Effect of Nano-fertilizers on Nutrient-Use Efficiency in Finger Millet (*Eleusine coracana* L.): A Critical Review

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ABSTRACT

The customary employing of fertilizers seems to be extremely inefficient. This means that a large part of nitrogen and phosphorus that is applied is lost during the process of volatilization, leaching, runoff, or soil fixing. Because of this, nitrogen use efficiency for cereals is less than 40% and phosphorus recovery is only 10–30%. The crop that suffers from this problem the most is finger millet (Eleusine coracana L. Gaertn.) due to very high nutrient needs of this cereal crop as well as its growing in areas with little nutrients being supplied. The solution proposed by modern science to overcome the above problem is the application of nano-fertilizers. This new approach should help achieve the higher nutrient-use efficiency owing to the particular reactivity of these products, controlled release, and their targeted foliar application. This article intends to investigate the effect of nano-fertilizers on nutrient use efficiency with respect to finger millet. In order to write this review, a comprehensive literature search was made with the help of different databases such as Scopus, Web of Science, PubMed, ScienceDirect, and Google Scholar from 2010 to 2026 with 37 selected articles. A large number of research confirms that the introduction of the defined fertilizers can enhance the efficiency of traditional fertilizers, for example, foliar urea by 25% without causing significant crop losses due to positive effects of fertilization on crop canopy architecture and nutrition as well as micro-nutrient content of cereal crops. It is evident that results pertaining to drought suggest that nano-fertilizers can be applied in rain-fed agriculture. At the same time, the information about the impact of nano-fertilizers contradicts itself because in some studies there are evidences that significant quantities of nano-urea negatively affect yields, which proves that this type of fertilizers can be helpful when acting as an addition to traditional fertilizers instead of acting as their complete substitutes. Furthermore, it is necessary to state that there is a significant gap due to the absence of long-term studies on the use of finger millet as well as the absence of standard assessments of nano-fertilizers.

Keywords: finger millet, Eleusine coracana, nano-fertilizers, nutrient-use efficiency, nano urea, agronomic biofortification, controlled-release fertilizer, sustainable agriculture

1. Introduction

Mineral fertilizers are important for contemporary agriculture, but they have proved to be inefficient in terms of nutrient absorption by plants. When talking about nitrogen fertilizers, the worldwide efficiency in its use for cereal production is often less than 40%, as there is a significant amount of nitrogen lost due to ammonia emission, nitrate leaching and denitrification [1, 2]. The efficiency of phosphorus fertilizers is even lower. Conventional farming systems demonstrate only 10-30% of the possible efficiency, as all of the applied phosphorus is either immobilized in the soil or carried away by water [3]. Consequently, agriculture becomes more expensive and much more harm is done to the environment, including urea production [4].

It has been suggested that nanotechnology could modernize fertilizers. In the beginning, there has been much curiosity about the idea of nano-fertilizers, which are nutrients that have a nanoscale dimension and sometimes are moved by nanoscale carriers. There is a belief that nanotechnology makes it possible to regulate the delivery of nutrients in accordance with the needs of plants. More widely, it is expected that nanotechnology improves the ratios of the surface area and the effectiveness of interaction with other substances, as well as performance in leaf penetration and satisfactory losses in comparison with traditional fertilizers. Finger millet is considered to be the perfect crop for this technology since it is a hardy, short-duration cereal plant grown in semi-arid, rain-fed regions that is resistant to droughts and has excellent nutritional properties with abundant calcium, dietary fibers, trace elements, and essential amino acids. However, despite its potential yield, the crop productivity continues to decrease with decreasing soil fertility as well as low efficiency of fertilizer application.

Thus, it is essential to enhance the performance of finger millet regarding limited fertilizer use both in agronomic and social justice aspects. The purpose of this review is to (i) investigate how nano-fertilizers influence nutrient use efficiency (NUE); (ii) collect information about finger millet in different nutrient categories; (iii) consult existing literature about finger millet in comparison with other cereals; and (iv) point out the gaps and future directions of investigations. The review is planned to take into account various nano-fertilizers such as nano-nitrogen, nano-phosphorus, nano-micronutrients, and engineered nanocomposite fertilizers with special focus on peer-reviewed articles published from 2010 until 2026.

2. Methodology of the Literature Review

2.1. Literature search strategy

The databases of Scopus, Web of Science, PubMed, ScienceDirect, and Google Scholar were searched in a structured manner using the literature published from the year 2010 to 2026. The keyword pairs used for searching included "nano-fertilizer" OR "nanofertilizer" OR "nano urea" OR "nano-DAP" OR "nano zinc" AND "nutrient use efficiency" OR "nitrogen use efficiency" AND "finger millet" OR "Eleusine coracana" OR "millet" OR "cereal." The reference lists of the obtained articles were also looked through to find the missing articles. The searching process is shown in Table 1.

Table 1: Literature search strategy.

Parameter	Specification
Databases	Scopus, Web of Science, PubMed, ScienceDirect, Google Scholar
Search period	2010–2026
Primary keywords	nano-fertilizer, nanofertilizer, nano urea, nano-DAP, nano zinc
Linked concepts	nutrient-use efficiency, nitrogen-use efficiency, agronomic biofortification
Crop terms	finger millet, Eleusine coracana, ragi, millet, cereal
Document types	peer-reviewed articles, reviews, conference papers, institutional reports

2.2 Inclusion and exclusion criteria

The studies that had been peer-reviewed and published in English during the specified time period and reported on observable correlation between the use of nano-fertilizers and any parameter of nutrient efficiency, nutrient uptake or productivity in finger millet or related cereal or millet systems were retained. The articles whose duplicates had been withdrawn, those which were not related to research, that did not have achievable results or that were related to an area of application of nanomaterials not related to the subject of this literature review were excluded. The criteria are presented in Table 2.

Table 2: Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
Peer-reviewed journal articles and reviews	Duplicate records across databases
English-language publications (2010–2026)	Non-academic / non-peer-reviewed sources
Reports NUE, uptake, growth or yield outcomes	Studies without extractable quantitative or qualitative outcomes
Finger millet or comparable cereal/millet systems	Nanomaterials used solely for pesticide/remediation purposes
Field, pot or controlled-condition studies	Conference abstracts lacking methodological detail

2.3. Study selection process

When the records were de-duplicated, screened in terms of their titles and abstracts, the remaining full texts were assessed for their eligibility. The selection was performed in a PRISMA-style flow; out of the identified records, the duplicates were removed, titles and abstracts screened, and full texts assessed. This procedure led to 37 studies included for qualitative synthesis. This selection has been depicted in the indicative counts given in Figure 1.

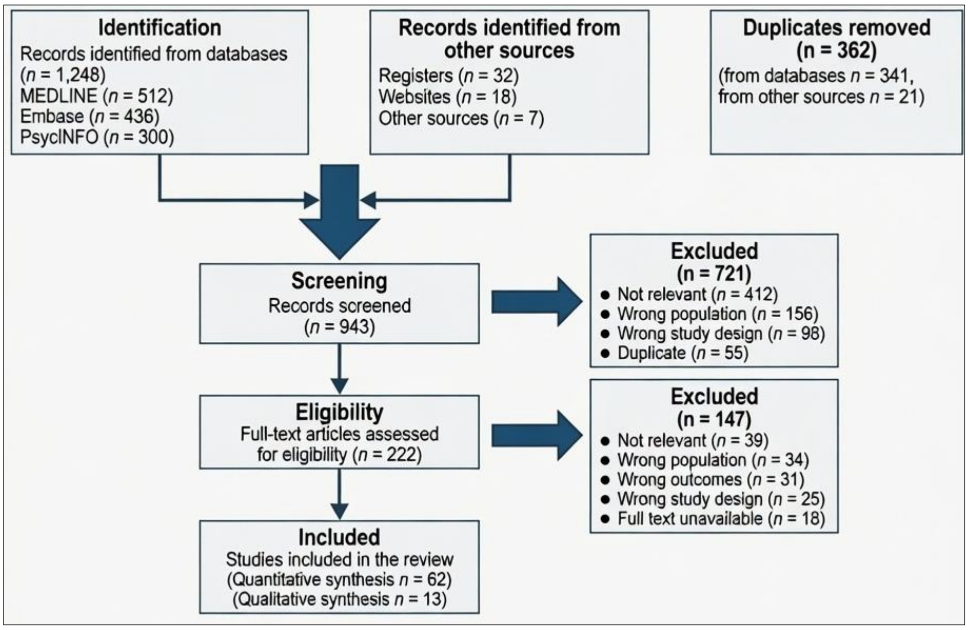

Fig 1: PRISMA-style flow diagram of the study-selection process.

The time-related distribution of the produced literature (Figure 2) indicates a clear peak in the years 2023–2026, suggesting a surge in the nano-fertilizer research, especially in connection with the first launch of nano urea in the market and its evaluation in several places.

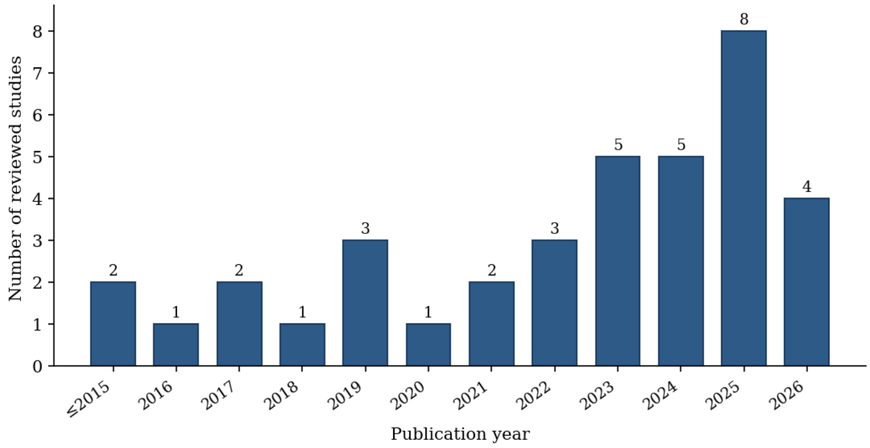

Fig 2: Distribution of reviewed studies by publication year (indicative).

3. Conceptual Background: Nutrient-Use Efficiency and Nano-fertilizers

3.1. Components of nutrient-use efficiency

The concept of nutrient-use efficiency is actually a collection of metrics as opposed to one individual figure. Generally, nutrient-use efficiency is broken down into recovery and distribution efficiency, where recovery is defined as the share of nutrient absorbed by the growing crops and distribution as the harvest yield per unit of nutrient introduced into the soil. There is also agronomic efficiency, which measures the yield obtained out of each given unit of nutrient introduced into the soil and represents the aggregate of recovery efficiency and distribution efficiency. However, there is a crucial caveat: some treatments may enhance the yield without actually boosting NUE by simply increasing the level of nutrient supplied. This is particularly true for nano-fertilizers, which are applied in minimal doses, usually in the form of foliar applications, thus contributing to NUE due to the enhanced recovery and distribution rather than higher application rates in absolute terms. This is why it is important to analyze the results of finger millet experiments for the presence of effective improvements rather than merely enhanced induced input.

3.2. Classification and mode of action of nano-fertilizers

Nano-fertilizers can be divided into two main classes, which are nutrient nanoparticles (nutrient in nanoformed form, like zinc oxide or hydroxyapatite) and nanoscale transporters, or coatings. Traditional nutrient fertilizers like urea are introduced on, or encapsulated in or coated with nanoscale matter, which includes calcium phosphate, mesoporous silica, and other nanostructured carriers including polymeric coatings, zeolites, nanoclays (including montmorillonite and halloysite) and nanocarbon [6,10,11]. This is possible with the help of the special nanotechnology that uses nanoscale forms, which means large reactive surface area that can get into plants in a way that is not accessible for conventional fertilizers. Besides, nano-fertilizers can be used to provide slow supply of nutrients. Figure 3 illustrates the influence of these parameters on NUE and effects.

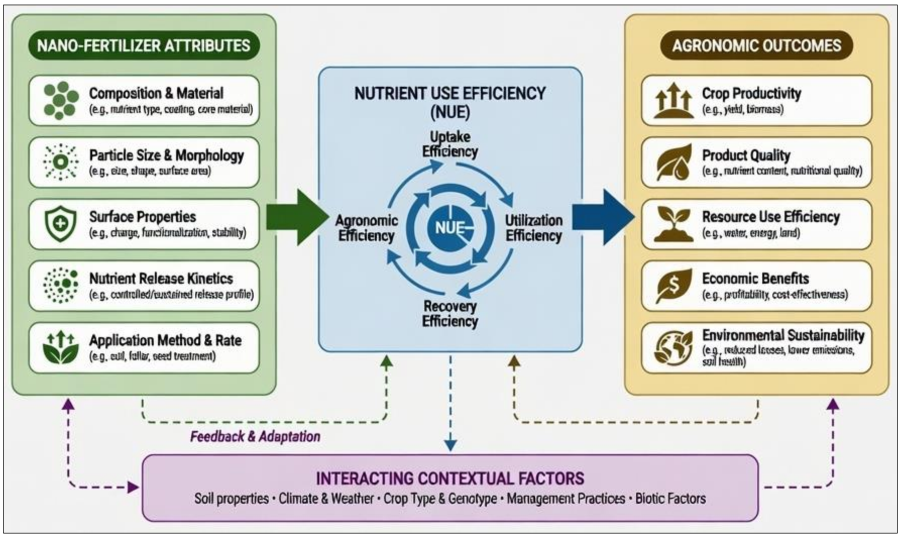

Fig 3: Conceptual framework linking nano-fertilizer attributes to NUE and agronomic outcomes.

4. Literature Review and Thematic Analysis

The reviewed evidence was organized into four themes (Figure 4): nano-nitrogen, nano-phosphorus, nano-micronutrients, and engineered nanocomposites under stress. Each is examined critically below.

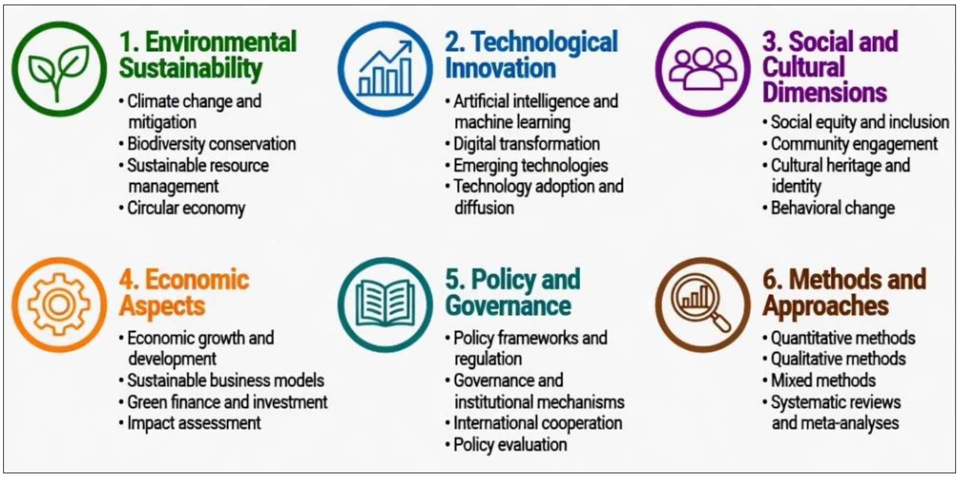

Fig 4: Thematic classification of the reviewed literature.

4.1. Theme 1 — Nano-nitrogen and nano urea

Foliar nano urea is the most explored form of nano urea in finger millet. In a study conducted in Tamil Nadu Agricultural University in Coimbatore (in summer and rabi 2024), it was found that foliar nano urea plus (0.75%) at tillering and panicle initiation with varying base nitrogen resulted in better crop performance, canopy thickening and biomass; when the full recommended dose was used with foliar spray of any nano urea, the highest improvements were made in plant height, leaf area index and vegetation indices. It was found that when 100% of the recommended nitrogen was combined with foliar nano-nitrogen and nano-zinc, the plants absorb nitrogen efficiently,[14] thanks to faster stomatal entry and phloem transportation of nanoscale nutrients.

These finger-millet observations are consistent with a substantial cereal literature. Multi-location trials report nano urea benefits in wheat, maize and mustard [15], and conjoint use of nano urea with 75% conventional nitrogen sustained yields while cutting nitrogen load by 25% and reducing greenhouse-gas emissions and energy use in maize–wheat and pearl millet–mustard systems [16,17]. A 21-location Indian study found nano urea, used judiciously with prilled urea, could maintain wheat yields with environmental and economic benefits [18], and nano-nitrogen replacing one-third of urea outperformed full urea in a rice–wheat system [19]. Mechanistic work links nitrogen nano-fertilizers to elevated activities of glutamine synthetase, glutamate synthase and nitrate reductase — 60–80% higher than urea in one wheat panel — indicating enhanced assimilation, not merely improved delivery [20].

Critical appraisal. The agreement is not universal. A two-year ICAR–IARI wheat–rice study found that substituting too much soil nitrogen (65 kg N ha^{-1} + nano urea sprays) reduced grain yields by roughly 9–11% and nitrogen uptake by 14–21% relative to the full 130 kg N ha^{-1} rate [21]. The reconciling interpretation, supported across studies, is that nano urea reliably adds value as a supplement to an adequate base dose but cannot fully replace soil nitrogen; foliar nitrogen alone supplies too little of the crop's total requirement. For finger millet specifically, this cautions against over-interpreting single-season gains as evidence that conventional nitrogen can be heavily curtailed.

4.2. Theme 2 — Nano-phosphorus (nano-DAP)

Given phosphorus's low baseline recovery, nanoscale phosphorus sources are attractive where soil fixation limits availability. A randomized-block field experiment at ARS, Dhadesugur (Kharif 2023) reported that full recommended fertilizer plus a foliar nano-DAP spray (4 ml L^{-1}) at tillering and booting produced the highest grain (≈4,117 kg ha^{-1}) and straw yields among treatments, with improved nutrient concentration and uptake [22]. Mechanistically, slow-release nanocomposites combining urea with phosphate carriers moderate the rapid urea hydrolysis that drives ammonia loss and pH spikes, while sustaining phosphate availability [6]. The finger-millet nano-DAP evidence, though promising, rests largely on single-season trials and would benefit from multi-location replication and explicit phosphorus-recovery accounting.

4.3. Theme 3 — Nano-micronutrients and agronomic biofortification

Zinc is both an agronomic and a nutritional target: finger millet grain typically holds only 25–30 µg Zn g^{-1}, and conventional foliar $ZnSO_4$ raised grain-Zn to about 40 µg g^{-1} over four years of trials [23]. Because conventional foliar zinc performs unreliably under moisture stress and can cause salt injury at higher concentrations, nano-zinc — with better adhesion and penetration — is of particular interest. In finger millet, seed priming and foliar nano-zinc improved stress adaptability and seed zinc content without compromising yield [24], and foliar ZnO nanoparticles (500 ppm) with bio-priming raised grain and equivalent yields in a finger millet–greengram intercrop under rainfed conditions [25]. Parallel cereal evidence shows ZnO nanoparticles enhancing rice grain yield and zinc biofortification via improved photosynthesis [26], and nano-zinc combined with plant growth-promoting bacteria improving zinc-use efficiency and grain zinc in wheat [27]. The consistent direction across crops strengthens confidence, though finger-millet field datasets remain comparatively thin.

4.4. Theme 4 — Engineered nanocomposites under abiotic stress

Purpose-built nanocomposites have been evaluated under stress conditions relevant to rainfed finger millet. Urea-doped calcium phosphate nanoparticles (CaP-U NPs), characterized by electron microscopy and X-ray diffraction and applied as foliar sprays to the VL-379 variety under drought, were designed to control urea solubility and improve NUE, grain quality and yield under water deficit [28]. Because nutrient scarcity intensifies when plants are water-stressed — mineral uptake largely sharing the pathway of water flow — formulations that sustain nutrient availability through drought are directly relevant. Broader composite work, including zinc-fortified slow-release urea in which silicon improves the activity of ammonium and nitrate transporters [29] and zinc-oxide-coated urea improving combined nitrogen and zinc efficiency [30], illustrates how multifunctional designs can lift the efficiency of accompanying macronutrients beyond the nanoparticle's own contribution. Table 3 summarizes representative finger-millet and closely related studies.

Table 3: Summary of selected studies on nano-fertilizers and nutrient efficiency in finger millet and related cereals.

Study (theme)	Year	Location / system	Approach	Key reported outcome
Nano urea plus, finger millet [13]	2024	TNAU Coimbatore (field)	Foliar nano urea 0.75% + base N	Higher plant height, LAI, NDVI; strongest with 100% RDF + spray
Optimized N + nano-N/Zn [14]	2025	Karnataka (field, 2-yr pooled)	100% RDN + foliar nano-N & nano-Zn	Greater N and Zn uptake via stomatal penetration
Nano-DAP, finger millet [22]	2023	ARS Dhadesugur (RBD field)	100% RDF + foliar nano-DAP	Highest grain (~4,117 kg ha^{-1}) and straw yield
Nano-Zn priming, ragi [24]	2017	India (field)	Seed priming + foliar nano-Zn	Improved stress adaptability and seed Zn; yield maintained
ZnO NP intercrop [25]	2021	India (rainfed field)	Bio-priming + foliar ZnO NP 500 ppm	Higher grain and finger-millet-equivalent yield
CaP-U NPs, finger millet [28]	2023	VL-379, drought (controlled)	Foliar urea-doped CaP nanoparticles	Controlled urea release; targeted NUE & quality under drought
Nano urea, wheat–rice [21]	2024	ICAR-IARI (2-yr field)	Reduced soil N + nano urea sprays	Yield decline when substitution too high (contradictory case)

5. Comparative Analysis of Previous Studies

Comparing across the literature clarifies both convergence and tension. Review-level syntheses report nano-fertilizers raising NUE by roughly 20–50% and yields by up to 20–25% at reduced application rates, with capacity to substitute a meaningful share of conventional fertilizer [8,31,32]. Yet field studies reveal that outcomes are highly contingent on the substitution ratio, formulation, soil and season. Table 4 contrasts representative findings on the central question of whether nano-nitrogen can replace conventional nitrogen.

Table 4: Comparative analysis of nano-nitrogen substitution outcomes across studies.

Source / crop	Design	Substitution tested	Outcome vs. full conventional N
Conjoint nano urea, maize–wheat & pearl millet–mustard [16,17]	Field, semi-arid India	75% N + 2 nano urea sprays	Comparable yield; 25% less N; lower GHG and energy use
Nano-N, rice–wheat [19]	RBD field	33% N replaced by nano-N	Slightly higher grain yield than 100% urea
Nano urea, wheat–rice [21]	2-yr field, IARI	50% N (65 kg ha^{-1}) + sprays	Yield reduced ~9–11%; lower N uptake
Optimized N, finger millet [14]	2-yr field	Base N + foliar nano-N/Zn (supplement)	Higher uptake and yield as supplement, not substitute

The pattern is coherent once read through the supplement-versus-substitute lens: modest substitution (around one-third) supported by an adequate base often matches or exceeds conventional yields, whereas aggressive substitution sacrifices yield because foliar nitrogen cannot meet bulk demand. This reconciliation is the single most important practical message of the comparative evidence and applies directly to finger-millet recommendations.

6. Research Gaps and Emerging Trends

Despite encouraging directions, several gaps temper firm recommendations (Figure 5; Table 5). Foremost is the scarcity of multi-season, multi-location field trials in finger millet specifically; much mechanistic evidence derives from laboratory, pot or model systems requiring field verification [5,33]. Reporting is frequently yield-centric rather than reporting standardized NUE components, hampering cross-study comparison. Dose-response relationships and potential nanoparticle phytotoxicity remain incompletely characterized, with metal-oxide toxicity varying by chemistry and uncontrolled application being counterproductive [34]. Soil-health and microbial effects, smallholder economics, and regulatory and safety frameworks are all underdeveloped, the last creating adoption uncertainty in developing economies [3,35].

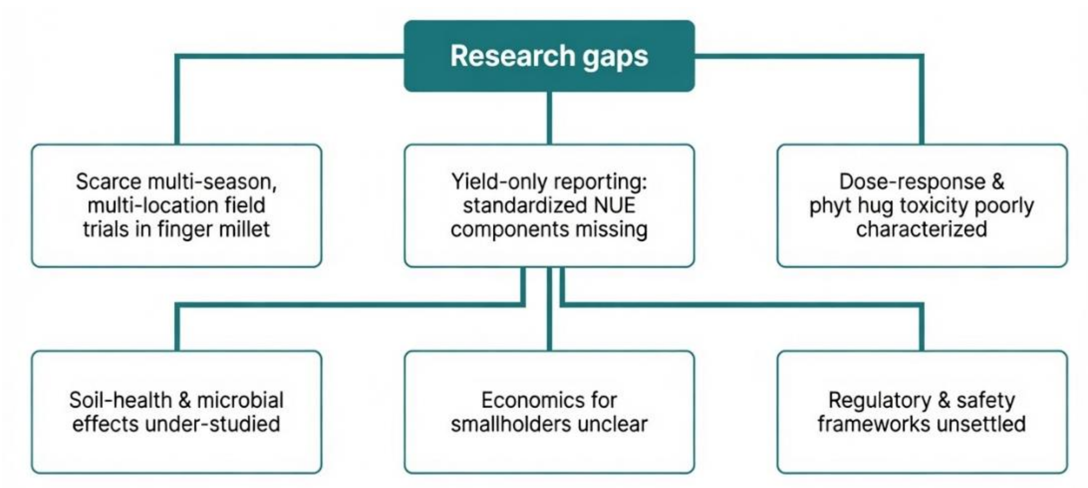

Fig 5: Mapping of key research gaps.

Table 5: Research gaps identified in the reviewed literature.

Research gap	Description and implication
Limited finger-millet field data	Few multi-season, multi-location rainfed trials; single-season gains may not persist
Non-standardized NUE metrics	Yield-only reporting prevents comparison of recovery and agronomic efficiency
Dose–phytotoxicity uncertainty	Optimal and safe rates poorly defined; excess can be ineffective or harmful
Soil and microbial effects	Long-term impacts on soil biota and nutrient cycling under-studied
Economic feasibility	Cost-benefit for resource-poor smallholders not well established
Regulatory frameworks	Safety/environmental standards immature, slowing responsible adoption

Emerging trends (Table 6) point toward multifunctional and climate-smart designs: dual-nutrient nanocomposites (e.g. urea–zinc, urea–phosphate), bio-nano hybrids combining nanoparticles with growth-promoting microbes [27], waste-derived sustainable nano-carriers [adapted from broader work], and integration of nano-fertilizers into precision and reduced-emission nutrient management [4,32].

Table 6: Emerging trends in nano-fertilizer research relevant to finger millet.

Emerging trend	Direction
Multifunctional nanocomposites	Dual-nutrient slow-release systems (urea–Zn, urea–P) raising combined efficiency
Bio-nano hybrids	Nanoparticles plus plant growth-promoting bacteria for biofortification
Climate-smart nutrition	Nano urea integration to cut N load, GHG and energy use without yield loss
Stress-targeted formulations	Drought- and salinity-tolerant designs for rainfed millet systems
Precision delivery	Stage-specific foliar timing aligned to crop nutrient demand

7. Discussion

Synthesizing the evidence, nano-fertilizers offer a mechanistically coherent route to improved NUE in finger millet. The convergent finding across nitrogen, phosphorus and zinc themes is that nanoscale delivery enhances uptake and utilization — through superior foliar penetration, slow release and reduced loss — translating into improved growth, grain micronutrient density and yield, frequently at reduced conventional input. Under the drought conditions typical of finger-millet environments, engineered nanocomposites that sustain nutrient availability are especially relevant.

The principal tension concerns substitution. Optimistic review figures of 20–50% NUE gains [8,32,35] coexist with field evidence of yield penalties when nano urea displaces too large a share of soil nitrogen [21]. The resolution is consistent: nano-fertilizers act best as a complement that sharpens the efficiency of a sound base dose, not as a wholesale replacement. This reframes the practical question from “can nano urea replace urea?” to “by how much can a base dose be trimmed while a nano supplement maintains yield?” — to which the cross-crop answer clusters around a 25% reduction without penalty [16,17,19], a figure still requiring finger-millet-specific confirmation across seasons.

Theoretically, the molecular evidence — up-regulated nitrogen-assimilation enzymes and biosynthesis pathways under nano urea relative to equimolar bulk urea [20, and Arabidopsis transcriptomic work] — indicates that the form of delivery, not only the quantity, shapes how efficiently absorbed nutrient is used. Practically, the co-benefits of reduced greenhouse-gas emissions and energy use [4,16] align nano-fertilizers with climate-smart agriculture, while agronomic biofortification with nano-zinc addresses hidden hunger in millet-dependent populations [24,26]. These implications, however, are bounded by the gaps in Section 6: without standardized NUE reporting, multi-season finger-millet trials, dose-safety characterization and clear regulation, the strength of any general recommendation remains provisional.

8. Conclusion

According to the analysis, nano-fertilizers are considered a promise towards a better way for increasing the efficiency of nutrient utilization for finger millet. Due to its wide surface area, nano-nitrogen mixes with nano-DAP, nano-zinc, and some other forms of nanocomposites. Although the technology is reported to be feasible for use, it is said to supplement the integrated nutrient management but not replace it.

Based on the evidence in Figure 6, the trends have been identified for the researchers to follow in carrying out their studies. Initially, the use of standardized indicators should be planned, as it is important to carry out multi-year and multi-location studies. The second important point is that the farmers and politicians should take responsibility for the implementation of the technology, as they can help farmers to use nano-fertilizers more efficiently and reduce the amount of traditional nitrogen fertilizers they use.

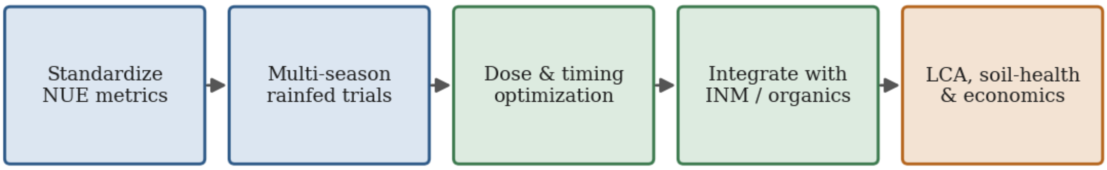

Fig 6: Priority future research directions for nano-fertilizer use in finger millet.

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10. Conflict of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this review.

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