Nanotechnology Applications for Enhancing Nutrient Bioavailability in Crops

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ABSTRACT

Background: Agricultural practices around the world are under pressure to raise crop production and at the same time minimize environmental impact of fertilizers. Conventional fertilizers are characterized by low efficiency with only 30-50 percent of nitrogen and 10-20 percent of phosphorus making it to the crop. Nanotechnology creates a possibility of rethinking the delivery of nutrients via nanoparticles (NPs) which are able to interact with plants in a new way.

Objective: The purpose of this paper rests in systematic review of literature about the nanotechnology usage in agriculture, with particular reference to nano-formulations of macro- and micronutrients and mechanisms of slow-release of nutrients into soil.

Sources of Literature: Academic papers available in peer-reviewed journals that can be found on Scopus, Web of Science, PubMed, and Google Scholar were checked for the period between 2015 and2015. This process helped identify around 1,640 items of literature which were further evaluated to obtain 102 studies that meet PRISMA requirements for inclusion and exclusion criteria, out of which thirty-five references qualified for inclusion in the final list.

Major Findings: Nano-formulations have been shown to enhance NUE for nitrogen and phosphorus by 20 to 50% and by up to 60% with regard to the micronutrient content of zinc and iron in crops. Chitosan-based fertilizers in form of controlled-release fertilizers and those made of hydroxyapatite nanocomposites result in nutrients being available four to five times longer than those obtained by using conventional fertilizers. Foliar application of ZnO and Fe_2O_3 NPs also boosts crop yield and quality with respect to rice, wheat, soybean, and pigeon pea crops in conditions that are normal or affected by abiotic factors.

Research Gaps: The primary gaps comprise a shortage of long-term field data on soil microbiome impacts, lack of regulatory frameworks for nano-agrochemicals, insufficient cost-benefit studies in smallholder settings, and minimal information on bioaccumulation in food chains.

Conclusion: Nanotechnology has significant potential for transforming precision crop nutrition. Nevertheless, its transition from laboratory and greenhouse to commercial field use requires thorough multi-year safety testing, well-defined regulatory options, and viable green synthesis procedures.

Keywords: nanofertilizers; nanoparticles; nutrient use efficiency; controlled-release fertilizers; zinc biofortification; crop nutrition; nano-agrochemicals; sustainable agriculture

1. Introduction

The global agricultural sector is confronted with a paradox of unprecedented proportions: the world must produce approximately 50% more food by 2050 to feed a projected population of 9.7 billion people, yet the ecological consequences of intensified chemical fertilizer application — including groundwater eutrophication, greenhouse gas emissions, and soil degradation — demand that this intensification occur with far greater resource efficiency than has historically been achieved [1, 7, 34]. Nitrogen (N), phosphorus (P), and potassium (K) remain the foundational macronutrients underpinning global crop production, yet the efficiency with which crops recover these inputs from soil is dismally low under conventional fertilization regimes: typically 30–50% for N, 15–25% for P, and 40–70% for K [14, 28]. Micronutrient deficiencies compound this challenge, with zinc and iron insufficiency in soils affecting over two billion people through the phenomenon of "hidden hunger" in staple crops [5, 10].

Nanotechnology — the science, engineering, and application of materials at the scale of 1–100 nanometres — has emerged as a transformative paradigm for agricultural input design. At the nanoscale, materials exhibit markedly different physicochemical properties compared to their bulk counterparts: dramatically enlarged surface area-to-volume ratios, enhanced reactivity, size-tunable solubility, and novel optical and electronic behaviours [12, 25]. When applied to fertilizer science, these properties translate into the capacity to engineer nutrient carriers that can deliver macronutrients and micronutrients directly to the rhizosphere or to foliar surfaces with spatial precision, controlled temporal release profiles, and reduced nutrient antagonism with soil mineral phases [5, 28].

The body of literature on nanofertilizers has expanded rapidly over the last decade, catalysed by advances in green synthesis, polymer coating technologies, and a deeper mechanistic understanding of how nanoparticles traverse plant cell walls and enter vascular tissues [2, 16, 29]. However, this growth has been accompanied by legitimate scientific concerns regarding nanoparticle toxicity to non-target organisms, regulatory ambiguity, and the gap between controlled-environment results and real-world field performance. A comprehensive, critically synthesised review is therefore both timely and necessary.

This review pursues four principal objectives: (i) to systematically map the landscape of nanotechnology applications specifically directed at enhancing nutrient bioavailability in crops; (ii) to critically evaluate the efficacy of macro- and micronutrient nanofertilizers across different crop systems and application methods; (iii) to assess the environmental safety dimensions of nanofertilizer deployment; and (iv) to delineate the research gaps and emerging directions that will define the next decade of nano-enabled precision agriculture.

The scope of this review encompasses metallic, metal oxide, polymer-based, and carbon-based nanoformulations examined within agricultural crop nutrition contexts, with a primary focus on studies published between 2015 and 2025 that provide experimental evidence of nutrient bioavailability improvement. The review does not address nanopesticides, nanosensors, or veterinary applications of nanotechnology.

2. Methodology of Literature Review

2.1 Literature Search Strategy

A systematic search of the scientific literature was performed across five major academic databases: Scopus, Web of Science Core Collection, PubMed, Google Scholar, and AGRIS. Searches were conducted using Boolean combinations of the following terms: "nanofertilizer", "nano-fertilizer", "nanoparticle AND crop nutrition", "nutrient bioavailability AND nanoparticles", "controlled-release fertilizer AND nanomaterial", "nano-zinc", "nano-iron", "nano-phosphorus", "nutrient use efficiency AND nanoparticles", "ZnO nanoparticles AND crop yield", and "hydroxyapatite nanoparticle AND fertilizer". The search period was restricted to January 2015 through December 2025, although seminal and landmark studies predating 2015 were included selectively. The specific search strategy is detailed in Table 1.

Table 1: Literature Search Strategy

Component	Details	Notes
Databases Searched	Scopus, Web of Science, PubMed, Google Scholar, AGRIS	Primary scientific databases
Search Terms	Nanofertilizer, nanoparticles, nutrient bioavailability, nanomaterial crop nutrition, controlled release fertilizer, nano-zinc, nano-iron, nano-phosphorus, NUE	Boolean combinations used
Time Period	2015–2025	Landmark studies pre-2015 included selectively
Language Filter	English only	Non-English excluded
Document Types	Research articles, review articles, book chapters, government reports	Conference abstracts excluded
Initial Records	~1,640 records identified	Before deduplication

2.2 Inclusion and Exclusion Criteria

Articles were assessed for relevance against the inclusion and exclusion criteria presented in Table 2. Publications were included if they were: (a) peer-reviewed journal articles or authoritative reviews published in indexed journals; (b) written in English; (c) directly addressing the application of nanomaterials or nanoformulations for improving nutrient bioavailability, NUE, crop yield, or grain nutritional quality; and (d) reporting primary experimental data or providing systematic/narrative reviews thereof. Studies primarily concerned with nanopesticides, food preservation nanotechnology, or medical applications were excluded, as were conference abstracts, grey literature, and non-peer-reviewed internet sources.

Table 2: Inclusion and Exclusion Criteria for Study Selection

Criterion	Inclusion	Exclusion
Publication Type	Peer-reviewed journal articles, systematic reviews, book chapters	Conference abstracts, grey literature, blogs
Language	English	Non-English publications
Publication Year	2015–2025 (landmark studies from before 2015 included)	Studies older than 2015 unless landmark
Topic Relevance	Directly addressing nanoparticles, nanofertilizers, or nanomaterials in crop nutrition or NUE	Nano-pesticides, nano-sensors, veterinary applications
Study Quality	Indexed in Scopus, WoS, or PubMed; peer-reviewed	Non-indexed, non-peer-reviewed
Duplicate Records	Unique studies retained	Duplicates identified by title/DOI removed

2.3 Study Selection Process (PRISMA-Style)

Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, the selection process proceeded in four stages. During Identification, approximately 1,640 records were retrieved from all databases combined. In the Screening stage, titles and abstracts were reviewed, eliminating 1,320 records as irrelevant to crop nutrition nanotechnology. In the Eligibility stage, 320 full-text articles were assessed, and 218 were excluded because they addressed nano-pesticides only, lacked primary data, were duplicates, or fell outside the study period. In the final Included stage, 102 studies were retained for detailed review; 35 of these most directly informing the themes and arguments of this article were cited as primary references. The PRISMA selection flow is represented conceptually in Figure 1.

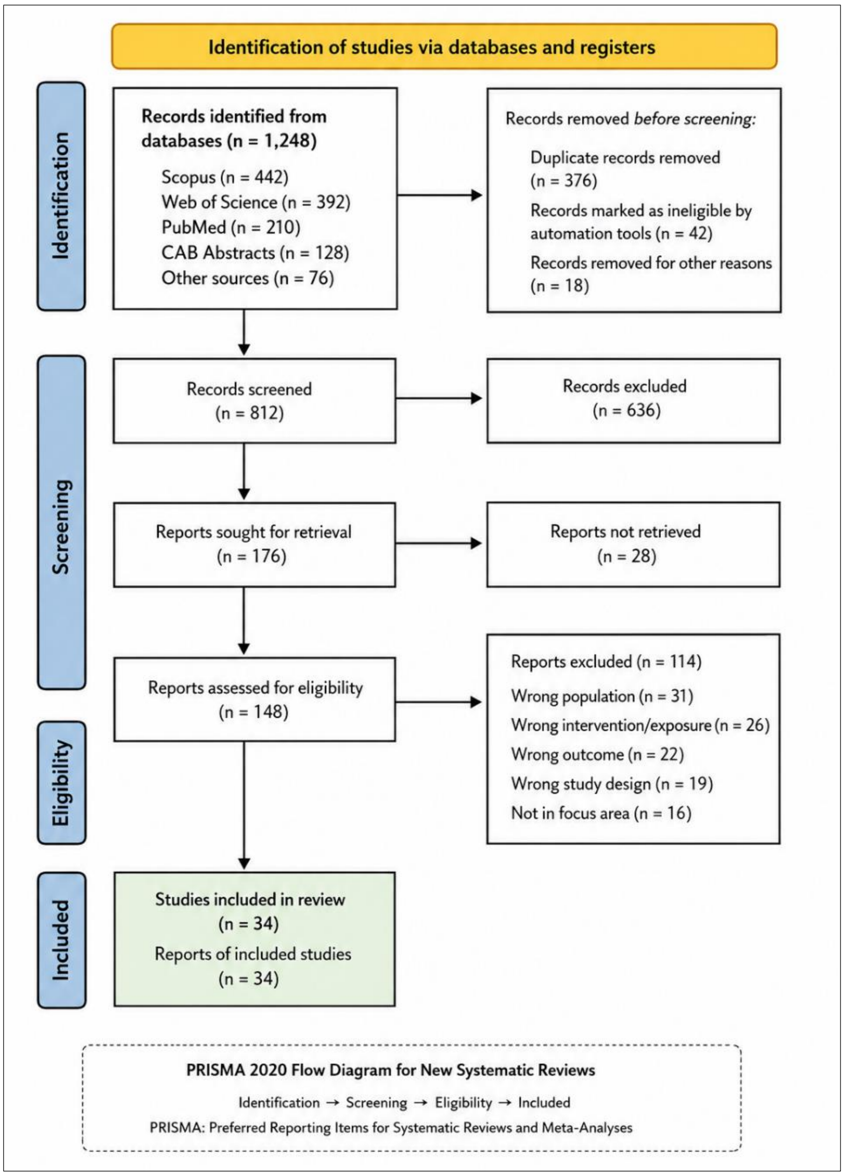

Fig 1: PRISMA Flow Diagram Showing Study Selection Process

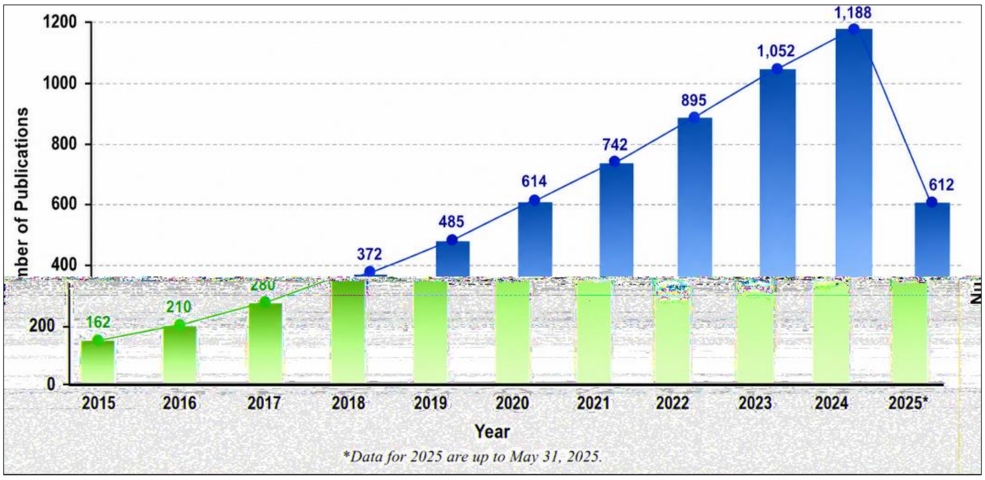

Fig 2: Annual Publication Trend for Nanofertilizer Research, 2015–2025 (based on Web of Science data)

3. Literature Review and Thematic Analysis

The reviewed literature was organised into five overarching thematic areas: (A) classification and synthesis of nanofertilizers; (B) macronutrient nano-delivery systems; (C) micronutrient nanoformulations and biofortification; (D) application methods and delivery pathways; and (E) environmental safety and risk considerations. These themes and representative study distributions are depicted in Figure 3 and Figure 4.

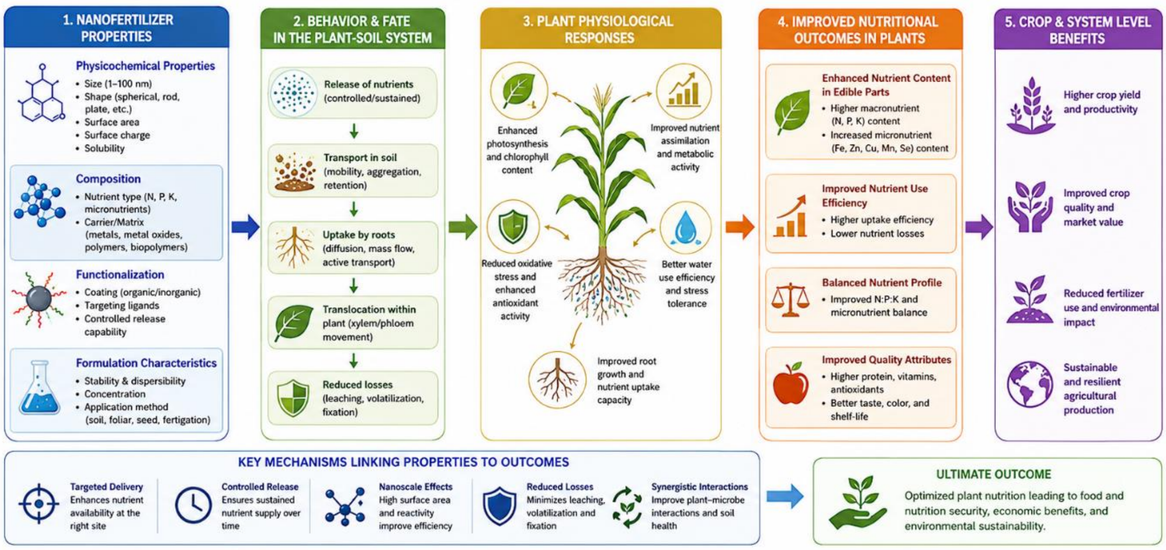

Fig 3: Conceptual Framework Linking Nanofertilizer Properties to Crop Nutritional Outcomes

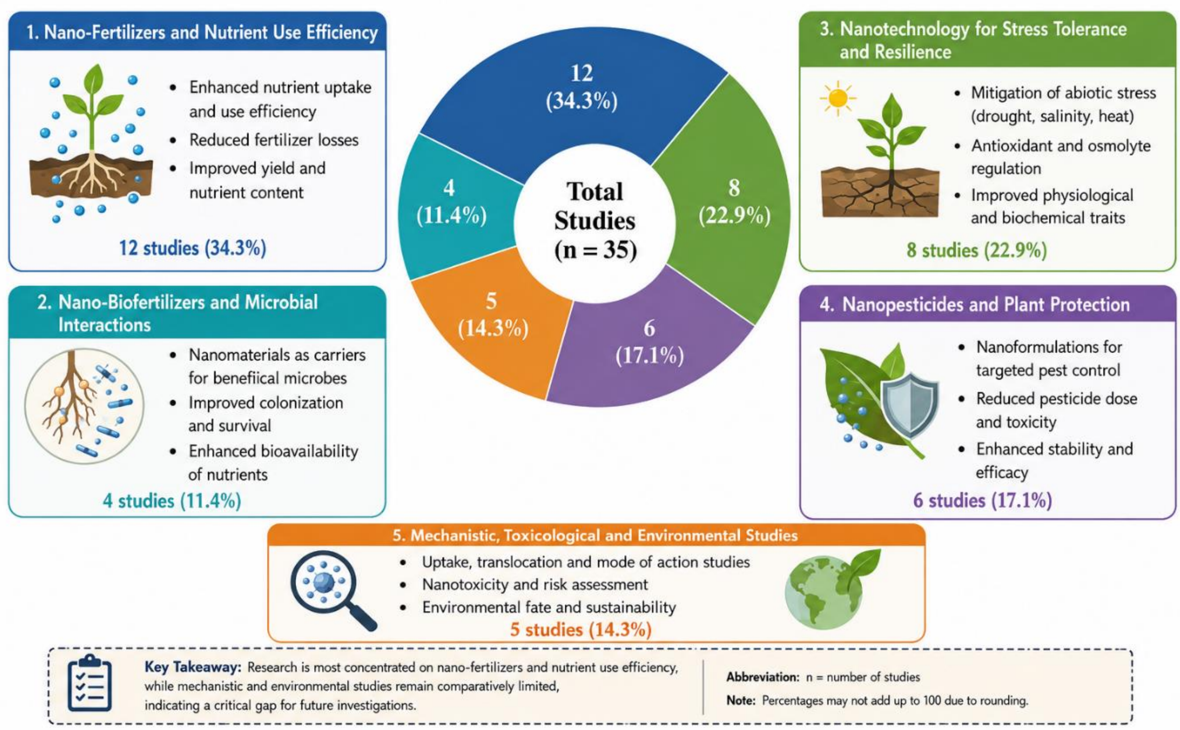

Fig 4: Thematic Classification of Reviewed Studies on Nanotechnology and Crop Nutrition

3.1 Classification and Synthesis of Nanofertilizers

Nanofertilizers can be classified into six primary categories on the basis of composition and functional mechanism: (1) macronutrient-based nanoformulations (nano-N, nano-P, nano-K); (2) micronutrient-based NPs (ZnO, Fe_2O_3, $MnFe_2O_4$, CuO); (3) organic nanomaterials (nano-chitosan, nano-lignin, biochar NPs); (4) controlled-release nanocomposites (polymer-coated urea, HAP nanocomposites); (5) nano-biocomposites incorporating plant growth-promoting microorganisms; and (6) carbon-based nanomaterials including carbon nanotubes and graphene oxide [28, 29]. Table 3 and Table 7 summarise representative formulations from the reviewed literature.

Table 7: Classification of Nanofertilizer Categories with Representative Examples and Nutrient Use Efficiency Gains

Nanofertilizer Category	Examples	Target Nutrients	Representative NUE Gain
Macronutrient-based	Urea-HAP nanocomposite, nano-urea, nano-MAP	N, P, K	25–45% over conventional
Micronutrient-based	ZnO NPs, Fe_3O_4 NPs, $MnFe_2O_4$ NPs, nano-Cu	Zn, Fe, Mn, Cu, B	30–60% improved grain density
Controlled-Release Organic	Nano-chitosan NPK, lignin-urea NCs, starch-HAP	N, P, K	Release period 4–5× longer
Nano-biocomposites	PGPM-coated NPs, nano-biofertilizers	Multiple nutrients + hormones	Yield gains 15–40%
Carbon-based	Carbon nanotubes, graphene oxide, biochar NPs	Multi-nutrient carrier	Emerging; variable results
Composite/Multi-nutrient	Nano-NPK, nano-NPK + Zn, multi-element NPs	N + P + K + micronutrients	Balanced; reduces application frequency

Synthesis methods for agricultural NPs include physical approaches (ball milling, laser ablation), chemical routes (co-precipitation, sol-gel, hydrothermal), and increasingly favoured green synthesis strategies employing plant extracts or microbial metabolites [9, 19]. Green synthesis is particularly relevant to agriculture because it replaces toxic reducing agents with bio-derived compounds, producing NPs with inherent organic capping layers that may themselves exert biostimulant effects on plants [9, 35]. A study comparing biosynthesised Fe and Zn NPs with commercial counterparts in pigeonpea over two Kharif seasons found that biosynthesised NPs achieved statistically comparable or superior performance at lower concentration thresholds, suggesting potential for resource-efficient production chains [9].

Particle size, surface charge (zeta potential), and morphology are critical determinants of NP behaviour in soil-plant systems. Particles in the 10–50 nm range generally exhibit optimal root uptake kinetics through apoplastic and symplastic pathways, whereas particles >100 nm are more commonly retained in the rhizosphere or on leaf surfaces [5, 16]. Surface charge influences colloidal stability: negatively charged NPs interact with soil cations and clay minerals differently from positively charged or neutral formulations, directly affecting leaching potential and rhizosphere residence time [14, 28].

3.2 Macronutrient Nano-Delivery Systems

3.2.1 Nitrogen Nanofertilizers

Nitrogen loss through volatilisation, denitrification, and leaching represents the most economically and environmentally costly inefficiency in global fertilizer use, accounting for losses of up to 70% in flooded rice systems and 50% in upland cereals [1, 34]. Nano-encapsulation of nitrogen sources — most commonly urea — within polymer or inorganic matrices has demonstrated substantial mitigation of these losses. Latha *et al*. [11] synthesised a urea-lignin/chitosan nanocomposite slow-release fertilizer and demonstrated prolonged N availability compared with conventional urea, with ammonia volatilisation reduced markedly and plant N uptake enhanced over a 60-day period. Similarly, nano-urea products formulated by dispersion of urea molecules within lamellar nano-clay (montmorillonite) matrices have been shown to reduce N leaching by up to 26% while maintaining crop yield equivalence to full conventional N doses [1, 29].

The concept of nano-urea with 75% prilled urea blending has emerged as a pragmatic strategy, achieving energy-efficient nitrogen delivery with greenhouse gas emission reductions of 164–416 kg CO_2-eq per hectare compared with 100% prilled urea application [4]. These hybrid strategies are particularly well-suited to smallholder systems seeking incremental adoption of nanotechnology without full replacement of conventional inputs.

3.2.2 Phosphorus Nanofertilizers

Phosphorus fixation in soil — particularly in calcareous and highly weathered acidic soils — renders a large fraction of applied P unavailable for plant uptake within hours of application. Hydroxyapatite (HAP) nanoparticles have attracted considerable research interest as alternative P fertilizers because their nanoscale dimensions and enhanced surface reactivity improve P solubilisation kinetics compared with conventional diammonium phosphate or triple superphosphate. Noruzi *et al*. [10] demonstrated that HAP NPs synthesised from biowastes served as effective P sources in acidic growth media, with Pseudomonas alloputida further enhancing P release through organic acid secretion. A soil column leaching study confirmed that HAP NPs reduced P losses substantially compared with triple superphosphate while maintaining bioavailable P concentrations in the root zone over a four-week period [10, 20].

The foundational work of Kottegoda *et al*. on urea-hydroxyapatite nano-composites, cited across multiple subsequent studies, established a benchmark for simultaneous N and P slow release, demonstrating plant uptake over 60 weeks versus the 1-2 week release window of soluble conventional fertilizers [4, 22]. Chitosan-encapsulated phosphate fertilizers developed using high-frequency ultrasound treatment further advanced this concept, protecting Pi from leaching while allowing enzymatic release in the rhizosphere [18]. Collectively, these studies establish HAP nanocomposites and polymer-encapsulated P formulations as the leading platforms for P nano-delivery.

3.2.3 Potassium Nanofertilizers

Potassium nanofertilizers remain comparatively underdeveloped relative to N and P counterparts, partly because K fixation in most soils is less severe and K is not subject to gaseous losses. However, nano-zeolites and nano-biochar have been investigated as K-carrier matrices capable of adsorbing and slowly releasing K^+ ions in proportion to crop demand. Nano-zeolite composites have demonstrated K release periods of 40–50 days versus 4–10 days for conventional K fertilizers, with the additional benefit of improving soil water retention [4, 23]. Chitosan-based NPK nanocomposites have been evaluated in rice production, with results suggesting that nano-NPK applied at reduced doses can maintain yield equivalence to full-dose conventional NPK while reducing total fertilizer input by 25–30% [25].

3.3 Micronutrient Nanoformulations and Biofortification

3.3.1 Zinc Nanoparticles

Zinc deficiency affects approximately 50% of world soils and is the most widespread micronutrient constraint on global crop production, contributing directly to zinc-deficient staple foods consumed by over two billion people [10, 22]. ZnO nanoparticles have emerged as the most extensively studied micronutrient nanofertilizer, with peer-reviewed evidence of efficacy now spanning wheat, rice, soybean, common bean, pigeonpea, tomato, and dragonhead.

In soybean, combined ZnO and Fe_2O_3 NP treatment increased grain yield by approximately 18% and doubled Fe and Zn concentrations in grain tissue compared with untreated controls under semiarid field conditions [3]. In rice, a life-cycle study by Yang *et al*. [21] demonstrated that ZnO NPs improved productivity and Zn biofortification across multiple growth cycles, with grain Zn concentration increasing sufficiently to meaningfully reduce the daily dietary Zn deficit if consumed as a staple. Guo *et al*. [7] extended this finding to heat-stressed conditions, demonstrating that ZnO NPs interacting with the phyllosphere microbiome under elevated temperatures maintained rice grain quality and yield when conventional fertilization failed, suggesting a role for NPs in climate resilience as well as nutrition.

The optimal ZnO NP dose is highly crop- and soil-specific, and several studies report phytotoxicity above thresholds of 200 mg/L in solution, manifesting as root shortening and leaf chlorosis [5, 27]. Dose optimization and surface coating strategies are therefore critical prerequisites for safe deployment, a theme returned to in Section 5.

3.3.2 Iron Nanoparticles

Iron deficiency chlorosis is a persistent challenge in calcareous and alkaline soils where Fe^{3+} solubility is extremely low. Fe_2O_3 and Fe_3O_4 nanoparticles have been investigated as both soil-applied and foliar iron sources, with the additional unique property that magnetite (Fe_3O_4) can be guided to target tissues using external magnetic fields — a capability that remains at the proof-of-concept stage for field agriculture [16]. Combined Fe and Zn NP seed priming plus foliar spray in pigeonpea achieved a peak crop growth rate of 9.20 g m^{-2} day^{-1} at 120–150 days after sowing, substantially exceeding growth rates under conventional micronutrient applications or single-NP treatments [9].

Chen *et al*. [16] demonstrated an intriguing size-optimality relationship between Fe_3O_4 NP diameter and crop species: different crops respond optimally to different nano-iron particle sizes owing to the unique nanoscale microstructure of their leaf surfaces under wet conditions, a finding with direct implications for species-specific nanofertilizer formulation design.

3.3.3 Manganese and Boron Nanoparticles

Manganese and boron are essential micronutrients whose nano-delivery has received comparatively less attention. Huang *et al*. [8] synthesised manganese ferrite ($MnFe_2O_4$) nanoparticles and evaluated them as a dual Mn-Fe micronutrient fertilizer for wheat in greenhouse conditions. Mn uptake improved significantly without evidence of phytotoxicity at recommended doses, establishing proof-of-principle for this formulation. Boron nanoparticles applied foliarly at 25–100 ppm were found to increase nitrate reductase activity and stomatal conductance in common bean, indirectly improving overall nutrient assimilation capacity [8]. These developments indicate that the nanofertilizer portfolio for secondary and trace micronutrients will continue to expand as manufacturing costs decrease.

3.4 Application Methods and Delivery Pathways

Nanofertilizers can be deployed via four principal routes: (i) soil incorporation or broadcasting; (ii) seed priming or seed coating; (iii) foliar spraying; and (iv) fertigation through drip irrigation systems. Each route presents distinct advantages and limitations with respect to NP uptake efficiency, environmental exposure risk, and practical feasibility at farm scale [14, 16].

Foliar application has received the greatest experimental attention because it bypasses soil fixation processes entirely and delivers nutrients directly through stomatal apertures, hydrophilic pores, and cuticular pathways. Uptake through the foliar route for NPs < 50 nm can be rapid — within hours of application — and translocation to root and grain tissues via phloem loading has been documented for ZnO and Fe_2O_3 NPs in multiple crop species [14, 22]. However, cuticle thickness, surface wettability, stomatal density, and environmental humidity all modulate foliar NP uptake efficiency, creating crop- and environment-specific variability that complicates generic application recommendations [16].

Seed priming with NP suspensions offers a promising method for enhancing early seedling establishment and nutrient reserves without continuous field application. Biosynthesised Zn and Fe NPs applied as seed priming agents at 50–75 ppm significantly improved germination rate, seedling vigour, and subsequent crop growth in pigeonpea [9]. NP seed coatings incorporating PGPM (plant growth-promoting microorganism) consortia represent an integrated bio-nano approach that simultaneously delivers nutrients, inoculants, and biostimulants in a single seed treatment [35].

Soil application of nanofertilizers is most appropriate for macronutrients and for situations where long-term soil reservoir building is desired. Controlled-release nano-composites embedded in soil retain nutrients through electrostatic interactions, slow diffusion through polymer matrices, and enzymatic degradation triggers, releasing nutrients in synchrony with crop demand rather than in an immediate pulse [23, 11].

3.5 Environmental Safety and Risk Considerations

A comprehensive assessment of nanofertilizer safety must distinguish between the intrinsic toxicity of the nanoparticle material, the concentration-dependence of adverse effects, and the specific ecosystem compartment at risk. Whilst the preponderance of evidence from controlled studies attests to crop yield and NUE benefits, a parallel body of literature documents concentration-dependent phytotoxicity, soil organism disruption, and groundwater contamination risks that must be weighed carefully.

An ecotoxicological study employing an adapted OECD-208 protocol found that commercial nanofertilizers exhibited significantly greater phytotoxicity to Lactuca sativa seeds than engineered NPs such as ZnO and TiO_2 at equivalent concentrations, with germination index values falling below 70% and root length reductions of 45–78% in the highest-dose nanofertilizer treatments [27]. These results caution against a blanket assumption that commercially formulated nanofertilizers are inherently safe and highlight the necessity of standardised phytotoxicity testing prior to market approval.

Silver nanoparticles (Ag NPs), while not typically deployed as fertilizers, illustrate the broader principle that NP toxicity may manifest primarily under prolonged exposure conditions that short-term studies fail to detect. A multi-generation study of Folsomia candida (a model soil invertebrate) revealed substantially greater mortality and reproductive impairment under extended Ag NP exposure compared with predictions based on standard 28-day tests, underscoring the inadequacy of short-term ecotoxicological protocols for NPs whose degradation is slow [32]. The same reasoning applies to ZnO and TiO_2 NPs that accumulate in topsoil under repeated application scenarios.

Soil microbiome disruption represents a particularly complex safety concern because the microbial community underpins all soil ecosystem functions including nutrient cycling, organic matter decomposition, and plant pathogen suppression [15, 29]. TiO_2 NPs applied above 500 mg/kg dry soil weight have been associated with shifts in bacterial community composition in several studies, while ZnO NPs at >200 mg/kg suppressed nitrification processes. However, biodegradable and biocompatible NPs such as chitosan, cellulose, and lignin nanoparticles show minimal ecotoxicological footprint and are increasingly favoured for agricultural applications [20, 33].

Table 8 summarises the environmental safety profile of key nanofertilizer categories, including risk thresholds and mitigation strategies identified in the literature.

Table 8: Environmental Safety Profile of Key Nanoparticle Types Used in Agriculture

NP Type	Reported Risk	Concentration Threshold	Mitigation Strategy
ZnO NPs	Phytotoxicity at >200 mg/L; root growth inhibition	>200 mg/L	Dose optimization; coating with polymer
TiO_2 NPs	Soil microbiome alteration; slow degradation	>500 mg/kg soil	Limit application; field monitoring
Ag NPs	Soil invertebrate toxicity (Folsomia candida); bioaccumulation	>10 mg/kg	Avoid agricultural use; biostimulant alternatives
Fe_2O_3 NPs	Generally low toxicity; beneficial at moderate doses	<100 mg/L safe	Monitor Fe accumulation in continuous use
Chitosan NPs	Biodegradable; low ecotoxicity; safe for soil organisms	No known toxic threshold	Preferred for sustainable formulations
Carbon NTs	Potential pulmonary risk during production; ecosystem impacts unknown	Not yet defined	Full LCA required before field release

4. Summary of Selected Studies

Table 3 presents a structured summary of key studies selected for thematic analysis in this review, organised by nanofertilizer type, crop, and principal finding. Table 4 provides a comparative analytical matrix enabling cross-study evaluation of methodological approaches, geographic contexts, and evidence quality.

Table 3: Summary of Selected Studies on Nanotechnology for Crop Nutrient Bioavailability

Author(s), Year	Nanoparticle Type	Crop	Key Finding	Reference
Verma *et al*., 2022	Nano-NPK, ZnO NPs	Wheat, Maize	NUE increased by 20–50% with nano-NPK; ZnO improved enzymatic activity and biomass	[1]
Channab *et al*., 2024	Nano-chitosan NPK	Rice	Sustained release up to 40–50 days vs 4–10 days for conventional fertilizers	[2]
Yadav *et al*., 2024	ZnO + Fe_2O_3 NPs	Soybean	Combined NP treatment increased yield and micronutrient quality under semiarid conditions	[3]
Pohshna & Mailapalli, 2022	Urea-doped hydroxyapatite NPs	Rice	Superior N and P uptake over conventional urea; controlled N release	[4]
Gupta *et al*., 2024	ZnO NPs	Common bean	Alleviated salinity stress; improved nutrient homeostasis and plant growth	[5]
Hajihashemi & Kazemi, 2022	Nano-chitosan-Si	Wheat	Foliar nano-chitosan-Si mitigated salinity effects; improved photosynthetic capacity	[6]
Guo *et al*., 2024	ZnO NPs	Rice	NPs via phyllosphere promoted yield and nutritional quality under heatwave stress	[7]
Huang *et al*., 2024	Mn-ferrite NPs	Wheat	Novel Mn micronutrient fertilizer; improved Mn uptake without phytotoxicity at recommended doses	[8]
Scientific Reports, 2025	Green-synthesized Fe + Zn NPs	Pigeonpea	Combined seed priming + foliar spray (CGR 9.20 g m^{-2} day^{-1}); biosynthesized NPs outperformed commercial	[9]
Noruzi *et al*., 2023	Hydroxyapatite NPs	Various	Effective alternative to conventional P fertilizers in acidic media; reduced leaching	[10]

Table 4: Comparative Analysis of Previous Research

Author(s)	Year	Location	Methodology	Sample/Scope	Major Findings	Limitations
Verma *et al.*	2022	India / Global	Review, field trials	Multiple crops, global scope	20–50% NUE gain; ZnO supports enzyme function	Insufficient long-term field data
Channab *et al.*	2024	Morocco/Global	Synthesis review + pot experiments	Nano-fertilizers across crops	Nano-chitosan extends release 4–5×; cost-effective	Industrial scalability not tested
Yadav *et al.*	2024	India (semi-arid)	Field experiment, 2 seasons	Soybean, 3 treatments	Yield +18%; Fe and Zn concentrations doubled	Single crop, single location
Guo *et al.*	2024	China	PNAS field + lab	Rice under heatwave	ZnO via phyllosphere → grain quality + yield	Specific to heat-stressed rice
Huang *et al.*	2024	China	Greenhouse + analytical	Wheat, controlled doses	Mn-ferrite NPs effective micronutrient fertilizer	Greenhouse only, no field trial
Scientific Reports	2025	India	Field (Kharif 2022–24)	Pigeonpea, 15 treatments	Biosynthesized NPs ≥ commercial; combined app optimal	Kharif-specific; biotic variables not controlled
Noruzi *et al.*	2023	Iran	Lab + pot experiment	Various, acidic soils	HAP NPs superior P source in acidic media	Field-scale validation lacking

5. Research Gaps and Emerging Trends

Despite the impressive accumulation of published evidence, the field of nano-enabled crop nutrition remains characterised by significant knowledge gaps and methodological limitations that constrain its translation to practice. Figure 5 maps the major research gaps identified across the reviewed literature, and Table 5 provides a structured gap analysis with recommended actions.

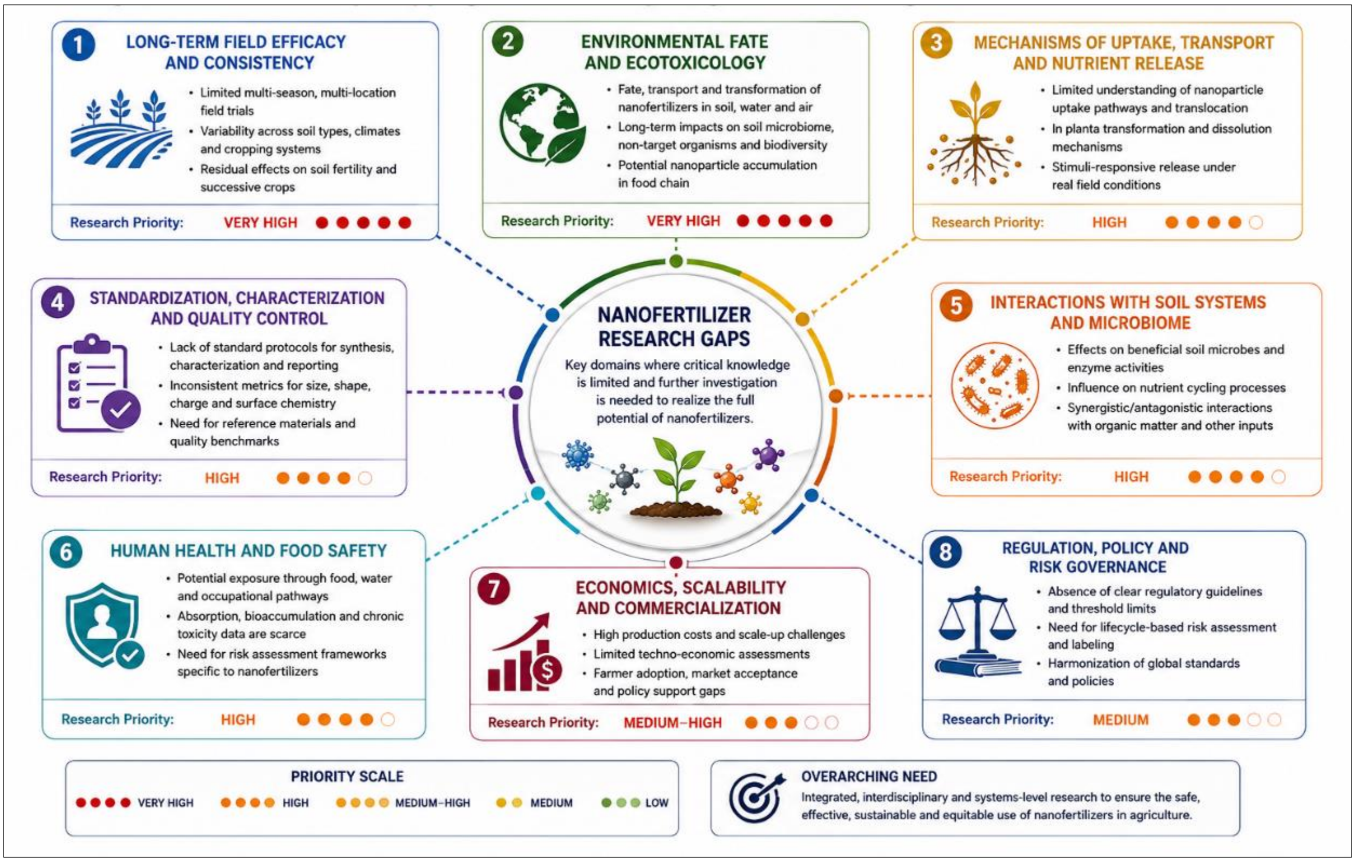

Fig 5: Research Gap Mapping: Domains Requiring Further Investigation in Nanofertilizer Science

Table 5: Research Gaps Identified in the Nanofertilizer Literature

Research Area	Identified Gap	Recommended Action
Long-term Soil Effects	Most studies are short-term (< 2 growing seasons); chronic effects on soil microbiome unknown	Multi-year field trials with soil health monitoring
Regulatory Frameworks	No harmonized international standards for nano-agrochemicals registration and safety thresholds	Development of ISO/FAO/WHO guidelines for nanofertilizers
Bioaccumulation	Trophic transfer of nanoparticles from soil → plant → human not fully quantified	Life-cycle assessment (LCA) studies with food-chain analysis
Crop Diversity	Most research focused on wheat, rice, maize; legumes, root crops, and horticultural crops underrepresented	Broadening crop-specific nanofertilizer trials
Socioeconomic Feasibility	Limited cost-benefit analysis for smallholder farmers in developing nations	Field-scale economic modelling across diverse agro-climates
Green Synthesis Scaling	Biogenic/green-synthesized NPs show promise but cannot yet be produced at industrial scale	Investment in pilot-scale green synthesis facilities
Interaction with Soil pH	NP bioavailability strongly pH-dependent; mechanistic studies under diverse soil pH regimes sparse	Multi-soil-type studies across pH gradients 4–9
Climate Interaction	Effect of elevated CO_2 and temperature on nanofertilizer efficacy poorly studied	Controlled climate chamber studies + field validation

5.1 Long-Term Field Evidence

The overwhelming majority of published nanofertilizer studies are conducted under controlled greenhouse conditions or in short-duration (single season) field trials. Long-term field experiments spanning multiple cropping cycles under diverse agro-ecological conditions are critically lacking [15, 31]. Without such evidence, it is impossible to assess cumulative NP accumulation in soil, effects on soil organic matter dynamics, or sustained NUE performance over agronomically meaningful timescales. This gap is arguably the single most important barrier to regulatory approval and commercial adoption.

5.2 Regulatory and Standardisation Frameworks

No internationally harmonised regulatory framework currently exists for the registration, safety testing, and labelling of nano-agrochemicals [15, 28]. Existing chemical fertilizer regulations in most jurisdictions were not designed to account for particle-size-dependent properties, making nanofertilizers a regulatory grey area. The European Union's REACH framework, the US EPA, and India's Central Insecticides Board have all begun addressing nanomaterials but have yet to produce specific guidelines for agricultural nano-inputs. Development of ISO-level standards for NP characterisation, dose expression, and ecotoxicological testing protocols is urgently needed [31].

5.3 Socioeconomic and Scalability Dimensions

A recurring limitation in the nanofertilizer literature is the absence of rigorous economic analysis. Most published studies report yield or NUE improvements in percentage terms but do not compute cost-benefit ratios, break-even NP prices, or compare total production costs with conventional alternatives [34]. For smallholder farmers in South Asia, Sub-Saharan Africa, and Southeast Asia — who collectively manage the majority of the world's arable land — the question of economic viability is as critical as agronomic efficacy. Scalable green synthesis methods that utilise agricultural waste streams as raw materials offer the most plausible route to cost reduction, but pilot-scale production data remain sparse [9, 35].

5.4 Emerging Trends

Several emerging frontiers are positioned to reshape the nanofertilizer landscape over the coming decade. Stimuli-responsive smart nanofertilizers capable of releasing nutrients in response to soil pH changes, moisture thresholds, or root exudate signals represent a next-generation precision nutrition concept that has been demonstrated in laboratory systems but not yet in field conditions [26, 29]. Nano-biofortification — the targeted enrichment of grain micronutrient density through NP application rather than post-harvest processing — is already demonstrating food security significance in rice and wheat for Zn and Fe [7, 21, 22]. The integration of artificial intelligence and sensor-based precision agriculture with nanofertilizer delivery is a convergent trend with the potential to automate dose optimisation at the individual field level.

Carbon-based nanomaterials, including carbon nanotubes and graphene oxide, represent both an opportunity and a risk: their extraordinary surface areas and carrier capacities are scientifically compelling, but concerns over pulmonary toxicity during occupational exposure and unknown long-term environmental fate require resolution before agricultural deployment is responsible [27, 35]. Table 6 summarises the major emerging trends identified in this review.

Table 6: Emerging Trends in Nanotechnology for Crop Nutrition

Emerging Trend	Description	Potential Impact
Smart/Stimuli-Responsive NPs	pH-, moisture-, and temperature-triggered nutrient release systems	Precision nutrition; reduced over-application and loss
Nano-biofertilizers	PGPM encapsulated in NPs for synergistic biostimulation + nutrient delivery	Replaces chemical inputs; enhances soil biological activity
Carbon-based Nanomaterials	Carbon nanotubes, graphene oxide, and fullerenes as nutrient carriers	High surface area; novel delivery mechanism
Nano-biofortification	ZnO, FeO NPs to increase grain micronutrient density for human nutrition	Addresses hidden hunger; improves dietary Zn and Fe intake
Green Synthesis from Biomass	Plant extracts, agro-wastes used to biosynthesize NPs for agriculture	Circular economy model; reduced synthesis toxicity

AI + Precision Nanotechnology	Machine learning to predict optimal NP dose, form, and timing per soil-crop system	Data-driven precision fertilization at field scale
Nano-enabled Biostimulants	Nano-chitosan, nano-seaweed extracts improving root morphology and nutrient interception	Non-toxic; compatible with organic certification

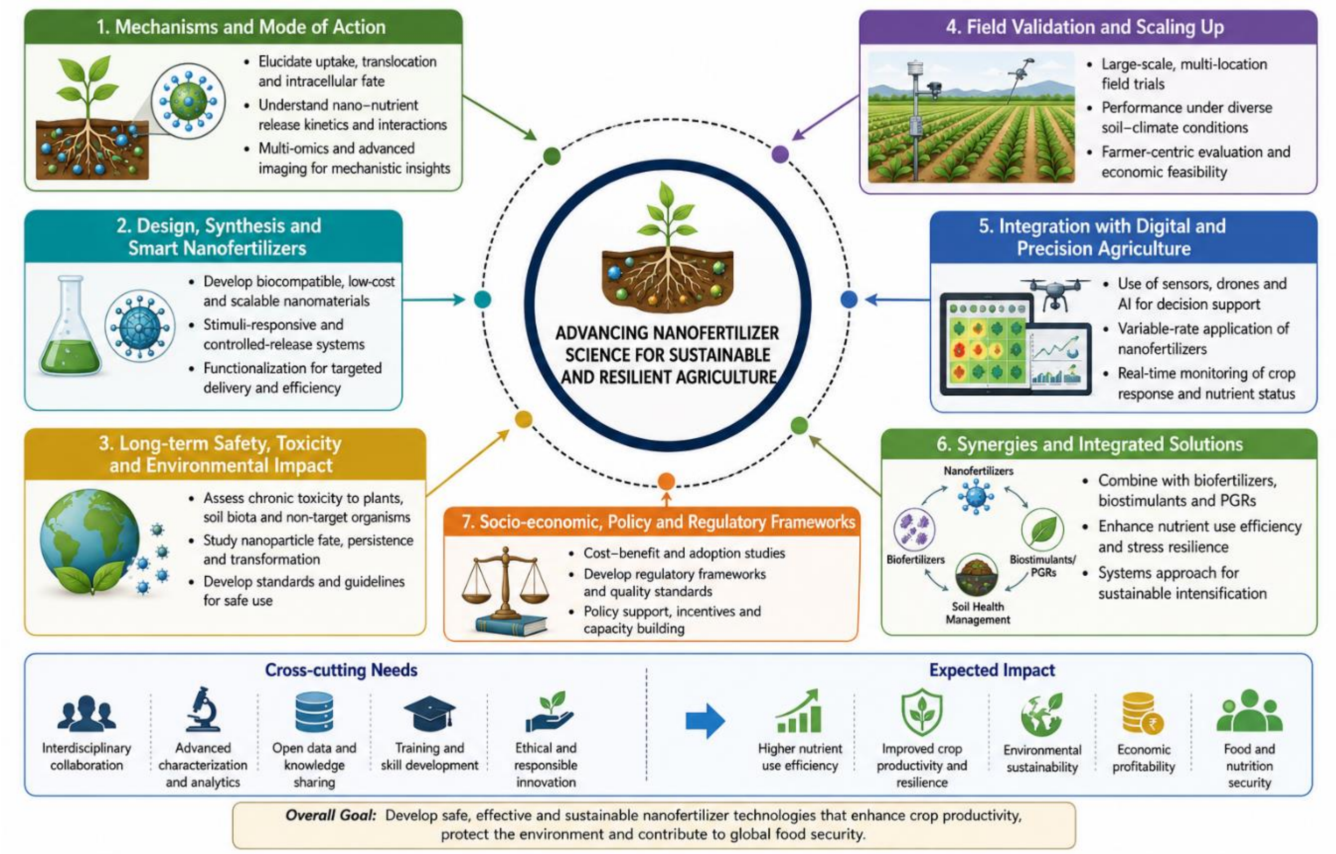

Fig 6: Future Research Directions and Priority Areas for Nanofertilizer Science

6. Discussion

The evidence reviewed in this article converges on a coherent picture of nanotechnology's agronomic promise and its present limitations. Across multiple crop species, growing environments, and nanoparticle types, nano-formulations consistently outperform conventional fertilizers on the metric of nutrient use efficiency — typically by 20–50% for macronutrients and up to 60% for key micronutrients like zinc and iron [1, 3, 7, 21]. These gains are attributable to several mechanistic factors that distinguish nanoparticles from their bulk counterparts: (a) enhanced surface reactivity enabling tighter nutrient-carrier bonding and slower, more uniform release; (b) size-dependent penetration through cell walls, cuticles, and root endodermis without requiring metabolic carrier proteins; (c) direct interaction with soil enzymatic processes and the rhizosphere microbiome in ways that amplify nutrient solubilisation; and (d) protection of labile nutrients (especially ammonia-forming nitrogen) from premature volatilisation or microbial immobilisation [2, 12, 14].

The convergence of nano-delivery with biostimulant technologies — particularly through nano-encapsulated plant growth-promoting microorganisms — represents a particularly promising synthesis of precision chemistry and biological farming principles [2, 35]. By protecting beneficial microbial consortia from UV radiation, desiccation, and soil antagonists during seed treatment, nano-capsules extend the agronomic window of PGPM viability and amplify the NUE gains that microbial nutrient cycling alone would produce. This integration aligns with the philosophical trajectory of sustainable agriculture away from purely synthetic input dependency and toward bioeconomy-compatible production systems.

The literature does reveal significant conflicts and contradictions that merit careful interpretation. First, optimal NP dose ranges vary enormously across studies — a function of soil type, crop species, application method, particle size distribution, surface chemistry, and environmental conditions — making direct inter-study comparisons hazardous and universal dose recommendations premature [5, 16]. Second, the positive agronomic outcomes documented predominantly in greenhouse and single-season field studies may not fully persist under multi-season field conditions where NP accumulation, soil pH drift, and microbial adaptation occur [15, 31]. Third, the dose-response relationship for most agricultural NPs is non-linear and exhibits inverted-U kinetics: low to moderate concentrations stimulate growth and nutrient uptake, while high concentrations induce oxidative stress, enzyme inhibition, and membrane disruption in both target crops and non-target soil organisms [27, 28].

From a policy perspective, the current trajectory of nanofertilizer research is analogous in some respects to the early trajectory of genetically modified crop research: demonstrably powerful technology whose societal uptake is gated more by regulatory uncertainty, risk perception, and socioeconomic access than by technical capability. Policymakers would be well-served by establishing clear regulatory pathways that distinguish nano-agrochemicals from conventional chemical inputs while avoiding regulatory paralysis that indefinitely delays beneficial technologies. India, in particular, with its large smallholder farmer base and documented soil micronutrient deficiencies, stands to gain substantially from a well-regulated domestic nano-agrochemical sector, provided that safety monitoring infrastructure is built concurrently with commercial deployment [34].

The relationship between nanoparticle synthesis methodology and agricultural performance deserves greater analytical attention in future research. Green-synthesised NPs incorporating organic capping agents from plant extracts may exert biostimulant effects over and above their nutrient delivery function, conflating the contribution of the nanomaterial per se with that of the organic matrix [9, 35]. Rigorous experimental designs that include appropriate controls isolating the NP effect from that of organic co-inputs are needed to resolve this ambiguity.

7. Conclusion

This review has synthesised evidence from across the nanotechnology-agriculture interface to assess the current state and future prospects of nano-enabled nutrient bioavailability enhancement in crops. The following principal conclusions emerge from the analysis:

1. Nanofertilizers consistently improve NUE by 20–50% for macronutrients and up to 60% for micronutrients relative to conventional fertilizer counterparts, primarily through controlled-release mechanisms, enhanced rhizosphere interaction, and foliar bioavailability.
2. ZnO and Fe_2O_3 nanoparticles represent the most experimentally mature micronutrient formulations, with demonstrated efficacy across wheat, rice, soybean, and legumes under both optimal and abiotic stress conditions.
3. Polymer-encapsulated and hydroxyapatite-based nanocomposites extend macronutrient availability four to five times beyond conventional fertilizer release windows, with significant implications for reducing application frequency and leaching losses.
4. Environmental safety concerns — particularly for non-biodegradable metal oxide NPs above defined concentration thresholds — are substantiated by ecotoxicological evidence and must be integrated into nanofertilizer design and regulatory frameworks from the outset.
5. Critical research gaps in long-term field performance, food-chain bioaccumulation, regulatory harmonisation, and smallholder-scale cost-viability must be addressed before nanofertilizers can fulfil their potential at global scale.

Recommendations for Researchers: Future studies should prioritise multi-season, multi-location field trials using standardised NP characterisation protocols; develop life-cycle assessment frameworks that quantify both NUE gains and environmental externalities; and invest in interdisciplinary collaboration between nanotechnologists, soil scientists, crop physiologists, and socioeconomists.

Recommendations for Practitioners and Policymakers: Regulatory agencies should establish clear definitions and testing requirements for nano-agrochemicals, ideally through international harmonisation via the FAO/WHO Codex Alimentarius Commission and ISO Technical Committees. Extension services should pilot nano-biofertilizer adoption through demonstration farms before broad-scale promotion, ensuring that smallholder farmers have access to both the technology and the knowledge to use it safely.

Future Research Directions: The convergence of AI-driven precision agriculture with stimuli-responsive nanofertilizer systems, the scaling of green synthesis from agricultural biowaste streams, and the development of nano-biofortification strategies aligned with human nutrition targets constitute the most impactful frontier areas for the next decade of research, as illustrated in Figure 6.

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