K)

Macronutrients form the foundation of plant nutrition, and their inefficient use is one of the biggest sustainability challenges in agriculture. Conventional nitrogen fertilizers, for example, suffer from enormous inefficiencies: crops typically recover only 30–40% of applied nitrogen, with the rest lost to leaching, volatilization, and denitrification (Mazumder et al., 2023). Phosphorus fertilizers are similarly inefficient, with less than 20% uptake efficiency due to soil fixation, while potassium is prone to leaching losses in light-textured soils (Weeks & Hettiarachchi, 2019). Macro-nanofertilizers aim to address these problems by enabling controlled, gradual nutrient release, ensuring plants receive a steady supply over time.

For nitrogen, several nano-enabled strategies have been explored. One of the most common methods involves using polymeric nanocarriers, such as chitosan, starch, or biodegradable synthetic polymers, to encapsulate urea or ammonium. These carriers slow the hydrolysis of urea by urease, thereby reducing ammonia volatilization (Achari & Kowshik, 2018). For example, chitosan–urea nanocomposites have demonstrated the ability to sustain nitrogen release for several weeks while enhancing soil enzyme activity and crop nitrogen uptake (Nkebiwe et al., 2016). In maize and rice, these systems have not only increased yield but also reduced the total fertilizer requirement by up to 30-40% (Meier et al., 2020).

Phosphorus nanofertilizers often employ hydroxyapatite nanoparticles or layered double hydroxides (LDHs) as carriers. Hydroxyapatite nanocrystals act as slow-release phosphorus sources, mimicking the mineral forms of calcium phosphate found in soils but with higher solubility at the nanoscale (Wang et al., 2016). LDHs, also known as "anion clays," are particularly promising because they can intercalate phosphate ions between their layers and release them in response to changes in soil pH or the presence of competing anions from root exudates (Qureshi et al., 2018). This ensures that phosphorus is supplied when roots are actively exuding organic acids, thereby enhancing synchronization between supply and demand.

For potassium, macro-nanofertilizers often rely on nanoclays, zeolites, or silica-based carriers. These porous materials can adsorb potassium ions and release them slowly into the soil solution, buffering plants against leaching losses (Rastogi et al., 2019). In sandy soils or regions with high rainfall, this property is especially valuable because conventional K fertilizers are quickly washed out. Recent research also highlights the use of graphene oxide composites to anchor potassium ions, enhancing their retention and bioavailability (Ghorbanpour et al., 2020).

The overall advantage of macro-nanofertilizers lies in their ability to reduce input quantities while maintaining or even increasing yields. By preventing nutrient bursts and subsequent losses, they align with the goals of precision agriculture and climate-smart farming (Singh & Kalia, 2019).

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2.2. Micro-nanofertilizers (Zn, Fe, Mn, Cu, B, Mo)

Micronutrients, though required in small amounts, play indispensable roles in enzymatic activity, photosynthesis, hormone regulation, and grain nutritional quality. Deficiencies of zinc, iron, and boron are especially widespread in cereals and horticultural crops, leading not only to reduced yields but also to human malnutrition (so-called "hidden hunger") (Kumar et al., 2019). Micro-nanofertilizers are designed to address these deficiencies with greater efficiency and precision than bulk salts.

The most common micro-nanofertilizers are metal and metal oxide nanoparticles such as zinc oxide (ZnO), iron oxide (Fe_3O_4 or Fe_2O_3), manganese oxide (MnO_2), and copper oxide (CuO). These nanoparticles can be applied via soil, foliar sprays, or seed priming. Their nanoscale size allows them to penetrate plant tissues through stomatal openings, cuticular pores, or root apoplasts, ensuring more efficient delivery (Alshaal & El-Ramady, 2017). Once inside the plant, they release ions gradually, ensuring sustained micronutrient availability.

For instance, ZnO nanoparticles have been shown to significantly increase grain zinc concentration in rice and wheat, while also enhancing antioxidant enzyme activity under stress conditions (Burman et al., 2013). Similarly, Fe nanoparticles can correct chlorosis more effectively than bulk iron salts, as they are less prone to oxidation and precipitation in calcareous soils (Adrees et al., 2020). Boron and molybdenum nanofertilizers, though less studied, are gaining attention for their roles in improving reproductive growth and nitrogen fixation (Ali et al., 2021).

One of the most exciting applications of micro-nanofertilizers is in biofortification the process of enriching staple crops with essential micronutrients to combat malnutrition. Foliar sprays of Zn and Fe nanoparticles, for example, have been shown to increase grain micronutrient content without reducing yields, making them a powerful tool for addressing human nutritional deficiencies in resource-poor regions (Budke et al., 2020).

However, micro-nanofertilizers must be carefully dosed. Because of their high reactivity, excessive application can cause oxidative stress or toxicity to plants (Hussain et al., 2019). Thus, formulation and delivery systems are critical for ensuring safe and effective use.

2.3. Nano-biofertilizers (Microbial, Organic, Polysaccharide-based)

Nano-biofertilizers represent a synergistic fusion of nanotechnology and microbial/organic inputs. Their aim is not just to supply nutrients directly but also to harness the natural abilities of microbes and organic carriers to mobilize and regulate nutrient availability (Nayana et al., 2020).

In one approach, beneficial microbes such as *Azotobacter*, *Rhizobium*, *Bacillus*, or phosphate-solubilizing fungi are encapsulated within nanostructured carriers (e.g., alginate beads, chitosan nanoparticles). These carriers protect the microbes from environmental stresses such as UV radiation, desiccation, or soil competition, thereby extending their survival and effectiveness in the rhizosphere (Mohd Yusof et al., 2019). Once established, the microbes produce enzymes and organic acids that mobilize nitrogen, phosphorus, and micronutrients, effectively complementing the mineral nutrient supply (Iqbal et al., 2019).

Another approach involves the use of biopolymeric nanocarriers, such as chitosan or starch that can simultaneously deliver nutrients and stimulate microbial activity. Chitosan, for example, has antimicrobial-modulating properties and can enhance root colonization by beneficial microbes (Mohajer et al., 2023). When combined with mineral nutrients, such systems provide both immediate supply and longer-term biological mobilization.

Nano-biofertilizers are also being explored for their role in stress mitigation. By improving root growth, water uptake, and antioxidant enzyme activity, they help plants withstand salinity, drought, and heavy-metal stress (Al-Shabib et al., 2020). Furthermore, they align closely with sustainable agriculture paradigms, as they reduce reliance on synthetic inputs and promote soil biological health (Kumari et al., 2022).

2.4. Smart Nanofertilizers (Controlled-release, Stimuli-responsive)

The most advanced category of nanofertilizers is smart systems, which can sense environmental cues or biological signals and release nutrients accordingly. These are sometimes described as "intelligent fertilizers" because of their capacity to self-regulate delivery (Achari & Kowshik, 2018).

One widely studied smart system involves layered double hydroxides (LDHs) intercalated with phosphate or nitrate. These materials can release nutrients in response to changes in soil pH, root exudates, or competing anions, ensuring that nutrients are available precisely when roots need them (Qureshi et al., 2018). Another approach uses biodegradable polymeric nanogels that swell or shrink in response to soil moisture, thereby controlling nutrient diffusion (Meier et al., 2020).

Stimuli-responsive nanocarriers can also be designed to react to temperature, redox conditions, or enzymatic activity. For example, urea encapsulated in chitosan nanoparticles may be released more rapidly in the presence of soil urease enzymes, synchronizing supply with plant demand (Nkebiwe et al., 2016). Similarly, nanocomposite coatings incorporating silica or graphene can create tortuous pathways that slow nutrient leaching after rainfall, effectively stabilizing fertilizer efficiency under fluctuating moisture conditions (Rastogi et al., 2019).

Beyond controlled release, smart nanofertilizers are also being designed for multi-functionality. Some formulations combine nutrients with biocides, growth regulators, or stress-alleviating agents, creating "all-in-one" packages for crop management (Kumar et al., 2019). Others are linked with nanosensors that can provide feedback on soil nutrient status or plant health, paving the way for integration with precision agriculture and digital farming (Singh & Kalia, 2019).

Although these categories macro, micro, bio, and smart are described separately, in practice they are complementary and overlapping. A single nanofertilizer product may, for example, combine macronutrients with micronutrient oxides in a biopolymer matrix, while also exhibiting controlled-release behavior (Wang et al., 2016). The classification is thus best viewed as a continuum of design strategies, ranging from simple nano-sizing of nutrients to highly engineered, stimuli-responsive systems.

Together, these advances represent a paradigm shift in plant nutrition. Where conventional fertilizers emphasized quantity, nanofertilizers emphasize quality, precision, and sustainability. They not only enhance nutrient-use efficiency but also contribute to stress resilience, soil health, and environmental protection. By aligning nutrient delivery with plant physiology and environmental conditions, nanofertilizers hold the potential to redefine fertilizer use in the era of climate change and resource scarcity (Ghorbanpour et al., 2020).

3. MECHANISMS OF NANOFERTILIZER ACTION

The superior performance of nanofertilizers over conventional formulations arises not merely from their small size, but from the unique ways in which they are taken up, translocated, and metabolically integrated within plants. Their mode of action can be understood by examining the physical entry routes, the kinetics of controlled nutrient delivery, physiological and molecular responses inside plant tissues, and their interactions with the rhizosphere microbiome. These processes act synergistically, resulting in higher nutrient-use efficiency, improved bioavailability, and stress alleviation compared with bulk fertilizers (Shoukat et al., 2024).

3.1. Uptake Pathways: Root, Foliar, and Stomatal Entry

Nanofertilizers can enter plants through multiple routes depending on their formulation, size, surface charge, and chemical composition. The two most studied entry points are roots and foliar surfaces (Alshaal & El-Ramady, 2017).

At the root interface, nanoparticles interact with mucilage and exudates, which alter surface charge and create conditions for adsorption (Fig. 1). Positively charged nanoparticles often show greater affinity for the negatively charged cell wall, but recent studies also indicate that negatively charged particles may bypass mucilage entrapment and move more effectively into the apoplast (Lv et al., 2019). Entry occurs via apoplastic flow between cell walls, symplastic movement through plasmodesmata, or active endocytosis in root epidermal cells (Pérez-de-Luque, 2017). Once inside, nanoparticles can be loaded into the xylem, facilitating upward transport to shoots and leaves (Banerjee et al., 2019).

On the foliar surface, penetration is constrained by the hydrophobic cuticle, yet nanoscale formulations are small enough to traverse aqueous pores (0.6–4.8 nm) or lipophilic channels. Foliar-applied nanoparticles may also enter via cuticular cracks or lenticels, especially under stress conditions (Clarke et al., 2020). For larger particles (>10 nm), stomatal pores are the dominant pathway (Larue et al., 2014). Stomatal density, distribution, and opening dynamics therefore directly influence uptake efficiency (Fig. 1). Once inside the mesophyll, nanofertilizers can be redistributed via phloem, ensuring delivery to developing tissues and grains (Avellan et al., 2021). This multi-route uptake allows nanofertilizers to bypass some of the limitations of conventional fertilizers, which are often immobilized in soil or blocked by cuticular barriers (Sun et al., 2020).

3.2. Controlled Nutrient Delivery and Bioavailability

A central advantage of nanofertilizers is their ability to deliver nutrients in a controlled, slow, and synchronized manner (Achari & Kowshik, 2018). Traditional fertilizers often dissolve rapidly, releasing nutrients regardless of crop demand, leading to significant losses. By contrast, nanofertilizers can be engineered as encapsulated formulations, layered double hydroxides, or porous carriers that gradually release ions in response to environmental triggers such as soil pH, moisture, or enzymatic activity (Qureshi et al., 2018).

For example, nitrogen encapsulated in biopolymer nanocarriers (e.g., chitosan) undergoes regulated degradation, providing a steady supply of ammonium or nitrate while minimizing volatilization (Nkebiwe et al., 2016). Hydroxyapatite nanoparticles supply phosphorus slowly, reducing fixation in calcareous soils (Weeks & Hettiarachchi, 2019). Such systems ensure that nutrient pulses align with critical growth phases like tillering, flowering, or grain filling, thereby improving nutrient-use efficiency. Additionally, nanoparticles have higher solubility and dispersibility than bulk salts, increasing the effective concentration of nutrients available in the rhizosphere or apoplast (Meier et al., 2020).

3.3. Plant Nanoparticle Physiological Interactions

Once internalized, nanofertilizers do not merely act as passive nutrient sources; they actively modulate plant physiology at multiple levels. At the cellular scale, nanoparticles can influence membrane transporters, alter ion fluxes, and stimulate signaling cascades (Gaafar et al., 2020). Transcriptomic and proteomic studies show that nanofertilizers can upregulate genes encoding nutrient transporters, photosynthetic proteins, and enzymes of nitrogen and carbohydrate metabolism (Song et al., 2021).

Nanoparticles can also mimic or amplify signaling molecules. For instance, some nanomaterials function as calcium analogs, triggering Ca^{2+}-dependent signaling pathways that regulate stress responses, hormone crosstalk, and transcription factors (Lee & Hong, 2019). This cascade ultimately enhances processes such as cell division, chloroplast development, and antioxidant defense. At the whole-plant level, these molecular changes manifest as improved photosynthesis, delayed senescence, greater water-use efficiency, and higher biomass accumulation (Yang et al., 2020).

Another critical aspect is vacuolar sequestration and detoxification. Nanofertilizers help in storing excess ions safely within vacuoles, thereby preventing toxicity while still ensuring availability during demand. This mechanism is especially relevant under salinity stress, where maintaining a favorable Na^+/K^+ balance is vital for plant survival (Manzoor et al., 2021).

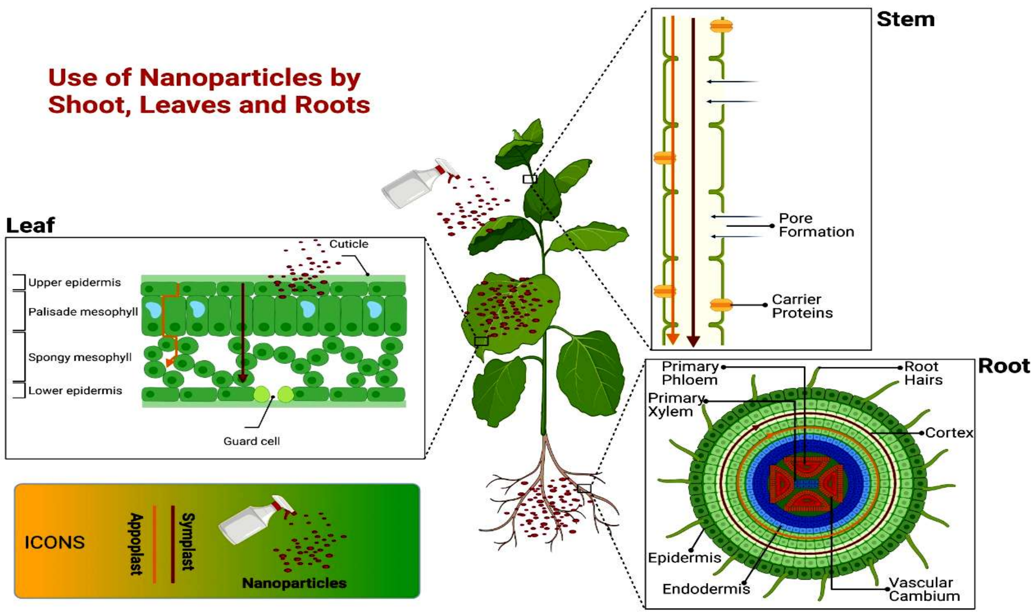

Fig. 1: Pathways of nanoparticle uptake, penetration and translocation in plants (Shoukat et al., 2024).

4. ROLE IN STRESS ALLEVIATION

Nanofertilizers (NFs) mitigate abiotic stress through three converging levers: (i) ion homeostasis and membrane protection (limiting toxic ion influx and preserving K^+ retention, membrane integrity, and water status); (ii) redox reprogramming (up-regulating enzymatic/non-enzymatic antioxidants; in some cases acting as catalytic "nanozymes"); and (iii) metabolic and developmental tuning (maintaining photosynthesis, osmolyte accumulation, and root system architecture). Below, each stress domain is treated in depth with specific nanoformulations, crop examples, and mechanisms (Etesami et al., 2021; Shoukat et al., 2024).

4.1. Salinity Stress — maintaining Na^+/K^+ Balance and Strengthening Antioxidant Defense

Salinity imposes osmotic shock and Na^+ toxicity, collapsing the Na^+/K^+ ratio, depolarizing membranes, and intensifying ROS formation. Effective NFs reduce Na^+ loading at the root, preserve high-affinity K^+ uptake (AKT/KUP/HAK transporters), stabilize membranes (e.g., via Si deposition in cell walls/cuticle), and elevate SOD–CAT–APX–POD activities to cap H_2O_2/MDA (Cui & Smith, 2022; Mahmoud et al., 2022). Zn- and Se-based NFs additionally cofactor antioxidant enzymes and glutathione metabolism; CeO_2 behaves as a ROS-scavenging nanozyme (Ce^{3+}/Ce^{4+} redox cycling) (Rajput et al., 2021) (Fig. 2).

Across cereals and vegetables, foliar or seed-priming ZnO-NPs commonly lower leaf Na^+, maintain K^+, and boost SOD/CAT/APX, improving growth/yield under NaCl (Khan et al., 2021; Huang et al., 2021). Reviews and primary studies converge that ZnO-NPs alleviate NaCl toxicity and raise productivity, with successful foliar biofortification of wheat and rice grains (higher Zn without yield penalties) (Burman et al., 2013). Mechanistically, Zn provides structural/enzymatic support (e.g., Cu/Zn-SOD), while nano-scale delivery improves leaf/stomatal uptake and phloem redistribution.

SiO_2-NPs reinforce epidermal/cell-wall barriers, reduce Na^+ entry, and buffer K^+ leakage by stabilizing membranes and H^+-ATPase activity; they also enhance enzymatic antioxidants (Alsaeedi et al., 2019). In salt-challenged rice, field-scale application of SiO_2-NPs increased yield by ~23–33% by sustaining grain filling and antioxidant capacity; similar protective effects are reported in maize and tomato (Hussain et al., 2019).

Low-dose Se-NPs act as potent redox modulators, elevating GSH–GR–GPX systems, lowering H_2O_2/MDA, and improving ionic balance under salt (Rajput et al., 2021). In rice, seed priming or foliar Se-NPs improved salt tolerance and concurrently biofortified grains with Se, a dual agronomic–nutrition win (Badawy et al., 2021). Co-application Se-NPs + ZnO-NPs in rice enhanced proteins and stress tolerance more than either alone, suggesting synergistic redox + ion-homeostasis protection. Dose windows matter (typically 25–150 mg L^{-1} for foliar ZnO; 0.25–0.5 g L^{-1} for SiO_2 sprays; 5–100 mg L^{-1} for Se-NPs). Over-dosing can invert benefits (oxidative load, growth inhibition).

4.2. Drought stress — enhancing Relative Water Content and Osmolyte Accumulation

Drought lowers relative water content (RWC), perturbs ABA signaling and aquaporins (PIP/TIP), throttles photosystems (PSII) and carbon metabolism, and elevates ROS (Fig. 2). NFs counter by (i) improving water relations (root growth, aquaporin expression, cuticular reinforcement), (ii) boosting osmolytes (proline, soluble sugars, glycine betaine), and (iii) protecting photosynthetic apparatus (PSII stability, chloroplast antioxidants) (Ashkavand et al., 2015; Behboudi et al., 2019).

Among the most consistent drought mitigators, SiO_2-NPs increase RWC, proline, total soluble sugars, and antioxidant enzymes; they also expand root length/volume and root tips, supporting soil water exploration (Etesami et al., 2021). In maize seedlings, 0.25 g L^{-1} foliar SiO_2-NPs significantly raised RWC and growth indices under drought; integrated omics in wheat show SiO_2-NPs re-balance ROS and up-regulate stress-responsive pathways (Ali et al., 2021).

Cationic chitosan NPs form thin hygroscopic films on leaves/roots and act as slow-release carriers for N or Zn, improving water-use efficiency and osmotic adjustment (Behboudi et al., 2019). In wheat, drought was mitigated at ~90 ppm chitosan-NPs; chitosan ZnO-NP foliar sprays improved WUE and yield under deficit irrigation, coupling structural film effects with Zn-mediated antioxidant gains (Nkebiwe et al., 2016).

Carbon dots (CDs, often plant-derived) enhance light harvesting and electron transport, improving photosynthesis and lowering excitation pressure; TiO_2-NPs increase chlorophyll content and photochemical efficiency, sustaining CO_2 fixation as stomata close (Jaberzadeh et al., 2013). As redox-active nanozymes (SOD-/CAT-mimetic), CeO_2-NPs curtail ROS surges during dehydration and rewatering. In perennial fruit trees (apple), CeO_2-NPs moderated drought injury; broader reviews document improved drought resilience via H_2O_2 scavenging and membrane stabilization (Van Nguyen et al., 2022) (Fig. 2).

4.3. Heat Stress — protecting Photosystems and Chlorophyll Stability

Heat destabilizes thylakoid membranes (D1 protein turnover), accelerates chlorophyll degradation, perturbs Rubisco activase, and intensifies ROS. NFs that stabilize PSII, enhance thermal dissipation (qE), and elevate HSPs/antioxidants reduce photodamage (Yang et al., 2020). At low doses (50–100 mg L^{-1}), TiO_2 maintains Fv/Fm, ETR, and chlorophyll content, improves enzymatic antioxidants, and can raise yield; excessive doses (>2,500 mg L^{-1}) become inhibitory underscoring the narrow therapeutic window (El-Saadony et al., 2022) (Fig. 2).

CeO_2 nanozymes neutralize heat-induced ROS and have been linked to higher HSP70 accumulation (Heikal et al., 2023), while ZnO-NPs improve chlorophyll stability and membrane integrity under heat in cereals (Gaafar et al., 2020). By fortifying membranes and modulating antioxidant networks, SiO_2 can indirectly stabilize photosystems during heat waves; this is frequently observed when SiO_2 is already deployed for drought–heat complexes in the field (Al-Khayri et al., 2023).

4.4. Nutrient-deficiency Stress — biofortification with Zn, Fe, Se (and others)

Under micronutrient deficits, NFs improve leaf/seed loading by exploiting stomatal/cuticular entry and phloem remobilization, while controlled release avoids precipitation/fixation (e.g., Fe in calcareous soils). They also up-regulate transporter networks (ZIP/IRT/FRO/YSL for Fe/Zn; sulfate/selenate assimilation for Se) and serve as enzyme cofactors, directly restoring metabolic capacity (Afzal et al., 2022).

Foliar ZnO-NPs consistently increase grain Zn density in wheat and rice while sustaining yield/quality, often outperforming bulk salts and enabling one-pass biofortification late in the season (booting/grain filling) (Burman et al., 2013). Fe_2O_3/Fe_3O_4-NPs (soil drench or foliar) correct Fe chlorosis more efficiently than Fe salts in alkaline soils (Adrees et al., 2020). Se-NPs are attractive for safe Se biofortification (lower toxicity vs selenite/selenate) in wheat and rice, with minimal growth penalty and strong redox co-benefits (Badawy et al., 2021) (Fig. 2). Advanced carriers

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(e.g., chitosan-Zn, LDH-phosphate) combine controlled release + foliar permeability; careful timing (e.g., wheat grain filling; rice booting) maximizes seed loading while minimizing foliar phytotoxicity (Nkebiwe et al., 2016).

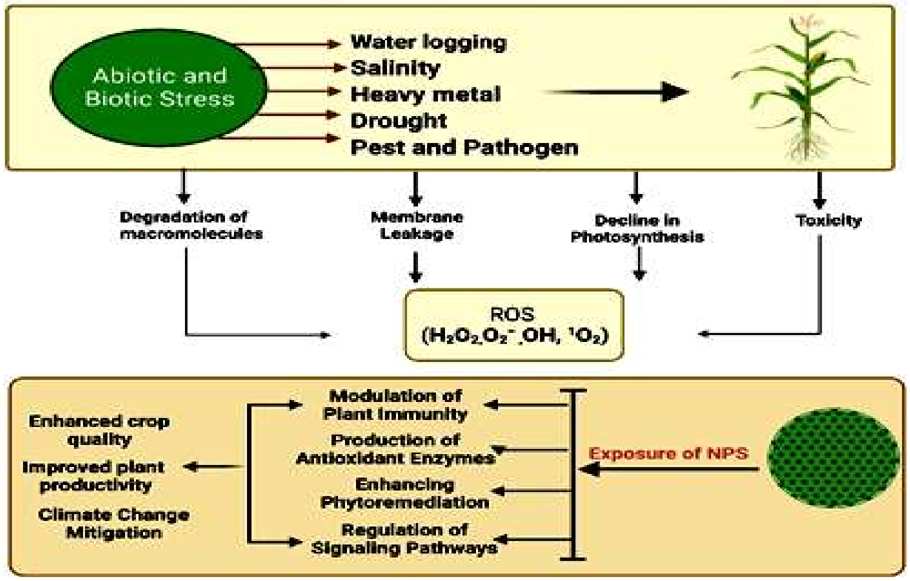

Fig. 2: Nanotechnology for Climate Change Mitigation: A Framework for Enhancing Plant Resilience to Abiotic and Biotic Stressors (Shoukat et al., 2024).

4.5. Combined Stress Conditions (salinity + drought) — the Emerging Frontier

Co-occurring stresses produce non-additive damage (ionic + osmotic + thermal/oxidative), so single-factor trials can overestimate performance. Still, encouraging case studies exist. Under combined salt–drought, low-dose Cu-NPs reduced oxidative damage and improved growth likely via Cu-SOD activity and membrane stabilization (Taran et al., 2017).

Field and pot studies indicate nano-biochar (often Si-enriched) improves quinoa performance under simultaneous drought–salinity by improving soil water retention, ion buffering, and antioxidant status (Hossain et al., 2021). In quinoa and wheat, Ag-NPs (and Ag-NPs combined with antioxidants/biostimulants) have mitigated salt and combined stresses, largely through ROS quenching and stomatal function protection (Shibli et al., 2022). However, silver's ecological footprint demands caution. Recent reviews emphasize stress-specific nanoformulations (e.g., SiO_2 for water relations + ZnO/Se for redox/ionic control; CeO_2 for extreme ROS conditions) and stacked NP cocktails tuned to the local stress complex and crop stage (Zeeshan et al., 2023). More multi-factor field trials and soil-microbiome safeguards are needed before scaling.

5. ENVIRONMENTAL AND ECOLOGICAL IMPLICATIONS

5.1. Nanofertilizer Fate in soil–plant–water Systems

Once applied, nano-enabled fertilizers (NFs) undergo a sequence of transport–transformation–uptake processes that govern their persistence and effects. In soils, engineered nanoparticles (ENPs) rapidly hetero/agglomerate with clays and organic matter, form eco-coronas with dissolved organics, and sorb to mineral surfaces—processes that slow mobility but can also gate slow ion release (Deng et al., 2017; Hong et al., 2021). Metal and metal-oxide NFs (e.g., ZnO, Fe_2O_3) often partially dissolve, with the ionic fraction (Zn^{2+}/Fe^{3+}) driving much of the biological response; the particulate fraction may be further transformed (e.g., ZnO → ZnS in sulfidic microsites; $Ag^0 \rightarrow Ag_2S$) with depth-dependent kinetics that depend on redox, pH, ligands, and microbial activity (Tripathi et al., 2017; Wang et al., 2016). These transformations typically reduce solubility and acute toxicity over time but prolong low-level nutrient availability—one reason NFs can sustain plant feeding with smaller doses (Qureshi et al., 2018; Weeks & Hettiarachchi, 2019). Fate models and recent experimental work emphasize that predictions must include multi-compartment fluxes (soil pore water ↔ surface water ↔ sediment ↔ atmosphere) and context-specific transformations, because single-factor lab tests often misestimate field persistence and mobility (Latif et al., 2020; Tahir et al., 2020).

In the plant compartment, uptake can occur at roots (apoplast/symplast, endocytosis) or foliage (cuticle aqueous pores, stomata). After entry, nutrients released from NFs move via xylem to shoots and phloem to sinks, while the residual nano-carriers (e.g., chitosan, hydroxyapatite, LDH platelets) are largely retained in root tissues or apoplast and are progressively biodegraded or immobilized (Alshaal & El-Ramady, 2017; Avellan et al., 2021; Achari & Kowshik, 2018; Weeks & Hettiarachchi, 2019). Runoff risks are generally lower than with bulk salts because matched-release NF programs use lower application rates and exhibit slower desorption, but erosion events and tile drainage can still export colloids—hence the importance of banded placement or foliar routes near critical phenophases (Meier et al., 2020; Salem et al., 2016).

5.2. Impact on Soil Microbial Diversity

Soil microbiomes respond dose-dependently to ENPs. Numerous field and mesocosm-level syntheses report that low, agronomic rates of certain NFs (e.g., ZnO, SiO_2; biopolymer carriers) either do not depress or can enhance functional guilds (N-fixers, P-solubilizers), partly by improving plant exudation and rhizosphere carbon supply (Rastogi et al., 2019; Alkharabsheh et al., 2021; Alsaeedi et al., 2019). Conversely, over-application or use of highly redox-active or biocidal NPs (e.g., excess Ag, Cu) can reduce microbial biomass and key enzyme activities, with effects strongest in sandy/low-OM soils and under repeated dosing (Hänsch & Emmerling, 2010; Bhadra et al., 2019). The balance of evidence in recent reviews is that hormesis (benefits at low, costs at high doses) is common, and that responses are often driven by dissolved ions (e.g., Zn^{2+} from ZnO) rather than particles per se—underscoring the need to calibrate rates to soil texture, pH, and organic matter (Patra et al., 2016; Singh & Kalia, 2019).

5.3. Environmental Safety vs. Conventional Fertilizers

Compared with conventional fertilizers, well-formulated NFs can sharply lower nutrient losses (leaching, runoff, volatilization) by synchronizing supply with crop demand, thereby shrinking eutrophication and greenhouse-gas footprints at the system scale (Qureshi et al., 2018; Meier et al., 2020; Subramanian et al., 2020). Meta-analyses and long-term trials on controlled/slow-release analogs (the nearest operational proxy when NF field data are sparse) show reduced NH_3 volatilization and NO_3^- leaching and lower N_2O emissions at equal N rates—benefits that NF platforms aim to match or exceed with biodegradable carriers and nanoscale control over release (Vega-Vásquez et al., 2020; Weeks & Hettiarachchi, 2019). At the same time, nanomaterial-specific risks (persistence of non-biodegradable coatings, trophic transfer of metal ENPs) require safe-by-design choices (e.g., chitosan/cellulose/lignin carriers; hydroxyapatite/LDH matrices; SiO_2) and contextual LCAs that include transformation products (e.g., ZnS, Ag_2S) and actual field emission factors (Kashyap et al., 2015; Vallet-Regí et al., 2001; Wu et al., 2020). The current literature highlights data gaps for nano-ag inputs but agrees on the potential for net impact reductions when NFs enable lower total nutrient use with maintained yields (Rai et al., 2018; Tortella et al., 2023).

6. ADVANTAGES AND OPPORTUNITIES

6.1. Enhanced Nutrient-use Efficiency (NUE)

NFs improve NUE via controlled/demand-driven release, shorter diffusion paths, and targeted entry (root apoplast, stomata). For N and P, nano-enabled carriers (e.g., chitosan–urea, hydroxyapatite-P, LDH-phosphate) flatten the typical "early pulse" from bulk salts, extending availability through tillering, booting, and grain-fill (Achari & Kowshik, 2018; Qureshi et al., 2018; Weeks & Hettiarachchi, 2019). Evidence from enhanced-efficiency analogs and NF reviews indicates double-digit NUE gains are realistic under field management translating directly into lower input rates for the same yield goal (Meier et al., 2020).

6.2. Yield and Nutritional-quality Improvements

By sustaining leaf N and P status and stabilizing photosystems under stress, NFs frequently deliver 5–15% yield gains in cereals and horticulture at equal or reduced nutrient rates (Shoukat et al., 2024) (Fig. 3). Micronutrient NFs (ZnO, Fe-oxides, Se-NPs) are especially effective for biofortification: late-season foliar ZnO in wheat/rice increases grain Zn without yield penalties (Burman et al., 2013); Se-NPs enrich Se with fewer phytotoxicity issues than selenite/selenate (Rajput et al., 2021); Fe-oxides alleviate chlorosis and improve chlorophyll under calcareous conditions (Adrees et al., 2020). Such nutrition–yield co-benefits are a central opportunity for low- and middle-income regions combating hidden hunger (Kumar et al., 2019) (Fig. 3).

6.3. Reduction in Fertilizer Losses (Leaching, Volatilization, Runoff)

The principal system-level advantage of NFs is loss prevention. By matching release to crop uptake and using biodegradable coatings (chitosan, gelatin, lignin) or inorganic nano-matrices (hydroxyapatite, LDH, SiO_2), NFs cut NO_3^- leaching, dampen NH_3 volatilization, and reduce storm-event pulses in runoff (Kashyap et al., 2015; Salem et al., 2016). Where direct NF field datasets are still building, slow/controlled-release evidence is instructive: NH_3 down ≈40–70%, NO_3^- leaching down ≈25–30%, and N_2O down ≈20–25%, contingent on climate/soil management

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(Vega-Vásquez et al., 2020; Subramanian et al., 2020). Safe-by-design NFs aim to deliver these benefits without legacy microplastics, replacing polyurethane with bio-based polymers (Tortella et al., 2023) (Fig. 3).

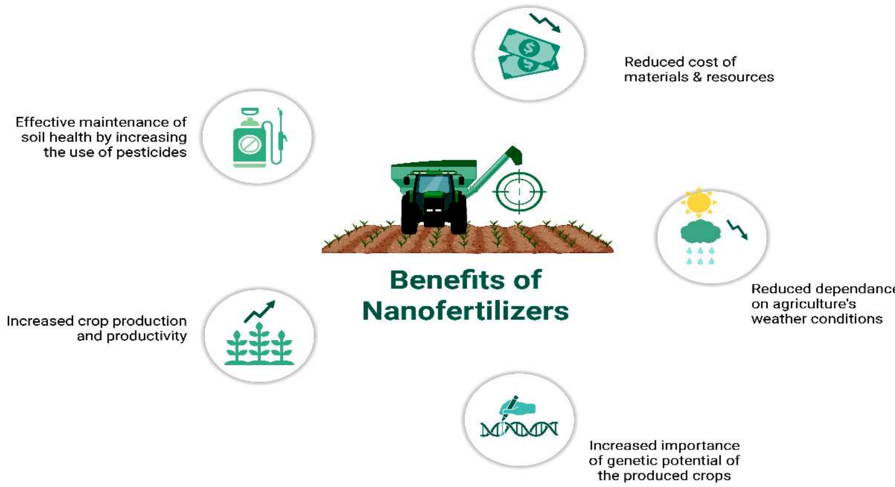

Fig. 3: Nanotechnology for Sustainable Agriculture: Advancements in Plant Growth and Protection.

6.4. Role in Achieving UN Sustainable Development Goals (SDGs)

Deployed responsibly, NFs align with multiple SDGs:

- **SDG 2 (Zero Hunger):** higher, more stable yields and micronutrient-dense grains via foliar nano-biofortification (Ali et al., 2021).
- **SDG 12 (Responsible Consumption and Production):** less fertilizer per ton of grain and reduced losses lower material intensity (Singh & Kalia, 2019).
- **SDG 13 (Climate Action):** diminished N_2O/NH_3 and fewer transport/production emissions when total N/P/K use falls (Rai et al., 2018).
- **SDG 6 & 15 (Clean Water, Life on Land):** lower eutrophication pressure and improved soil function when microbial communities are not over-stressed (Etesami et al., 2021).

Recent syntheses conclude NFs are a credible lever for sustainable intensification, provided rates are calibrated and carriers are biodegradable (Tortella et al., 2023).

7. LIMITATIONS AND CHALLENGES

Despite clear agronomic promise, nanofertilizers raise legitimate safety and performance questions that must be confronted before widespread deployment. The most fundamental concern is nanotoxicity and long-term biosafety. Adverse effects can arise from particle-intrinsic properties—highly reactive surfaces that catalyze reactive oxygen species or perturb membranes—as well as from the dissolved ions released by metal and metal-oxide nanoparticles (for example, Zn^{2+} from ZnO or Cu^{2+} from CuO) (Patra et al., 2016; Bhadra et al., 2019). Short-term phytotoxicity is usually dose-related and reversible, but the chronic picture is more complex: progressive retention in roots and the apoplast, transformation in soils into new mineral forms with different bioavailability, subtle shifts in rhizosphere enzymes and nutrient transporters, trophic transfer to soil fauna, and potential impacts on non-target organisms (Hänsch & Emmerling, 2010; Hong et al., 2021). Addressing these risks requires a "safe-by-design" philosophy from the outset: favoring biodegradable carriers such as chitosan, alginate, lignin, cellulose nanofibers, or mineral matrices with benign fates (hydroxyapatite, layered double hydroxides, amorphous silica) (Kashyap et al., 2015; Vallet-Regí et al., 2001); moderating dose to the effective low window; and engineering release profiles that are tightly coupled to plant demand so that free nanoparticle load in soil and water stays minimal over time (Wu et al., 2020).

A second limitation is the paucity of large-scale, multi-year field validation. Many impressive results originate from pots, lysimeters, or single-site trials where soils, climate, and management are tightly controlled (Latif et al., 2020; Tahir et al., 2020). Real farms are heterogeneous: texture, pH, salinity, organic matter, irrigation schedules, and weather shocks all interact with formulation performance. Signal-to-noise can be low when trying to detect a modest gain in nutrient-use efficiency against variable rainfall or heat waves. What is needed now are multi-location, multi-season trials using harmonized protocols—defined dose ranges, phenology-matched timings, common agronomic baselines, and standardized outcome metrics (Rai et al., 2018). Such designs enable robust meta-analyses that separate true technology effects from site and season idiosyncrasies.

Cost and farmer acceptance present a third barrier. Manufacturing nanofertilizers that are consistent in particle size, colloidal stability, and coating integrity is more expensive than producing bulk salts, and added value must be obvious at the farm gate (Shoukat et al., 2024). Shelf stability across hot and cold chains, ease of redispersion in hard water, compatibility with common adjuvants and pesticides, and reliable performance in standard sprayers or fertigation systems all shape adoption. Equally important is perceived risk: the word "nano" can trigger caution unless transparent safety dossiers, local demonstrations, and clear economic cases are available (Tortella et al., 2023).

Finally, regulation and ethics are still catching up. Definitions of what constitutes a nanomaterial, the triggers for safety testing, and labeling requirements vary across jurisdictions (Wu et al., 2020). Agricultural frameworks must account for product performance claims (such as reductions in leaching or volatilization), environmental release and monitoring, worker exposure during mixing and application, and end-of-life behaviors in soils and waterways (Tortella et al., 2023). Ethically, pilots should avoid two-tiered technology access that favors only large, capitalized farms; informed consent, right-to-know labeling, and equitable access to training and after-sales support are crucial for public trust (Rai et al., 2018).

8. FUTURE PERSPECTIVES

The next wave of innovation will likely be stress-specific nanofertilizers that are designed around the dominant abiotic constraints of a target agro-ecosystem. In saline environments, silica-rich carriers that reinforce membranes and improve Na^+/K^+ homeostasis can be co-formulated with low-dose zinc or selenium nanoforms to strengthen antioxidant systems. Under drought, hygroscopic chitosan nano-films that reduce cuticular water loss can be paired with nano-silica to improve relative water content and root system architecture, while carbon dots or TiO_2 provide photoprotection and sustain photosynthesis at low stomatal conductance. For heat-prone regions, combinations of TiO_2 and ceria nanozymes can stabilize photosystem II and detoxify heat-induced reactive oxygen species, with co-delivered manganese or zinc to support enzyme stability. On calcareous soils where phosphorus fixation limits yields, hydroxyapatite or layered double hydroxide matrices can meter P release and enhance availability. These formulations should be timed to phenological windows—booting and grain filling in cereals, for example—so that source–sink fluxes are maximized and total dose minimized.

Integration with AI-driven precision agriculture can multiply these gains. Modern sensing (soil moisture and salinity probes, canopy temperature, chlorophyll and fluorescence indices, and high-resolution imagery) feeds into predictive models that estimate short-term nutrient demand and stress risk. Decision layers convert those forecasts into micro-doses delivered by variable-rate boom sprayers or drones, precisely where and when the plant can use them. The feedback loop—sense, decide, apply, verify—is uniquely compatible with nanofertilizers because their controlled-release kinetics and foliar entry routes are well suited to small, frequent, targeted applications. Over time, field-specific digital twins can learn which formulations and timings deliver the best nutrient-use efficiency and quality outcomes for a given soil–climate–crop combination.

Sustainability will be anchored by biodegradable, eco-friendly nanoformulations. Bio-based carriers and benign mineral matrices, synthesized via green routes (plant extracts, microbial processes, mechanochemistry, low-temperature sol–gel), can reduce embedded energy and solvent footprints. Triggerable linkers that respond to pH, moisture, or enzymes ensure on-demand release and rapid post-function degradation, shrinking environmental persistence. To scale responsibly, a pragmatic policy and commercialization roadmap is needed: harmonized metrology and reporting standards; performance measurement, reporting, and verification protocols for nutrient-use efficiency, leaching, runoff, and nitrous oxide; tiered safety testing that includes transformation products and non-target taxa; and incentive mechanisms that reward verified loss reductions, such as nutrient stewardship credits or climate-finance channels. Extended producer responsibility, open data portals, and smallholder-sized product SKUs will help ensure access and accountability.

None of this will happen without interdisciplinary collaboration. Materials scientists, plant physiologists, soil microbiologists, toxicologists, agronomists, economists, and data scientists must work together in ring-trial networks spanning diverse soils and climates. Shared ontologies, curated repositories that link formulation, dose, context, and outcomes, and participatory research with farmers will accelerate learning and ensure solutions are fit for practice rather than merely promising in the lab.

9. CONCLUSION

Nanofertilizers mark a shift from bulk, pulse-release nutrition toward precise, demand-matched delivery that can raise nutrient-use efficiency, stabilize yields under stress, and enrich grains with essential micronutrients while reducing losses to air and water. The same nanoscale attributes that create value also create obligations: conservative dosing, biodegradable carriers, and rigorous multi-year field validation, transparent safety assessments that include transformation products and non-target organisms, and equitable access. Taken together, the evidence supports a balanced view: well-designed, properly dosed nanofertilizers can become a central pillar of climate-smart agriculture, advancing food security and nutritional quality while shrinking environmental footprints. Realizing that promise will depend less on isolated demonstrations and more on integrated systems—stress-specific formulations guided by real-time data, clear standards and verification, and collaborative networks that translate innovation into trusted, farmer-ready practice.

Declarations

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Ethics Statement: Not applicable.

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