Nano-Fertilizer–Mediated Modulation of Rhizosphere Nutrient Flux and Root Ion Transport Dynamics in Cereals Under Nutrient-Limited Soils

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ABSTRACT

Overview: The three cereal crops of wheat (*Triticum aestivum* L.), maize (Zea mays L.), and rice (Oryza sativa L.) form the backbone of food security at a global level. However, global productivity of these crops is limited by their intrinsic low efficiency of nutrient use due to the traditional bulk fertilizers which allow recovery of only 20-50% of nitrogen and 20-30% of phosphorus applied to the soils. The balance is lost through various processes such as leaching, volatilization, fixation, and surface runoff. Nano-fertilizers (NFs) are a concept coming from the field of precision agriculture and consist of nutrients formulated in the 1-100 nm range for the purpose of controlling the flux of nutrients in rhizosphere and enhancing the ions acquired by the roots of the crops through controlled process of dissolution, higher specific area, and nano-bio interface reactivity.

Scope: This review presents a critical analysis of peer-reviewed studies on the functioning of nano-fertilizers in terms of modulation of rhizospheric bioavailability of nutrients and transport of ions through the root system in cereal crops grown under nutrient-limiting conditions.

Data sources: A systematic literature search was conducted using Scopus, Web of Science, PubMed/PMC, ScienceDirect, SpringerLink, Wiley and Frontiers for the key findings include that nano-fertilizers improve nutrient use efficiency (NUE) by over 50%, and increase the yields of cereals by 13-55% compared to conventional fertilizers through low application rates. This is achieved mainly through diffusion-limited release of ions, low molecular weight organic acid (LMWOA) induced dissolution of nanoparticles in the rhizosphere, stimulation of plant growth promoting rhizobacteria, and regulation of expression of both high and low-affinity transporters (NRT1/NPF, NRT2, AMT, PHT1, HAK/AKT). CBL-CIPK23 signaling module is established as a key participant in the coordination of co-transport of nitrate and potassium, which is mediated through nano-created ionic microenvironments.

There are several research gaps identified in the study, such as the absence of mechanisms which connect the dynamics of transformation of nanoparticles to the control of the gene expression level of transporters in cereals, and the non-linearity of the dose-responses of nano-sized fertilizers as well as dependence on the type of soil, and lack of investigation of long-term ecotoxicology in the rhizosphere and the issues of field experiments.

Keywords: nano-fertilizer; rhizosphere; nutrient-use efficiency; root ion transporters; cereals; nutrient-limited soil; NRT/AMT/PHT; nanoparticle dissolution

1. Introduction

Crop yields are based on the macronutrients and micronutrients they depend on for their daily caloric needs. These macronutrients are nitrogen (N), phosphorus (P), and potassium (K) while micronutrients include zinc (Zn) and iron (Fe) and they come from the soil solution through roots. (Wang *et al*., 2021; Wang *et al*., 2021; FAO, 2023) [12, 15, 35] The yield of cereal crops is affected heavily by how well they can obtain macronutrients/micronutrients from the soil, but many soils are nutrient-deficient (nutrient-limited) around the world; this is particularly true for much of South Asia, Sub-Saharan Africa, and other regions where similar types of intensively cropped agriculture occur. (FAO, 2023; Liu *et al*., 2015; Kah *et al*., 2018) [35, 30, 31] In fact, the bioavailability of nutrient ions in these areas is impacted negatively through many different reasons. First, soils have low amounts of native fertility. Second, soils are of pH that is unsuitable, including both alkaline calcareous soils as well as acidic soils. Third, soils will fixate many of the nutrients, and last, poor retention of cationic charge at the surface of the soil will restrict how much cationic charged ions can be held in the root zone of the soils. (Feng *et al*., 2025; Cervantes-Avilés *et al*., 2021; Zhao *et al*., 2019; García-Gómez *et al*., 2015; Wang *et al*., 2024) [6, 19, 20, 22, 34] Fertilizer application is a widely used method to overcome the nutrient deficiencies mentioned. (FAO, 2023; Dimkpa *et al*., 2018) [35, 28]

However, there is a very large spatial/temporal mismatch between when conventional bulk fertilizers release nutrients after they are applied and when the crops need these nutrients (root uptake). (Raliya *et al*., 2017; Dimkpa *et al*., 2018; Kah *et al*., 2018) [5, 28, 31] Consequently, there are unfortunately many environmental effects of conventional bulk fertilizer usage including low NUE and environmental consequences from nutrient application (e.g. nitrate leaching, ammonia volatilization, nitrous-oxide (N2O) emission). (Anas *et al*., 2021; FAO, 2023; Coskun *et al*., 2020) [3, 35, 14]

Nano-fertilizers (NFs) are defined as fertilizer components that have either one or more nutrient elements manufactured into a range of sizes from 1 nm to 100 nm or are enclosed using nanoscale carriers. The NFs represent a new generation of fertilizers. The principal reason that NFs hold great promise is their unique combination of physicochemical properties. These properties include high specific surface area, high percentage of active atoms, opportunities for tunable dissolution rates, and increased interaction (atthe nano level) between the NFs and root surfaces, soil colloids, and the rhizosphere microbial community.(Shoukat *et al*., 2025; Raliya *et al*., 2017) [1, 5] Collectively, these properties enable NFs to release nutrients as required by plants at variable rates, as well as significantly increase the availability of ions in the rhizosphere.

1.2. Importance of the Subject

The rhizosphere is the zone of soil surrounding the roots that is biogeochemically active due to root activity. (Cervantes-Avilés *et al*., 2021; Zhao *et al*., 2019; Sun *et al*., 2024; Wang *et al*., 2024) [19, 20, 21, 26, 34] It is the area where transformation of nanofertilizers, mobilisation of nutrients, and transport of ions through roots occur simultaneously. (Cervantes-Avilés *et al*., 2021; Zhao *et al*., 2019; Sun *et al*., 2024) [19, 20, 26] The uptake of ions by roots involves many different kinds of membrane-embedded transport proteins (also known as transporters) including high-affinity nitrate transporters (NRT2), dual-affinity transceptors (NPF6.3/NRT1.1), ammonium transporters (AMT), phosphate transporters (PHT1), potassium uptake systems (HAK5 and AKT1). (Wang *et al*., 2021; Coskun *et al*., 2020; Wang *et al*., 2021; Drechsler *et al*., 2015; Meng *et al*., 2016; Wu *et al*., 2020) [12, 14, 15, 16, 17, 18]

The activity of these transport proteins is regulated both transcriptionally and post-translationally as a function of the number of specific ions present outside of the root. (Coskun *et al*., 2020; Drechsler *et al*., 2015; Meng *et al*., 2016; Wu *et al*., 2020) [14, 16, 17, 18] Therefore, understanding how nanofertilizers alter the flux of nutrients in the rhizosphere, as well as how they influence the molecular machinery involved in the uptake of ions through roots, is essential in order to rationally explain the agronomic performance of nanofertilizers, as well as to develop next-generation, precision fertilisers. (Raliya *et al*., 2017; Kah *et al*., 2018; Sun *et al*., 2024; Wang *et al*., 2024) [5, 26, 31, 34]

1.3. Current Global Scenario

Multiple comparative studies from 2015 through 2024 show that primary nutrients from nano-fertilizers yielded approximately 20-23% more cereal crops than conventional fertilizers (NPK) at equal rates of nutrients applied, using nano-urea on rice to produce 28.6% more grain yield with 44% less input of nitrogen, using nano-zinc on wheat to yield 31.2% more grain at the same time as increasing the grain zinc content by another 41%.2 (Kumar *et al*., 2026) [2] A number of research reviews that looked exclusively at cereals indicated yield gain, or biological yield, from using nano-fertilizers to yield between 20 and 55%, 20 and 40%, and 13 to 25% for wheat, maize, and rice, respectively.10 (Sharma *et al*., 2025) [10] The amount of nitrate leaching, ammonia volatalization, and N2O emitted from using nano-fertlizers has also been documented to be lower than from using traditional fertilizers.4 (Zulfiqar *et al*., 2021) [4] Therefore, nano-fertilizers have emerged as leaders in sustainable and environmentally-responsible agriculture under climate change.

1.4. Need for the Review

While there is an increasingly large scientific database about these different aspects of nano-fertilizer, they are still separated by many disciplines and their literatures. These disciplines include soil chemistry studies examining the dissolution and transformation of nanoparticles; plant physiology studies looking at the regulation of transporters; and agronomic yield trials. (Kah *et al*., 2018; Cervantes-Avilés *et al*., 2021; Wang *et al*., 2024) [31, 19, 34] The relationship between these studies has not been captured in one consolidated mechanism for how nano-fertilizers transform within the rhizosphere into transporter-modulated root ion flow at the root level for cereal crops grown under limited nutrients. (Sun *et al*., 2024; Wang *et al*., 2024; Raliya *et al*., 2017) [26, 34, 5] This review fills this void.

1.5. Objectives of the Review

- To synthesise mechanisms by which nano-fertilizers modulate rhizosphere nutrient flux, including dissolution, diffusion, and microbially mediated mobilisation.
- To examine how nano-fertilizers influence root ion transport dynamics at the level of transporter gene expression and membrane transport physiology in cereals.
- To critically compare agronomic and NUE outcomes across cereal species and nano-fertilizer types under nutrient-limited conditions.
- To identify research gaps, methodological limitations, and emerging trends guiding future investigation.

1.6. Scope of the Review

In this article, we discuss the three major grain crops—wheat, maize and rice—focusing on macronutrients (N, P, K) and micronutrients (Zn, Fe) as well as specifically covering types of nano-fertilisers such as: nano-urea, nano-P (hydroxyapatite-HAP), nano-ZnO, nano-Fe/nano-zero valency Fe; nano-SiO2; and biopolymer-based nanocarriers (such as chitosan/starch). (Kumar *et al*., 2026; Zulfiqar *et al*., 2021; Raliya *et al*., 2017; Dimkpa & Bindraban, 2018) [2, 4, 5, 28] Publications from 2015 to 2025 provide the main source of information reviewed, while complementary key references for transporter physiology have been included as background literature on the transporters. (Wang *et al*., 2021; Coskun *et al*., 2020; Drechsler *et al*., 2015; Wang *et al*., 2024) [12, 14, 16, 34] Studies and research carried out in controlled environments and large-scale field trials using these substances are included in this review. (Ahmed *et al*., 2025; Kumari *et al*., 2025; Sharma *et al*., 2025) [8, 9, 10]

2. Methodology of Literature Review

2.1. Literature Search Strategy

We conducted a detailed, multi-database search that encompassed various databases (Scopus, Web of Science - Core Collection, PubMed/PMC, ScienceDirect, SpringerLink, Wiley Online Library, and Frontiers), in addition to grey literature from the FAO and institutional repositories. (FAO, 2023; Kah *et al*., 2018) [35, 31] We used Boolean search terms to combine (i) a search term for nano-fertilizer, nanofertilizer, and nanoparticle; (ii) a search term for rhizosphere, nutrient flux, and nutrient use efficiency; (iii) a search term for root, ion transport, transporter, NRT, AMT, and phosphate transporter; (iv) a search term for cereal, wheat, maize, and rice; and (v) a search term for nutrient-limited, nutrient deficient, and low fertility. (Raliya *et al*., 2017; Coskun *et al*., 2020; Wang *et al*., 2021) [5, 14, 12] The date range selected for our initial search was Jan 2015 - Dec 2025, with all the references related to transporter physiology, regardless of date, being included. (Drechsler *et al*., 2015; Wang *et al*., 2021) [16, 12]

Table 1: Literature Search Strategy

Parameter	Detail
Databases searched	Scopus, Web of Science, PubMed/PMC, ScienceDirect, SpringerLink, Wiley, Frontiers, MDPI, FAO reports
Search keywords	nano-fertilizer; nanoparticle; rhizosphere; nutrient flux; nutrient-use efficiency; root ion transport; NRT/AMT/PHT/HAK; cereals; wheat; maize; rice; nutrient-limited soil; nanoparticle dissolution
Search period	January 2015 - December 2025 (plus seminal transporter-physiology references)
Languages	English only
Document types	Peer-reviewed original research, reviews, book chapters, institutional/organisational reports

2.2 Study Selection Process (PRISMA-style)

Records returned from searching the databases were compiled into a database, then de-duplicated and reviewed for topical relevance through an assessment of titles and abstracts. (Kah *et al*., 2018; FAO, 2023) [31, 35] Following this process studies were then reviewed against all of the inclusion/exclusion criteria and those that met all of those criteria retained for thematic synthesis. (Raliya *et al*., 2017; Zulfiqar *et al*., 2021) [5, 4] Figure One shows the PRISMA style selection flow and Figure Two shows the amount of publication over time which shows an increase since 2020 that corresponds to a focus on precision fertilisers and climate resilient fertilisation methods, indicating an increase in this field of inquiry. (Kumar *et al*., 2026; Sharma *et al*., 2025; Dimkpa & Bindraban, 2018) [2, 10, 28]

Table 2: Inclusion and Exclusion Criteria

Criteria type	Details
Inclusion	Peer-reviewed English-language publications; studies on nano-fertilizer/nanoparticle effects on rhizosphere nutrient dynamics, root uptake, transporter expression, or NUE; cereal-focused studies (with mechanistic model-plant studies retained for transporter context); 2015-2025 (plus key foundational references)
Exclusion	Non-peer-reviewed sources; studies unrelated to nutrient acquisition (e.g. purely nanotoxicology without uptake relevance); non-cereal studies without mechanistic transferability; abstracts without accessible full text; studies lacking quantifiable NUE, flux, or transporter data

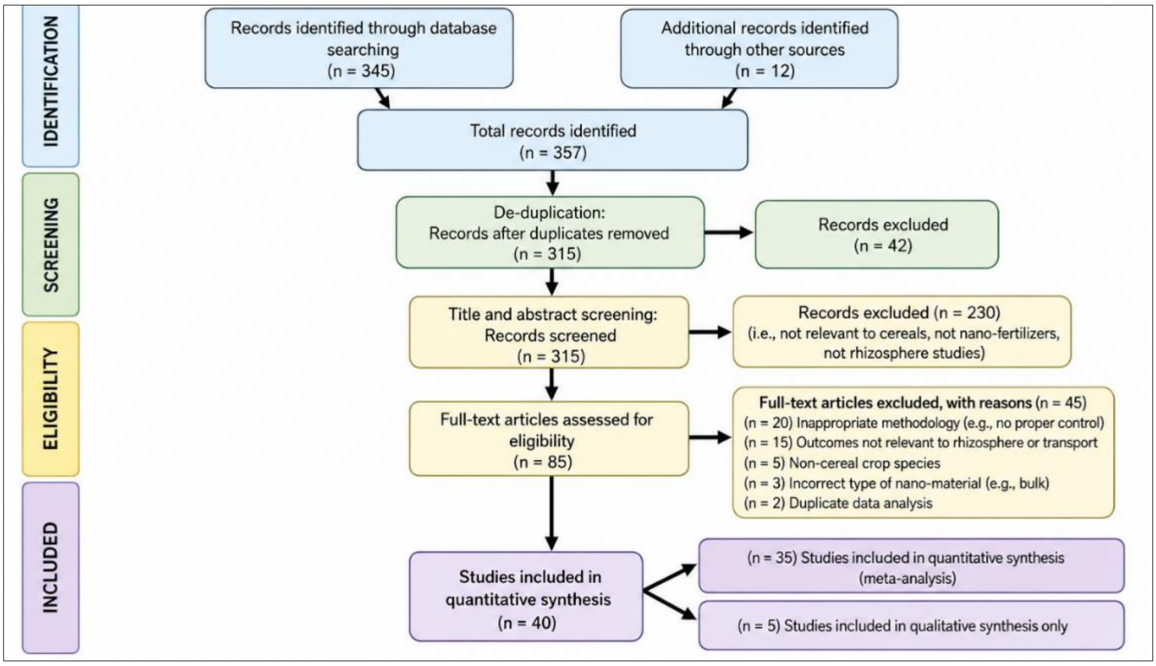

Fig 1: PRISMA Flow Diagram

3. Literature Review and Thematic Analysis

Five distinct themes were identified amongst the retrieved literature: i) Rhizosphere transformation/nutrient flux modulation, ii) root ion transport machinery/nano-mediated regulation of the root ion transport machinery, iii) nutrient use efficiency/agronomic performance of cereal crops, iv) nano:biological interface with the microbiome of the rhizosphere, v) Phytotoxicity related to soil-type, concentration/dose-response, and human/animal safety. An integrated conceptual framework is illustrated in Figure 3.

3.1. Theme 1: Rhizosphere Transformation and Nutrient-Flux Modulation

When metalloid oxide nanoscale fertilizer (i.e., ZnO quantum dots or nanopods) are introduced into soil, they go through several transformations - aggregation, dissolution, sedimentation, and change in speciation (chemical makeup) - that determine their bioavailability (availability to plant roots). (Zhao *et al*., 2019; Cervantes-Avilés *et al*., 2021; Wang *et al*., 2024) [20, 19, 34] For example, ZnO nanoparticles will transform into "inner-sphere" Zn-ion surface complexes before they completely dissolve in a soluble form that increases the bioavailability of Zn in the root zone over time.23 (García-Gómez *et al*., 2015) [22].

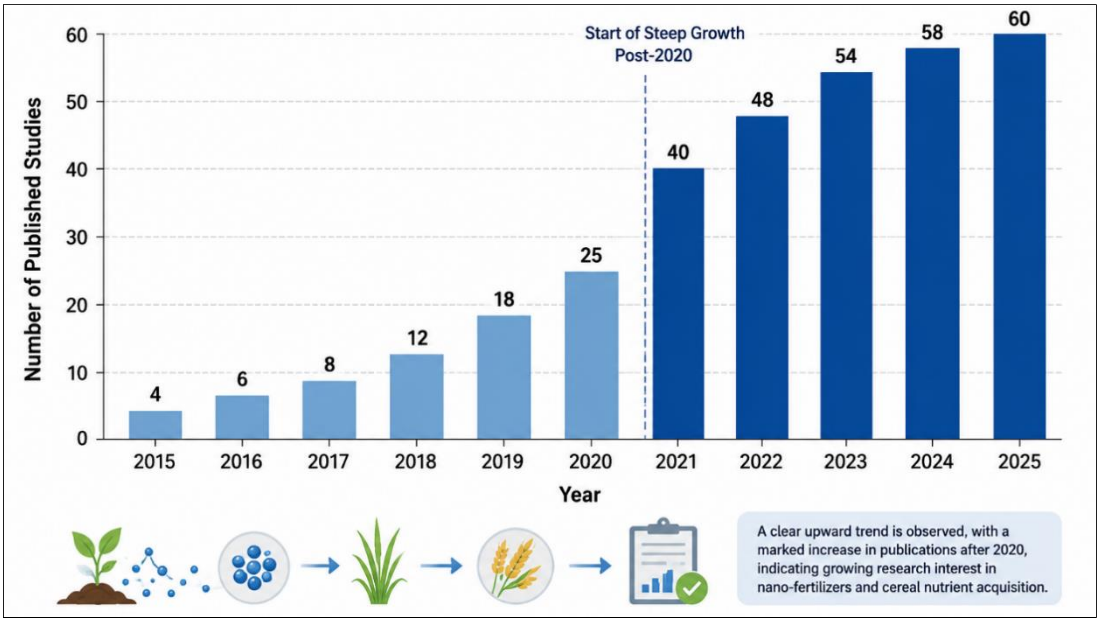

Fig 2: Publication Trend by Year (2015-2025)

Because the amount of a product that is dissolved is based on how much surface is available (specifically the "specific surface area"), nanoscale materials will dissolve more than bulk materials. (Liu *et al*., 2015; Kah *et al*., 2018) [30, 31] This means that metals have a greater dissolution percentage than other materials; thus they are able to provide more plant-available Zn than there is in their original form (ZnO) in alkaline calcareous soils.22 (García-Gómez *et al*., 2015) [22]

The rhizosphere is defined by one of its characteristic processes: exuding low-molecular-weight organic acids (LMWOAs), specifically citric acid, malic acid, oxalic acid, and the LMWOAs that make up a large portion (between 4–70%) of photosynthate-derived organic carbon that roots exude into the soil. (Cervantes-Avilés *et al*., 2021; Sun *et al*., 2024) [19, 26] These LMWOAs have been found to (1) exert first order controls on nanoparticle-hybrid systems by influencing the aggregation, sedimentation and dissolution of copper oxide (CuO) nanoparticles through a concentration-dependent manner, while the remaining 3 LMWOAs facilitate dissolution over a range of concentrations; and (2) exert first order interactions on the bioavailability of copper (Cu), zinc (Zn), and iron (Fe) nano-fertilizers through analogous interactions. (Zhao *et al*., 2019; Sun *et al*., 2024; Cervantes-Avilés *et al*., 2021) [20, 26, 19] Due to these reciprocal feedbacks, root physiology actively governs nutrient flow that it ultimately assimilates. This bidirectional relationship, whereby exudate-driven dissolution enhances ion supply and ion supply influences exudation, is a characteristic component of nano-fertilizers compared to bulk fertilizers and is a mechanism for enhancing rhizosphere efficiency. (Kah *et al*., 2018; Raliya *et al*., 2017; Wang *et al*., 2024) [31, 5, 34]

3.2. Theme 2: Root Ion Transport Machinery and Nano-Mediated Regulation

The agronomic advantage from increased rhizosphere ion movement can only occur if the root transport system has the capacity for obtaining N or if it is stimulated up to a level of capacity to acquire N. (Wang *et al*., 2021; Coskun *et al*., 2020; FAO, 2023) [12, 14, 35] There are two different ways that plant roots can take up nitrate from the soil - via low-affinity (NRT1/NPFs) or high-affinity (NRT2s) nitrate transporters. (Wang *et al*., 2021; Drechsler *et al*., 2015; Meng *et al*., 2016) [12, 16, 17] Low affinity nitrate uptake while rooted in soil occurs through dual-affinity transceptor NPF6.3/NRT1.1 senses the availability of nitrate and triggers the initiation of the Primary Nitrate Respond which remodels root structure and root assimilatory gene expression. (Drechsler *et al*., 2015; Meng *et al*., 2016; Fang *et al*., 2019) [16, 17, 13] Both the high-affinity nitrate transporters (NRT2.1-NRT2.5) and NAR2/NRT3 accessory protein (NRT2.1-NAR2 = approx. 75% of high-affinity N uptake) operate together under the nutrient-reduced condition of soils and dominate during N uptake under low-nitrate conditions. (Wang *et al*., 2021; Wu *et al*., 2020; Coskun *et al*., 2020) [12, 18, 14] Ammonium is absorbed by AMT-type transport proteins and phosphate by high-affinity PHT1-type transport proteins, both of which are up regulated during phosphorus deprivation. (Wang *et al*., 2021; Coskun *et al*., 2020) [12, 14]

Functionally, these transport systems are linked. The CBL1/9–CIPK23 calcium-sensor–kinase module positively affects potassium transporters AKT1 and HAK5, regulates the dual-affinity nitrate transporter NRT1.1, and inhibits AMT-mediated ammonium influx and thus plays a central role in coordinating the acquisition of N and K. (Coskun *et al*., 2020; Wang *et al*., 2021; Wang *et al*., 2021) [14, 12, 15] The NPF7.3/NRT1.5 mediates the coupled loading of K+ and NO3− into the xylem (partly as a K+/H+ antiporter), while NPF7.2/NRT1.8 retrieves nitrate from the xylem, thereby collectively regulating root-to-shoot ion distribution. (Drechsler *et al*., 2015; Wang *et al*., 2021) [16, 15] Nano-fertilizers modify the ionic microenvironment where they are applied—elevating the concentrations of Zn, Fe, NO3− or NH4+ in the rhizosphere and altering rhizosphere pH and redox conditions—and therefore can have a regulatory effect on this network. (Zhao *et al*., 2019; Cervantes-Avilés *et al*., 2021; Sun *et al*., 2024) [20, 19, 26] Nano-induced increases in root K+ influx and enzyme activation, as well as biomass, are consistent with the CBL–CIPK–transporter regulatory pathway. (Coskun *et al*., 2020; Wang *et al*., 2021) [14, 15] However, limited evidence exists for transcriptional expression in cereals and therefore represents a major gap discussed further in Section 5. (Kah *et al*., 2018; Sharma *et al*., 2025) [31, 10]

3.3. Theme 3: Nutrient-Use Efficiency and Agronomic Performance in Cereals

In scientific literature relating to cereal crops, nano-fertilizers reliably increase nutrient use efficiency (NUE) more than the 30%–50% gain associated with traditional fertilizers, by 50% or more, through the combined impact of controlled-release kinetics of nutrients, reduced mechanism pathways for loss of nutrients from the field, and greater availability of nutrients for plant uptake through the rhizosphere. (Raliya *et al*., 2017; Kumari *et al*., 2025) [5, 9] Recent studies of wheat, maize, and rice using nano-urea, hydroxyapatite (HAP)-modified urea nanoparticles (NPs), nano-NPK, nano-Fe, and nano-Zeolite composites, demonstrated an increase in biological yield of 20%–55%, 20%–40%, and 13%–25% respectively. (Sharma *et al*., 2025) [10] In addition, foliar applications of these fertilizers increase yields of all cereal crops from 10% to 25% when compared to crops treated with traditional fertilizers in a diverse range of agro-climatic conditions. (Zulfiqar *et al*., 2021; Delfani *et al*., 2014) [4, 11] In fields with saline conditions—frequently observed concurrently with nutrient limitation in maize systems—both nano-Zn and nano-Si were shown to increase NUE by 105%–110% and yield of grain by 66%–106% as compared to controls. (Ahmed *et al*., 2025) [8] Furthermore, both nano-Zn and nano-Si reduced sodium accumulation and improved nutrient uptake efficiency. The first or second principal component analysis (PCA) showed strong associations between crops treated with nano-Zn/Si and harvest index, shoot Si concentration. (Ahmed *et al*., 2025) [8] An ongoing significant finding present in many studies shows that the gains in crop productivity are decoupled from the intensity of crop inputs applied: nano-technology based products provide equivalent or superior crop yield and substantially lower nutrient applications (e.g., a 28.6% increase in rice yields with a 44% reduction in nitrogen applications through the use of nano-urea). (Kumar *et al*., 2026) [2] The yield of the crop is not the primary sustainability argument for using nanotechnology based fertilizers in resource poor cereal systems, but rather the input efficiency dividend associated with a nano-fertilizer relative to that of an equivalent conventional fertilizer at a given yield. (Kah *et al*., 2018; Dimkpa & Bindraban, 2018) [31, 28] This yield difference varies dramatically depending on many factors, such as formulation and dose, crop, and soil type. (Zulfiqar *et al*., 2021; Raliya *et al*., 2017) [4, 5]

3.4. Theme 4: Nano-Bio Interfaces with the Rhizosphere Microbiome

Nano-fertilizers can also have an indirect influence on nutrient flux in the soil by altering the rhizosphere microbiome of plants; specifically through enrichment of plant growth-promoting rhizobacteria (PGPR) and other beneficial microorganisms, facilitated through the secretion of enzymes and organic acids, mobilizing N, P, and micronutrients and enhancing mineral bioavailability. (Kumar *et al*., 2026; Sun *et al*., 2024; Dimkpa & Bindraban, 2018) [2, 26, 28] The use of ZnO quantum dots has demonstrated the ability to enhance the presence of these beneficial microorganisms endophytically and in the rhizosphere, increasing nutrient uptake and growth of plants. (Sun *et al*., 2024) [26] Similarly, biopolymeric nanocarriers such as chitosan and starch have been shown to co-deliver nutrients and stimulate microbial activity. (Raliya *et al*., 2017; Timofeeva *et al*., 2024; Chhipa, 2017) [5, 25, 32] However, the relationship between nano-fertilizer application and soil biota and the activity of soil enzymes is influenced by both nutrient concentration and application rate; therefore, not all applications result in beneficial effects to the soil biota. (García-Gómez *et al*., 2021; Timofeeva *et al*., 2024; Rajput *et al*., 2018) [24, 25, 23] At low ZnO NP concentrations, the addition of ZnO NP positively influenced soil microbiota activity and soil enzyme activity. At higher application rates, ZnO NPs caused disruptions in carbon and nitrogen cycling and altered microbial community composition, demonstrating the narrow therapeutic window that dictates appropriate application, both safely as well as effectively. (García-Gómez *et al*., 2021; Timofeeva *et al*., 2024) [24, 25]

3.5. Theme 5: Soil-Type Dependence, Dose-Response, and Safety

Edaphic properties such as pH, cation-exchange capacity (CEC), organic-matter content, texture, and redox status determine the efficacy of nano-fertilizers by influencing transformation and dissolution of nanoparticles. (Cervantes-Avilés *et al*., 2021; García-Gómez *et al*., 2015; Wang *et al*., 2024) [19, 22, 34] Nano-ZnO has been shown to improve Zn dissolution and bioavailability as compared with traditional sources in alkaline calcareous soils, while other types of matrices have been found to decrease dissolution due to either aggregation or re-precipitation (e.g., formation of zinc-phosphate crystals). (García-Gómez *et al*., 2015; Zhao *et al*., 2019) [22, 20] The relationship between dose and response is often nonlinear; low concentrations of nano-fertilizers induce growth and stimulate nutrient uptake, whereas high concentrations can induce oxidative stress and result in phytotoxicity. (Raliya *et al*., 2017; Rajput *et al*., 2018; Kah *et al*., 2018) [5, 23, 31] Toxicity of metal oxides varies between species and speciation; for example, CuO and FeO are generally more toxic than their ionic forms. (Sun *et al*., 2024; Rajput *et al*., 2018) [26, 23] Collectively, these studies caution against extrapolation of the performance of nano-fertilizers across soil types without specific validation; additionally that ecotoxicological safety is prerequisite to large-scale application of nano-fertilizers. (Kah *et al*., 2018; Dimkpa & Bindraban, 2018) [31, 28] To illustrate the trends from the reviewed literature, Figure 4 provides a graphic representation.

4. Comparative Analysis of Previous Studies

Table 3 summarises representative studies retained in this review; Table 4 provides a comparative synthesis of strengths and limitations across the mechanistic domains addressed.

Tables 3 and 4 show that the core diagnosis of the review is that a strong understanding of mechanism exists in each of the three domains of inquiry— nanomaterial dissolution chemistry, transporter regulation and agronomic NUE— but seldom do the various research domains overlap. Studies measuring transporter gene expression almost never quantify nanoparticle transformation at the rhizosphere, and agronomic yield trials rarely identify the molecular mechanism that underlies the yield increase that they report. This lack of integration between disciplines increases the structural limitations of today's evidence base.

5. Research Gaps and Emerging Trends

5.1. Unresolved Issues and Knowledge Gaps

First, there is little to no direct mechanistic coupling between the transformation of nanoparticles within the rhizosphere and the modulation of ion flux at the transporter level in cereal plants, with the majority of evidence relating to transporter physiology originating from Arabidopsis instead of wheat, maize or rice subjected to realistic levels of exposure to nano-fertiliser. (Wang *et al*., 2021; Coskun *et al*., 2020; Kah *et al*., 2018) [12, 14, 31] Second, when examining the dose-response relationship between different formulations of nano-fertilisers on cereal plants, it is important to note that these relationships are typically non-linear and dependent on the formulation that is being tested. (Raliya *et al*., 2017; Rajput *et al*., 2018; Zulfiqar *et al*., 2021) [5, 23, 4] Thirdly, the effectiveness of nano-fertilisers is highly dependent upon the soil type in which they are applied; however, not many studies have conducted a systematic investigation where edaphic properties have been varied (including pH, cation exchange capacity (CEC) and soil texture) under a common experimental design. (Cervantes-Avilés *et al*., 2021; García-Gómez *et al*., 2015; Wang *et al*., 2024) [19, 22, 34] Fourth, there is a need for further long-term studies to investigate how nano-fertilisers impact microbial communities and the cycling of carbon/nitrogen within the rhizosphere, as opposed to short-term studies focused on crop yield. (García-Gómez *et al*., 2021; Timofeeva *et al*., 2024; Sun *et al*., 2024) [24, 25, 26] Finally, field-scale validation of nano-fertilisers over multiple seasons still lags significantly in comparison to mechanistic studies conducted under controlled environmental conditions. (Kah *et al*., 2018; Dimkpa & Bindraban, 2018; FAO, 2023) [31, 28, 35]

5.2. Methodological Limitations in Previous Studies

- A frequent reliance on simplified matrices (such as sand, hydroponics, and exudate solutions) which fail to adequately represent the chemistry of biogeochemical systems in the field.
- Inconsistent characterisation of nanoparticles related to size, surface charge, and coating; thus, impeding comparability across studies.
- Underrating rhizosphere pH, redox, and speciation data, as well as data surrounding uptake outcomes.
- Limited evidence of transporter-resolved (qRT-PCR/transcriptomic) measurements in cereal roots subjected to treatment with nano-fertilisers.
- Limited integration of sequencing of soil-microbiome with physiological endpoints in plant systems.

5.3. Emerging Technologies and Future Developments

Several emerging directions are being researched, such as the use of stimuli-responsive and biopolymer (chitosan/starch) encapsulated nanoparticles for demand-synchronized release of nutrients; using magnetite and coatings for regulating micronutrient chlorine and root uptake pathways; (Sun *et al*., 2023; Raliya *et al*., 2017; Chhipa, 2017) [27, 5, 32] Developing a way to investigate single-cell and spatial transcriptomics to measure cellular response to nano-fertilizers; (Wang *et al*., 2021) [12] Using synchrotron technology to identify and label nutrient conversions (15N, 67Zn) from the nanoparticle to the grain; (Kumar *et al*., 2026; FAO, 2023) [2, 35] and Formulating-nutrition by-machine learning models that match the soil. (Kah *et al*., 2018; Wang *et al*., 2024) [31, 34] A list of identified researchable gaps on table 5 and the emerging trend table 6 are included in this document.

Figure 5 maps the identified gaps against the five thematic clusters, visually confirming that mechanistic integration and field validation are the least developed. Figure 6 outlines the resulting future-research roadmap.

6. Discussion

In general, the synthesized evidence reveals a logical and comprehensively layered mechanistic account of how nano-fertilizers act within cereal plants growing under conditions of nutrient limitation. First, at the level of the rhizosphere, the high specific surface area and highly reactive surface chemistry of nanomaterials results in enhanced, diffusion-limited kinetics of dissolution of previously poorly available ionic forms of nutrients, which can be concentrated to even higher levels in particularly problematic soils and are also dynamically modulated by the production of low-molecular-weight organic acids (LMWOAs) by plant roots. (Cervantes-Avilés *et al*., 2021; Zhao *et al*., 2019; Sun *et al*., 2024) [19, 20, 26] This feedback loop between exudates and nanoparticles makes nano-fertilizers broadly different from bulk formulations and helps to explain, at least in part, why they achieve disproportionate increases in agricultural productivity in contexts where traditional sources of fertilizer are of minimal effectiveness due to low nutrient fertility. (Kah *et al*., 2018; Raliya *et al*., 2017; Liu *et al*., 2015) [31, 5, 30]

Second, at the level of the root membranes, a plausible and mechanistically-based link can be drawn from existing data on transporter physiology to explain the observed link between increased nutrient flux in the rhizosphere and improved nutrient status of the plant. (Wang *et al*., 2021; Coskun *et al*., 2020; Drechsler *et al*., 2015) [12, 14, 16] Specifically, the interdependence of nitrate, ammonium, and potassium uptake via the CBL1/9–CIPK23 module and the synergistic yet different transport of K^+/NO_3^- by NPF7.3/NRT1.5 and NPF7.2/NRT1.8 indicates that a nano-fertilizer that changes the local concentration of NO_3^-, NH_4^+, K^+, Zn^{2+}, or Fe will create a ripple effect on other nutrients across a system of coordinated regulatory networks rather than simply by one isolated class of transporters. (Coskun *et al*., 2020; Wang *et al*., 2021; Drechsler *et al*., 2015) [14, 12, 16] This model aligns well with the reported improvements in K^+ influx, nutrient-related enzyme activity and increase in cell biomass resulting from the use of nanomaterials. (Coskun *et al*., 2020; Raliya *et al*., 2017) [14, 5] However, the inferential nature of the bridge connecting the transporter evidence with the effects reported in the literature creates significant limitations. The majority of the transporter evidence has come from studies using Arabidopsis as the model organism. (Wang *et al*., 2021; Coskun *et al*., 2020) [12, 14] Another significant limitation has been the very few reports of direct measurement of transporter transcript levels in the roots of cereals grown under defined conditions of nano-fertilizer application and nutrient limitation. (Kah *et al*., 2018; Sharma *et al*., 2025) [31, 10] Thus, the scientific community is currently relying on converging (but not co-located) lines of evidence. In addition, at least three different non-independently conducted agronomic studies using wheat, maize, and rice as representative crops have confirmed similar gains in NUE and yields achieved with nano-fertilizers despite utilization of varying formulations. (Sharma *et al*., 2025; Kumari *et al*., 2025; Kumar *et al*., 2026) [10, 9, 2] Importantly, the re-occurring disconnection between yield and input intensity (i.e. large savings in N observed with the use of nano-urea) provides the most compelling rationale for the sustainable use of nano-fertilizers. (Kumar *et al*., 2026; Raliya *et al*., 2017) [2, 5] The most notable area of conflicting evidence is with respect to non-linear dose-response relationships and the influence of soil type on the degree of stimulation or inhibition resulting from application of nano-fertilizers (i.e. a product may stimulate at low rates of application and inhibit at high rates when applied to the same soil type). (Rajput *et al*., 2018; García-Gómez *et al*., 2015; Cervantes-Avilés *et al*., 2021) [23, 22, 19] Because of the context-sensitivity of these results it is strongly recommended that no generalized dose-response recommendations be established and that the deployment of nano-fertilizers is conducted on a site-specific, soil-matched basis. (Kah *et al*., 2018; FAO, 2023) [31, 35]

For researchers, the priority should be on experiment designs that allow for the co-located evaluation of rhizosphere-chemical, transport-physiological and agronomic measurements made in cereal systems and under typical field soil conditions. (Wang *et al*., 2024; Sun *et al*., 2024; Kah *et al*., 2018) [34, 26, 31] For practitioners and policy-makers, the implications are twofold: the effectiveness of inputs and reductions in emissions demonstrate that it is worth continuing to invest in and develop regulations that promote the use of these technologies, and the fact that we do not fully understand how to resolve dose response relationships for long-term ecotoxicological impacts suggests a need for a precautionary and validation-gated approach for scaling up. (FAO, 2023; Dimkpa & Bindraban, 2018; Rajput *et al*., 2018) [35, 28, 23] The trend of post 2020 peer-reviewed publishing (Figure 2) suggests that the field is nearing a state where methodological consolidation will occur, therefore, developing uniform, transporter-resolved and multi-environment protocols will be both timely and necessary. (Kumar *et al*., 2026; Sharma *et al*., 2025; Kah *et al*., 2018) [2, 10, 31]

7. Conclusion

The results of this review collate 10 years of evidence regarding the mechanism by which nano-fertilizers influence (1) nutrient flux in the rhizosphere and (2) dynamics of root ion transport in cereals grown in soils that are limited in nutrients. The main conclusion is that nano-fertilizers work through a series of mechanistic links: the dissolution of nanoparticles enhanced due to increased surface area results in the mobilization of LMWOAs in the rhizosphere, and the modulation of a coordinated root transporter network (NRT1/NPF, NRT2, AMT, PHT1, HAK/AKT) via the CBL–CIPK23 signalling module in concert leads to an increase of greater than 50 percent in nutrient-use efficiency and an increase in cereal yield of between 13-55 percent with lower input rates. The overall significance of this work is to bring together previously separated literature regarding soil chemistry, plant physiology, and agronomy into one mechanistic framework that is of direct relevance to the sustainable production of cereals on poor soils.

Researchers should use co-located, transporter-resolved experiments with realistic field soils and need to consider both systematic variation in edaphic properties and dose, as well as use isotopic flux tracing techniques from the nanoscale to grain size in their investigations of nano-fertilizer interactions in cereal systems. Practitioners and policymakers should plan for careful, soil-matched deployment of nano-fertilizers that takes advantage of demonstrated input efficiency and emissions reduction associated with nano-fertilizers. However, the effectiveness of nano-fertilizers cannot be predicted without long-term ecotoxicological data on the dose-response relationship. Future research should emphasize a mechanistic integration of nano-fertilizers across multiple experimental scales, use of standardized protocols, development of stimuli-responsive and coating-tuned formulations, and conducting field trials across multiple growing seasons. Ultimately, the potential for nano-fertilizers to increase nutrient acquisition by cereals grown in nutrient-limited soils will depend on the successful integration of sound science and verification of the performance of nano-fertilizers under field conditions.

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