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Nano Fertilizers as a Potential Substitute for Conventional Fertilizers in Modern Agriculture: Evidence, Opportunities, Challenges and Future Perspectives

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ABSTRACT

Modern intensive agriculture relies heavily on synthetic fertilizers, yet nutrient-use efficiency (NUE) is low, typically 30–35% for nitrogen, 18–20% for phosphorus and 35–40% for potassium. The unrecovered fraction is lost through volatilization, leaching, runoff and soil fixation, and contributes to groundwater contamination, eutrophication and greenhouse gas emissions. Nano fertilizers, defined as nutrient formulations with at least one dimension in the 1–100 nm range, have been proposed as a way to improve nutrient delivery. This review synthesizes laboratory and field evidence on uptake mechanisms, agronomic performance, substitution potential, and environmental and economic implications. It distinguishes engineered nanoparticle fertilizers from commercial liquid nano-urea and nano-DAP formulations, and it draws on field studies in rice, wheat, teosinte, forage sorghum and cotton, with supporting reports in maize and pearl millet. The evidence supports partial, not complete, substitution, and only under specific conditions. In rice, 50% of the soil-test N and P dose combined with nano-DAP seedling root dipping and two foliar sprays gave grain yields statistically at par with the full dose (4.08 and 4.02 versus 4.12 and 4.05 Mg ha^{-1} in two seasons) and the highest benefit–cost ratio (2.26). In contrast, in a two-year rice–wheat trial, 50% of the recommended nitrogen dose (RDN) plus two foliar sprays of liquid nano-urea reduced grain yield by 13% in rice and 17.2% in wheat relative to 100% RDN, together with lower SPAD values, tiller density, dry matter and grain protein (−35% in rice, −24% in wheat). These contrasting outcomes are consistent with differences in delivery mode and in the absolute nutrient mass supplied, but they come from different crops, products and sites, so the comparison is indicative rather than definitive. Long-term field evidence on nanoparticle accumulation, soil microbial effects and aquatic toxicity remains limited. Priorities include multi-location, multi-year trials, clearer uptake mechanisms, crop- and soil-specific dose and timing, long-term ecotoxicity assessment, and harmonized regulation.

Keywords: *Nano fertilizers*, *nutrient-use efficiency*, *nano-urea*, *nano-DAP*, *partial substitution*, *sustainable agriculture*, *environmental safety*

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1. Introduction

Modern agriculture faces the challenge of securing food and nutritional security for a fast-growing world population (Verma *et al.*, 2022; Zulfiqar *et al.*, 2019). Population pressure, together with shrinking arable land, scarce freshwater and climate change, has led to excessive use of synthetic agrochemicals (Verma *et al.*, 2022; Bhardwaj *et al.*, 2022). Synthetic N, P and K fertilizers have long been used to sustain crop yields in intensive cropping systems (Bhardwaj *et al.*, 2022; Seleiman *et al.*, 2021).

Although conventional fertilizers contribute substantially to food production, their efficiency is low and has stagnated (Zulfiqar *et al.*, 2019; Nongbet *et al.*, 2022). The NUE of conventional fertilizers typically does not exceed 30–35% for N, 18–20% for P and 35–40% for K (Zulfiqar *et al.*, 2019; Seleiman *et al.*, 2021). Prilled urea is highly water soluble and mineralizes rapidly, and 50–70% of the applied N may be lost through leaching, volatilization and denitrification (Bhardwaj *et al.*, 2022; Zulfiqar *et al.*, 2019). Phosphatic fertilizers are even less efficient because a large share of the applied P is immobilized in the soil (Bhardwaj *et al.*, 2022; Zulfiqar *et al.*, 2019).

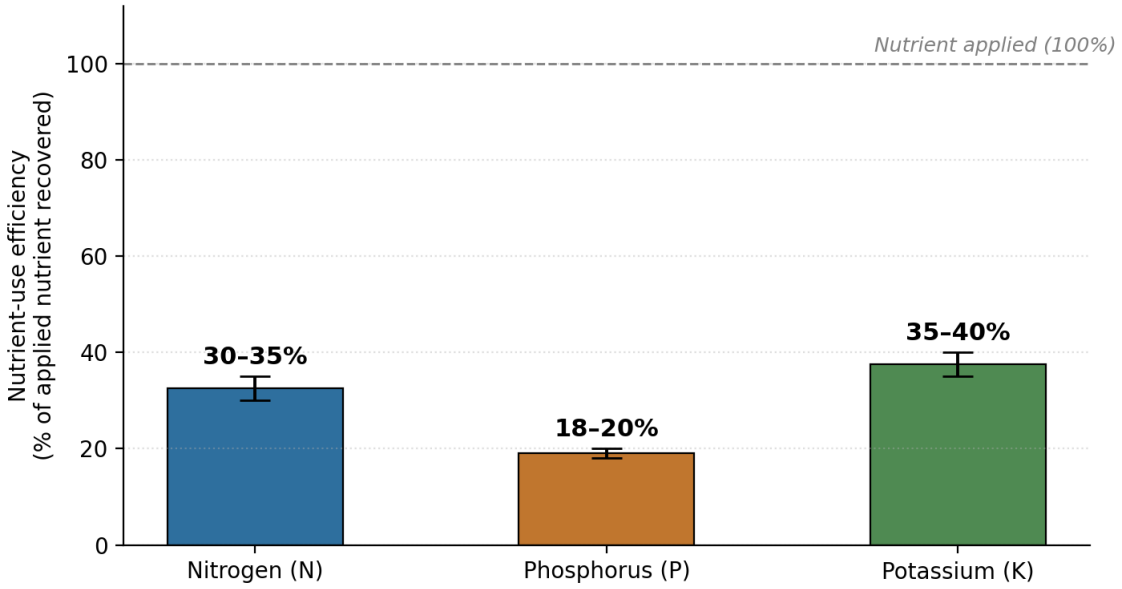


Figure 1. Reported nutrient-use efficiency (NUE) of conventional fertilizers for the three primary macronutrients. Bars show the midpoint and whiskers show the lower and upper bounds of the ranges reported in the literature (N, 30–35%; P, 18–20%; K, 35–40%); the dashed line marks 100% of the nutrient applied. The whiskers are literature ranges, not standard deviations. Sources: Seleiman *et al.* (2021) and Yadav *et al.* (2023a). Intensive and imbalanced fertilizer use has contributed to environmental degradation, including eutrophication, groundwater contamination and high greenhouse gas emissions (Bhardwaj *et al.*, 2022; Yadav *et al.*, 2023a). These problems call for more precise nutrient management that sustains productivity while limiting environmental impact (Seleiman *et al.*, 2021; Nongbet *et al.*, 2022; Avila-Quezada *et al.*, 2022). Nanotechnology offers a potential route to engineered nano fertilizers (NFs) that operate at the 1–100 nm scale and exploit high surface area, reactivity and controlled nutrient release (Nongbet *et al.*, 2022; Goyal *et al.*, 2025; Seleiman *et al.*, 2021).

1.1 Research Gap and Objectives

Existing reviews describe the types, synthesis routes and potential benefits of nano fertilizers, mostly treating them as a single group (Zulfiqar *et al.*, 2019; Seleiman *et al.*, 2021; Nongbet *et al.*, 2022; Bhardwaj *et al.*, 2022). Less attention has been given to three issues that matter for practice: (i) the difference between engineered nanoparticle fertilizers and the commercial liquid nano-urea and nano-DAP products now used in the field; (ii) how field outcomes of substitution vary with crop, delivery method, nutrient mass and experimental conditions; and (iii) how apparently conflicting field results can be reconciled. As a result, general statements that nano fertilizers can replace part of the conventional dose are often made without the qualifications that the underlying trials require.

The objectives of this review are therefore: (1) to distinguish engineered nanoparticle fertilizers from commercial liquid nano-urea and nano-DAP in terms of particle size, nutrient concentration and mode of action; (2) to synthesize field evidence on partial and complete substitution of conventional fertilizers, qualified by crop, application method and experimental conditions; (3) to examine why reported outcomes differ, with attention to

delivery method and absolute nutrient mass; and (4) to summarize environmental safety evidence and the gaps that limit confident recommendations.

1.2 Review Methodology

This is a structured narrative review. Literature was searched in [Web of Science, Scopus, ScienceDirect, Google Scholar and the publisher platforms of MDPI, Springer, Frontiers and Wiley — AUTHORS TO CONFIRM] for publications from [2016 to the date of the last search, month/year — AUTHORS TO CONFIRM]. Search terms combined "nano fertilizer/nanofertilizer", "nano-urea", "nano-DAP", "nutrient-use efficiency", "partial substitution", "foliar application", "yield", "soil microbial" and "ecotoxicity" using Boolean operators. Reference lists of retrieved articles were also screened.

Studies were included if they were peer-reviewed articles or reviews that (a) reported nano fertilizer effects on crop growth, yield, NUE, soil properties, economics or environmental safety, and (b) for agronomic evidence, compared nano fertilizer treatments with a conventional fertilizer reference. Field trials were given priority in the substitution analysis; pot and controlled-environment studies were used for mechanisms and were identified as such. Studies were excluded if they had no conventional-fertilizer comparison, did not report treatment doses or application methods, or were not available in full text. Evidence was grouped by crop, nano fertilizer type, delivery method and substitution level. No formal risk-of-bias scoring or meta-analysis was undertaken, and the conclusions should be read as a qualitative synthesis.

2.0 Nano Fertilizers: Concept and Types

2.1 Definition and Scope

A nano fertilizer is a synthetic or modified conventional fertilizer, or a nutrient carrier, produced by nanotechnology methods so that at least one dimension lies in the nanometer range (1–100 nm) (Nongbet *et al.*, 2022; Zulfiqar *et al.*, 2019; Seleiman *et al.*, 2021). The physicochemical properties, high surface reactivity and solubility of nanomaterials distinguish them from their bulk counterparts (Bhardwaj *et al.*, 2022; Nongbet *et al.*, 2022).

2.2 Classification of Nano Fertilizers

Nano fertilizers are commonly classified into three structural types (Nongbet *et al.*, 2022; Yadav *et al.*, 2023a; Goyal *et al.*, 2025):

- **Nanoscale fertilizers (direct nanoparticles):** conventional nutrients reduced to the nanoscale, such as nano-urea and nano-ZnO (Nongbet *et al.*, 2022; Seleiman *et al.*, 2021).
- **Nanoscale additives:** bulk fertilizers containing very low concentrations of nanomaterials that improve the physical properties of the fertilizer (Yadav *et al.*, 2023a; Bhardwaj *et al.*, 2022).
- **Nanoscale coatings and host systems:** nutrients entrapped in or adsorbed onto polymeric, clay, silica or chitosan matrices with controlled-release properties (Nongbet *et al.*, 2022; Bhardwaj *et al.*, 2022; Zulfiqar *et al.*, 2019).

By nutrient content, nano fertilizers are also grouped into macronutrient nano fertilizers, micronutrient nano fertilizers (mostly metal-oxide nanoparticles) and nano-biofertilizers, which combine beneficial microbes with nanoparticle carriers (Nongbet *et al.*, 2022; Seleiman *et al.*, 2021; Irewale *et al.*, 2024).

2.3 Synthesis Methods

Synthesis follows either top-down routes (mechanical size reduction) or bottom-up routes (chemical or biological assembly) (Goyal *et al.*, 2025; Channab *et al.*, 2024; Nongbet *et al.*, 2022). Green or biogenic synthesis using plant extracts or microbes is becoming more popular because it reduces the toxicity of chemical reagents (Irewale *et al.*, 2024; Goyal *et al.*, 2025; Channab *et al.*, 2024).

2.4 Engineered Nanoparticle Fertilizers versus Commercial Liquid Nano-urea and Nano-DAP

The term "nano fertilizer" is applied to two groups of products that differ in particle size, nutrient concentration and mode of action, and that should not be treated as equivalent (Table 1). Engineered nanoparticle fertilizers include direct nanoparticles, nano-additives and coated or host-based systems made in the laboratory or industrially; examples are nano-ZnO, urea milled to below 30 nm (Salama & Badry, 2020) and nutrients loaded on polymer,

clay, silica or chitosan matrices. Commercial liquid nano-urea and nano-DAP, such as the products of the Indian Farmers Fertiliser Cooperative Limited (IFFCO), are ready-to-spray liquid formulations. Nano-urea has been described as a chitosan-derived formulation mixed with urea and processed physically to reach the nanoscale (Sikka *et al.*, 2024).

For commercial nano-urea, particle sizes of 20–80 nm and a nitrogen content of 4% (w/v) have been reported (Singh *et al.*, 2023). Sikka *et al.* (2024) measured an average hydrodynamic size of 56.79 nm by dynamic light scattering, with several peaks that may indicate aggregation. Nano-DAP contains 8% N and 16% P_2O_5 and is applied as a foliar spray or as a seedling root dip (Sahoo *et al.*, 2024; Reddy *et al.*, 2024; Karn *et al.*, 2025). Because these liquids are dilute, the absolute nutrient mass they deliver is small. In the trial of Sikka *et al.* (2024), two foliar sprays of nano-urea at 4 mL L^{-1} supplied about 0.1 kg N ha^{-1} in total, compared with 105 kg N ha^{-1} (rice) and 120 kg N ha^{-1} (wheat) in the 100% soil-applied N treatments. The mode of action of commercial liquids is therefore best understood as supplementary foliar or seedling-stage nutrition and a possible stimulus to N metabolism, rather than as a bulk nutrient supply. In contrast, coated and host-based systems act as soil-applied slow-release nutrient sources that carry a much larger nutrient mass, and have been reported to release nutrients over 40–50 days compared with 4–10 days for conventional fertilizers (Avila-Quezada *et al.*, 2022).

Table 1. Comparison of engineered nanoparticle fertilizers and commercial liquid nano-urea and nano-DAP formulations.

Attribute	Engineered nanoparticle fertilizers	Commercial liquid nano-urea and nano-DAP
Composition and form	Direct nanoparticles (e.g., nano-ZnO, urea milled to nanoscale), nano-additives, and nutrients entrapped in or adsorbed onto polymer, clay, silica or chitosan matrices (Nongbet *et al.*, 2022; Salama & Badry, 2020).	Ready-to-spray liquid formulations of urea (nano-urea) or diammonium phosphate (nano-DAP); nano-urea described as chitosan-derived and mixed with urea (Sikka *et al.*, 2024).
Particle size	By definition 1–100 nm; for example, urea milled to below 30 nm (Salama & Badry, 2020).	20–80 nm reported for nano-urea (Singh *et al.*, 2023); hydrodynamic size of 56.79 nm by dynamic light scattering, with several peaks that may indicate aggregation (Sikka *et al.*, 2024).
Nutrient concentration	Variable. Laboratory suspensions can be dilute (50–200 mg L^{-1} nanoparticle urea; Salama & Badry, 2020); coated or host systems can carry a larger nutrient load.	Nano-urea 4% N (w/v) (Singh *et al.*, 2023); nano-DAP 8% N and 16% P_2O_5 (Sahoo *et al.*, 2024). Two nano-urea sprays at 4 mL L^{-1} supplied about 0.1 kg N ha^{-1} in total, against 105–120 kg N ha^{-1} in the 100% soil N treatments (Sikka *et al.*, 2024).
Mode of action	Foliar or root uptake of particles; slow or stimuli-responsive release from coated and host systems over about 40–50 days, compared with 4–10 days for conventional fertilizers (Avila-Quezada *et al.*, 2022; Nongbet *et al.*, 2022).	Foliar spray (nano-DAP also as seedling root dip) intended to supply nutrient through stomata and cuticle and to stimulate N metabolism; because of the small nutrient mass it acts as a supplement to soil-applied nutrients (Sahoo *et al.*, 2024; Sikka *et al.*, 2024).
Evidence reviewed here	Mostly laboratory and pot studies; few field trials (e.g., teosinte, Salama & Badry, 2020).	Field trials in rice, wheat and other crops with mixed outcomes (Sahoo *et al.*, 2024; Sikka *et al.*, 2024; Kumar *et al.*, 2023).

3.0 Mechanisms of Uptake and Nutrient-Use Efficiency

3.1 Nutrient Uptake and Penetration Pathways

Nano fertilizers interact with plants differently from ionic fertilizers. After foliar application, uptake occurs mainly through the stomata and, for smaller particles, through the cuticle (Nongbet *et al.*, 2022; Bhardwaj *et al.*, 2022; Seleiman *et al.*, 2021). Translocation can follow the apoplastic or symplastic pathway, and particle size and charge play a crucial role (Bhardwaj *et al.*, 2022; Nongbet *et al.*, 2022).

3.2 Controlled and Synchronized Nutrient Release

Conventional fertilizers mineralize rapidly and supply nutrients faster than plants can use them, which leads to losses (Zulfiqar *et al.*, 2019; Bhardwaj *et al.*, 2022). Nano formulations can be polymer-, clay- or silica-coated and release nutrients over a longer period; some contain stimuli-responsive mechanisms triggered by moisture, pH or root exudates (Zulfiqar *et al.*, 2019; Raiesi Ardali *et al.*, 2024; Nongbet *et al.*, 2022). According to Avila-Quezada *et al.* (2022), nutrients can be released from such formulations over 40–50 days, compared with 4–10 days for conventional fertilizers, which may allow nutrient release to be synchronized with plant demand. This applies mainly to coated and host-based systems rather than to commercial liquid sprays.

3.3 Basis of NUE Enhancement

Nanoparticles are less prone to fixation by clay lattices and, under suitable conditions, may bypass some soil loss pathways, which can raise recovery efficiency (Bhardwaj *et al.*, 2022; Singh *et al.*, 2023; Nongbet *et al.*, 2022). Bhardwaj *et al.* (2022) explain this with ion size: the ammonium ion (NH_4^+) has a diameter of about 2.8 Å, close to the inner clay lattice spacing of about 2.89 Å, so ammonium becomes fixed in interlayer spaces and is unavailable to plants and beneficial microbes. Nanoparticles are 10 to 100 times larger than ions and therefore have a lower chance of lattice fixation and of leaching from the soil. However, the absolute mass of nutrient delivered must still meet crop demand for higher recovery efficiency to translate into an agronomic benefit, as observed in rice and wheat by Sikka *et al.* (2024).

4.0 Use of Nano Fertilizers Compared with Conventional Fertilizers

4.1 Crop Growth, SPAD Chlorophyll and Grain Yie

This section summarizes effects on crop growth, SPAD chlorophyll and grain yield. Targeted nano fertilization has been reported to stimulate photosynthesis, enzyme activity and dry-matter accumulation (Nongbet *et al.*, 2022; Goyal *et al.*, 2025; Seleiman *et al.*, 2021). Higher yields have been reported for integrated regimes combining nano fertilizers with a reduced conventional dose in rice, wheat, maize, cotton, pearl millet and forage crops (Sahoo *et al.*, 2024; Singh *et al.*, 2023; Gousia *et al.*, 2024; Ahari *et al.*, 2024; Goyal *et al.*, 2025; Vegda *et al.*, 2024). Improvements in SPAD, plant height and tillering have been observed with foliar nano fertilizer supplements (Sahoo *et al.*, 2024; Reddy *et al.*, 2024; Gousia *et al.*, 2024). These responses are not universal, as Section 5 shows.

4.2 Nutrient Uptake and Biofortification

Nano micronutrients can raise grain micronutrient concentrations and uptake efficiency compared with bulk micronutrients (Nongbet *et al.*, 2022; Seleiman *et al.*, 2021; Verma *et al.*, 2022). A compilation cited by Avila-Quezada *et al.* (2022) reports plant growth increases of about 19% and 18% for macronutrient and micronutrient nano fertilizers, respectively, compared with conventional fertilizers, and about 29% for macronutrient nano fertilizers with nanoscale carriers. These effect sizes should be treated with caution because they rest mostly on controlled-environment and pot trials rather than multi-season field trials (Sikka *et al.*, 2024; Santos *et al.*, 2025).

4.3 Fertilizer-Use Efficiency

In rice and some other crops, combining a reduced soil fertilizer dose with nano foliar spraying or root dipping has been reported to give higher agronomic and recovery efficiency than the full conventional soil dose (Sahoo *et al.*, 2024; Singh *et al.*, 2023). The result depends on the product and delivery method, as discussed in Section 5.

4.4 Environmental Nutrient Losses

Controlled-release nano formulations and foliar application are reported to reduce leaching and gaseous losses compared with a full conventional broadcast rate (Sahoo *et al.*, 2024; Singh *et al.*, 2023; Bhardwaj *et al.*, 2022). Direct measurements of losses under field conditions remain scarce.

5.0 Potential of Nano Fertilizers as Substitutes

5.1 Complete Substitution: Limitations

Field evidence does not support complete replacement of soil-applied macronutrient fertilizers by foliar nano products alone. The evidence base is small, but it is consistent in direction. Sikka *et al.* (2024) ran a two-year rice–

wheat field trial (2020–2021 and 2021–2022) in which two foliar sprays of IFFCO nano-urea (4 mL L^{-1}) were applied with no soil N (treatment T3) or with 50% of the recommended N dose (RDN; T6). In T3, grain N content was far below that of 100% RDN (0.81% versus 1.71% in rice; 1.19% versus 1.75% in wheat). In T6, grain yield fell by 13% in rice and 17.2% in wheat relative to 100% RDN applied to the soil, and SPAD, dry matter accumulation, tiller density, root growth and macronutrient content were also reduced. Grain protein fell by 35% in rice and 24% in wheat. Two foliar sprays of 3% conventional urea, which supplied about 4.3 kg N ha^{-1} compared with about 0.1 kg N ha^{-1} from nano-urea, gave statistically similar yields to the nano-urea treatment when combined with 50% RDN (T7 versus T6), so the nano formulation did not outperform plain urea sprays in this trial.

The nutrient mass carried by dilute liquid formulations is far below crop demand, so once soil-applied N is reduced the sprays cannot make up the difference (Sikka *et al.*, 2024). Kumar *et al.* (2023), in a review, summarize wheat trials in which 100% of the recommended N dose (120 kg N ha^{-1}) was more productive than 50% RDN plus two nano-urea sprays or 75% RDN plus one nano-urea spray. This result is consistent with Sikka *et al.* (2024), although it comes from a review and not from a single controlled experiment. These findings apply to the tested products, crops and sites. They show that foliar nano-urea did not replace soil-applied N in these trials, but they do not exclude benefits from other nano fertilizer types, such as coated slow-release soil-applied systems, which have been tested far less in the field.

5.2 Partial Substitution: Agronomic Evidence

Several studies report that reducing conventional soil fertilizer by 25–50% and adding nano fertilizers by foliar spraying or seedling root dipping can maintain yield. The evidence is conditional on crop, product, application method and experimental conditions, as the following examples show:

- Sahoo *et al.* (2024) reported that, in transplanted rice grown on a sandy loam in a two-season field trial, 50% of the soil-test N and P dose (STD) plus seedling root dipping in nano-DAP (5 mL L^{-1}) plus two foliar sprays of nano-DAP (4 mL L^{-1} at 25 and 45 days after transplanting; T10) gave grain yields statistically at par with 100% STD (T2). Yields were 4.08 and 4.02 Mg ha^{-1} for T10 and 4.12 and 4.05 Mg ha^{-1} for T2 in the two seasons. T10 also gave the highest benefit–cost ratio (2.26, which was 3.5% higher than T2). Soil microbial biomass and enzyme activities were highest in T2 and second highest in T10, so the nano-DAP regime maintained soil biological indicators at a level close to the full dose but did not exceed it.
- Salama and Badry (2020) reported that, in teosinte forage, 50% nanoparticle urea (NPU) applied as a foliar spray plus 50% bulk urea applied to the soil gave fresh yield, plant height and stem diameter similar to 100% bulk urea, with crude protein of 66.10 g kg^{-1}. This study used urea milled to below 30 nm in the laboratory, not a commercial formulation, over two summer seasons, so it cannot be extended directly to commercial nano-urea.
- Singh *et al.* (2023), Reddy *et al.* (2024) and Upadhyay *et al.* (2024) reported that 50–75% of conventional N plus nano-urea foliar sprays maintained or increased yield in the crops they tested, and Singh *et al.* (2023) also reported lower fertilizer use and energy consumption.
- Gousia *et al.* (2024) and Ahari *et al.* (2024) reported positive growth and yield responses in Bt cotton and forage sorghum, respectively, under integrated nano-nitrogen or nano-urea and nano-DAP regimes.

Taken together, partial substitution has been reported to maintain yield in some crop–product–method combinations, but these results are mostly from short-duration, single-site trials and should not be generalized beyond the conditions tested.

5.3 Evidence from Field Studies by Crop

Evidence for partial substitution has been reported from several agro-ecological settings, summarized below by crop group. Doses, methods and comparison treatments are given in Table 2.

- **Transplanted rice:** Reddy *et al.* (2024) and Sahoo *et al.* (2024) reported good agronomic performance and profitability with 50% of the recommended N and P dose combined with nano-urea and nano-DAP applied as foliar sprays or as root dipping plus foliar sprays (Reddy *et al.*, 2024; Sahoo *et al.*, 2024), compared with the full conventional dose. In contrast, Sikka *et al.* (2024) found yield penalties in rice with 50% RDN plus foliar nano-urea alone (−13%).
- **Wheat and other cereals:** Kumar *et al.* (2023) summarize results in which 75% of the recommended N applied basally as prilled urea, with a full dose of P and K and foliar nano-urea plus nano-Zn, gave grain yields comparable to the full dose in wheat, mustard, maize and pearl millet, whereas other wheat trials favoured 100% RDN over 50% RDN plus two sprays or 75% RDN plus one spray. Singh *et al.* (2023) reported maintained yields with reduced N plus nano-urea in cereals. Sikka *et al.* (2024) tested only 0% and 50% RDN with nano-urea and recorded a 17.2% reduction in wheat grain yield at 50% RDN over two seasons. Upadhyay *et al.* (2024) examined integrated nano-N and nano-Zn in a wheat–maize system. Outcomes therefore depend on the substitution rate, site and system, and a positive result at one rate cannot be assumed at another.

- **Forage sorghum and teosinte:** Ahari *et al.* (2024) reported growth and yield benefits of forage sorghum under an integrated nano-urea and nano-DAP scheme. Salama and Badry (2020) reported that 50% NPU plus 50% bulk urea gave plant height, stem diameter, fresh yield and crude protein similar to 100% bulk urea in teosinte.
- **Cotton:** Gousia *et al.* (2024) reported that reducing soil N and adding foliar nano-nitrogen increased plant height, sympodial branches, leaf area index, dry matter and seed cotton yield. The comparison reported is with the control, and the dose details should be checked in the original article (Table 2).

5.4 Summary of Evidence Strength

Several independent field studies report that reducing conventional soil fertilizer by 25–50% and adding foliar nano fertilizer can maintain or improve crop performance: Sahoo *et al.* (2024), Salama and Badry (2020), Singh *et al.* (2023), Reddy *et al.* (2024), Upadhyay *et al.* (2024), Ahari *et al.* (2024) and Gousia *et al.* (2024). The evidence is not consistent, however. Sikka *et al.* (2024) found that 50% RDN plus two foliar sprays of nano-urea reduced grain yield by 13% in rice and 17.2% in wheat compared with 100% RDN (Table 2; Figure 2).

Two features distinguish the successful rice trial of Sahoo *et al.* (2024) from the unsuccessful trial of Sikka *et al.* (2024). First, the successful regime combined seedling root dipping with two foliar sprays, whereas the unsuccessful regime used foliar sprays only, with no root-zone nano delivery. Second, the nutrient mass differed: the nano-urea sprays supplied about 0.1 kg N ha^{-1} in total (Section 2.4). This suggests that delivery method and total nutrient mass, and not only the percentage reduction in soil fertilizer, influence whether partial substitution succeeds. This reading is indicative, not conclusive, because the two studies also differ in nano product (nano-DAP versus nano-urea), nutrient (N and P versus N), crop (rice versus rice and wheat), site and soil-test dose, and no study has compared the delivery methods directly within one experiment. Complete substitution by foliar nano products alone conflicts with Sikka *et al.* (2024) and Kumar *et al.* (2023) and with the small nutrient mass supplied by commercial liquid formulations.

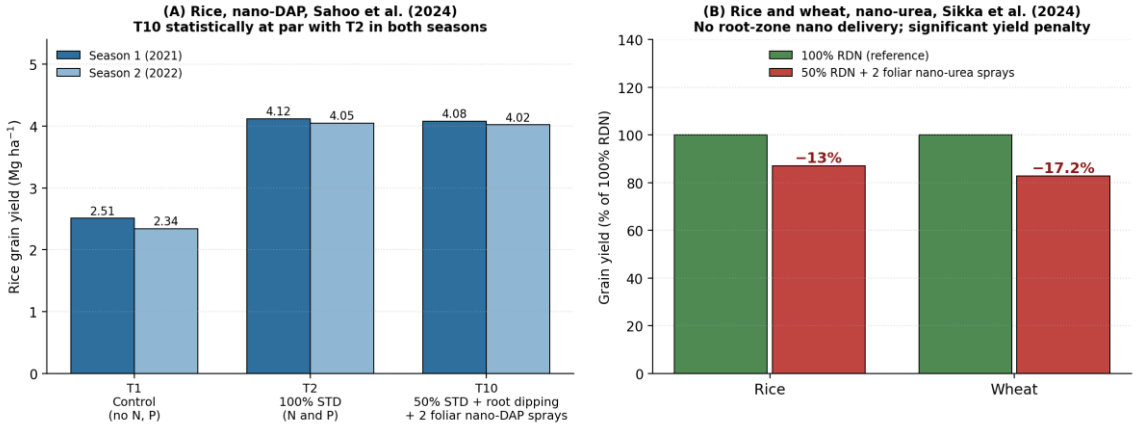


Figure 2. Grain yield responses to partial substitution in two field studies. (A) Rice, Sahoo *et al.* (2024): T1, control without N and P; T2, 100% soil-test dose (STD) of N and P; T10, 50% STD plus seedling root dipping and two foliar sprays of nano-DAP; T10 was statistically at par with T2 in both seasons. (B) Rice and wheat, Sikka *et al.* (2024): grain yield with 50% of the recommended N dose (RDN) plus two foliar sprays of nano-urea, expressed as a percentage of 100% RDN applied to soil (−13% in rice, −17.2% in wheat, both significant). The two studies differ in product, crop, site and dose, so the panels are not a controlled comparison of delivery methods.

6.0 Sustainability, Economics and Environmental Effects

6.1 Soil Health and Soil Microbial Dynamics

Indiscriminate use of conventional fertilizers can acidify soil, raise rhizosphere salinity and damage beneficial microflora (Bhardwaj *et al.*, 2022; Zulfiqar *et al.*, 2019). Integrated nano management has been reported to improve soil microbial biomass carbon, nitrogen and phosphorus and enzyme activities (Sahoo *et al.*, 2024; Bhardwaj *et al.*, 2022). In the rice trial of Sahoo *et al.* (2024), however, these indicators were highest under 100% STD and second highest under the nano-DAP regime, so the benefit relative to the full conventional dose was maintenance, not improvement. Chitosan- and carbon-based nano formulations have shown favourable rhizosphere effects with no short-term toxicity in several studies (Bhardwaj *et al.*, 2022; Nongbet *et al.*, 2022).

6.2 Control of Environmental Pollution

Reduced conventional rates combined with nano foliar application have been reported to lower nitrate leaching and N_2O emission compared with full conventional fertilization (Bhardwaj *et al.*, 2022; Singh *et al.*, 2023; Sahoo *et al.*, 2024). Such claims should be confirmed with direct field measurements of losses.

6.3 Economic Benefits and Logistics

Partial substitution systems have been reported to give higher benefit–cost ratios and lower logistical costs (Sahoo *et al.*, 2024; Singh *et al.*, 2023). In rice, the highest benefit–cost ratio (2.26) was recorded for the nano-DAP root dipping plus foliar regime, which was 3.5% higher than for the full conventional dose (Sahoo *et al.*, 2024). Economic results depend on local product prices and subsidies and have not been established across regions.

6.4 Ecotoxicological Risks and Safety Concerns

Potential risks include aquatic toxicity of some metal-oxide nanoparticles (MONPs) (Santos *et al.*, 2025; Avila-Quezada *et al.*, 2022), trophic transfer, and phytotoxicity at high concentrations (Saurabh *et al.*, 2024; Nongbet *et al.*, 2022). Silver nanoparticles have been reported to affect dehydrogenase activity and suppress bacterial growth at soil concentrations of 0.1–0.5 mg kg^{-1}, and denitrifying bacteria appear especially susceptible, which could disturb the soil nitrogen cycle (Avila-Quezada *et al.*, 2022). Copper and iron nanoparticles and carbon nanotubes have likewise been reported to affect beneficial soil microflora. In aquatic systems, Zn^{2+} accumulation from zinc nanoparticles has been reported in aquatic organisms, and graphene oxide nanoparticles have been found to enter freshwater algal cells and cause oxidative stress and membrane damage (Avila-Quezada *et al.*, 2022). Santos *et al.* (2025) also reported phytotoxic effects of copper oxide nanoparticles, which highlights the need for dose optimization and for evaluation of bioavailability and permissible limits before safe deployment.

Long-term field evidence on these endpoints is limited. First, nanoparticle accumulation: most published data come from laboratory, pot or short-term studies, and reviews note a lack of long-term studies on the accumulation, distribution, persistence and degradation of nanomaterials in soils, and on bioaccumulation in crops and the food chain (Santos *et al.*, 2025; Saurabh *et al.*, 2024). Second, soil microbial effects: reported effects on microbial activity and community composition vary with particle type, size, coating, dose and soil properties, and are mostly from short-duration experiments. The two-season rice trial of Sahoo *et al.* (2024) found microbial biomass and enzyme activity under nano-DAP close to the full conventional dose, but two seasons cannot show cumulative effects. Third, aquatic toxicity: evidence is concentrated on metal-based and carbon-based nanomaterials in laboratory exposures, and data on runoff and leaching of nano fertilizers from fields into water bodies, and on effects on aquatic communities, are scarce (Avila-Quezada *et al.*, 2022; Saurabh *et al.*, 2024). Toxicity results for metal-based nanoparticles should not be extrapolated automatically to commercial nano-urea and nano-DAP, which have a different composition, and the absence of harm in short trials does not establish long-term safety. Multi-year field studies combining nanoparticle residue analysis, microbial community profiling and runoff monitoring are needed.

7.0 Challenges, Research Gaps and Future Prospects

7.1 Technical and Industrial Bottlenecks

Scalable and cost-effective manufacture and long-term formulation stability (no agglomeration or loss of zeta potential) remain constraints (Channab *et al.*, 2024; Santos *et al.*, 2025; Kumar *et al.*, 2023; Goyal *et al.*, 2025).

7.2 Scientific and Agronomic Gaps

Field results are inconsistent across soils, climates and seasons, and multi-location, multi-year trials are still inadequate (Sikka *et al.*, 2024; Kumar *et al.*, 2023; Santos *et al.*, 2025; Saurabh *et al.*, 2024). Mechanisms of molecular uptake and assimilation are not fully understood (Bhardwaj *et al.*, 2022; Nongbet *et al.*, 2022). Few trials compare delivery methods directly within one experiment, and most do not report the absolute nutrient mass supplied by nano products.

7.3 Regulatory Gaps

Few countries have harmonized safety standards and registration frameworks for agricultural nanomaterials (Santos *et al.*, 2025; Avila-Quezada *et al.*, 2022; Saurabh *et al.*, 2024).

7.4 Future Research Directions

Priority areas include green and biogenic synthesis, multi-nutrient nanocomposites, fertilizers integrated with biosensors for precision delivery, and long-term monitoring of ecotoxicological effects (Irewale *et al.*, 2024; Goyal *et al.*, 2025; Raiesi Ardali *et al.*, 2024; Yadav *et al.*, 2023b; Santos *et al.*, 2025; Channab *et al.*, 2024).

8.0 Conclusion and Key Recommendations

Partial-substitution regimes that reduce conventional soil fertilizer by 25–50% and add nano fertilizers by foliar spraying or root dipping have maintained nutrient-use efficiency, reduced losses and improved economic returns in some trials, notably nano-DAP root dipping plus foliar sprays in rice (Sahoo *et al.*, 2024) and partial replacement with nanoparticle urea in teosinte (Salama & Badry, 2020), with supporting reports for other crops (Singh *et al.*, 2023; Reddy *et al.*, 2024; Upadhyay *et al.*, 2024). These benefits depend on crop, product, delivery method and conditions. Complete substitution by foliar nano products alone is not supported by field evidence and has caused yield penalties in the trials examined (Sikka *et al.*, 2024; Kumar *et al.*, 2023). Evidence on long-term environmental safety is still insufficient.

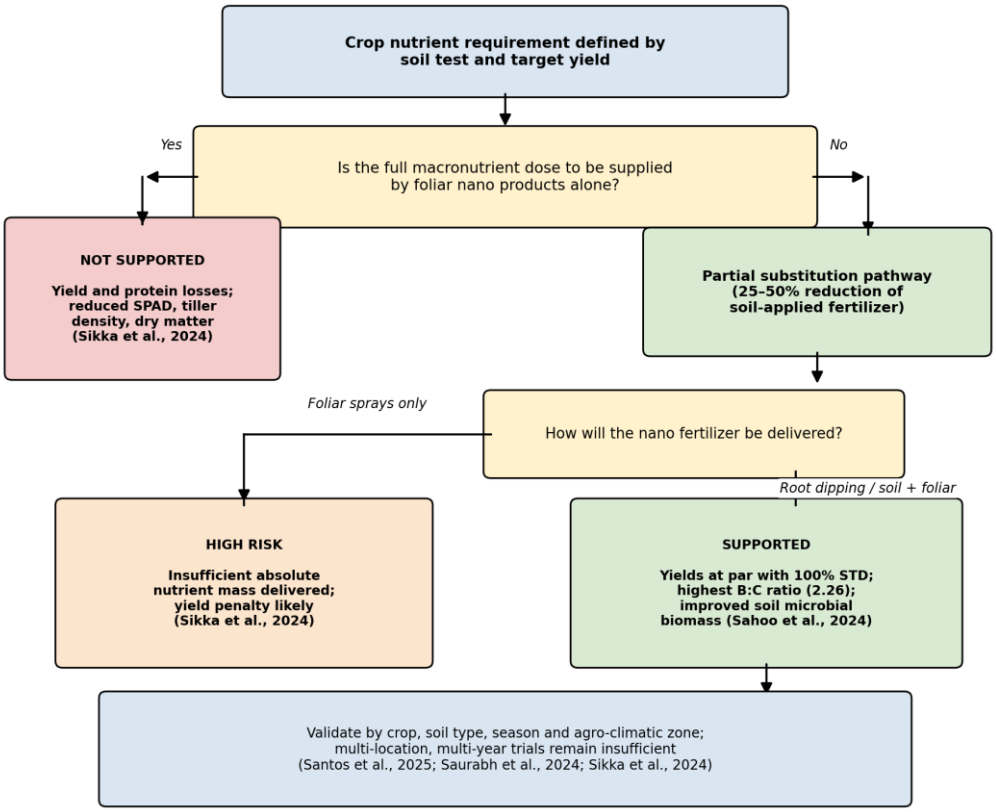


Figure 3. Conceptual decision framework for substituting conventional fertilizers with nano fertilizers, synthesized by the authors from Sahoo *et al.* (2024) and Sikka *et al.* (2024) and supported by Kumar *et al.* (2023), Santos *et al.* (2025) and Saurabh *et al.* (2024). The framework is a reasoning aid, not a validated model; it should be tested by crop, soil and site. "Foliar sprays only" refers to regimes without root-zone nano delivery.

Key Recommendations

-
- Encourage integrated partial-substitution programs that combine root-zone products (soil application or root dipping) with foliar application, and avoid foliar-only complete replacement (Sikka *et al.*, 2024; Kumar *et al.*, 2023; Sahoo *et al.*, 2024; Singh *et al.*, 2023).
- Develop and implement science-based regulatory and safety protocols (Santos *et al.*, 2025; Avila-Quezada *et al.*, 2022; Saurabh *et al.*, 2024).
- Evaluate doses and timing by crop type, soil and climatic conditions before wide adoption (Sahoo *et al.*, 2024; Santos *et al.*, 2025).
- Invest in scalable green synthesis and long-term field monitoring (Irewale *et al.*, 2024; Goyal *et al.*, 2025; Channab *et al.*, 2024).

Table 2. Summary of agronomic field trials on nano fertilizer substitution: nano fertilizer type, treatment doses and application methods, conventional comparison, and findings.

Crop	Nano fertilizer type	Nano treatment: dose and application method	Conventional comparison treatment	Key findings and substitution outcome	Reference
Transplanted rice (2 seasons)	Nano-DAP (8% N, 16% P_2O_5)	T10: 50% soil-test dose (STD) of N and P (STD 100:50:50 kg N:P_2O_5:K_2O ha^{-1}) + seedling root dipping in nano-DAP 5 mL L^{-1} + two foliar sprays of nano-DAP 4 mL L^{-1} at 25 and 45 days after transplanting	T2: 100% STD of N and P, no nano-DAP	Grain yield 4.08 and 4.02 Mg ha^{-1} (T10) versus 4.12 and 4.05 Mg ha^{-1} (T2): statistically at par. Highest benefit–cost ratio in T10 (2.26; 3.5% above T2). Soil microbial biomass and enzymes highest in T2, second highest in T10. Partial substitution maintained yield when root dipping was combined with foliar sprays.	Sahoo *et al.* (2024)
Rice and wheat (2 seasons, rotation)	Liquid nano-urea (IFFCO, 4% N)	T6: 50% RDN to soil (rice 52.5 kg N ha^{-1}; wheat 60 kg N ha^{-1}) + recommended P (wheat 62.5 kg P_2O_5 ha^{-1}) + two foliar sprays of nano-urea 4 mL L^{-1} (about 0.1 kg N ha^{-1} in total); no root-zone nano delivery	T5: 100% RDN (rice 105 kg N ha^{-1}; wheat 120 kg N ha^{-1} + 62.5 kg P_2O_5 ha^{-1}) applied to soil	Grain yield fell 13% (rice) and 17.2% (wheat) versus T5. SPAD, tiller density, dry matter, root growth and macronutrient content decreased; grain protein fell 35% (rice) and 24% (wheat). Yield statistically similar to 50% RDN + two sprays of 3% urea (T7). Partial substitution at 50% RDN not supported for this regime.	Sikka *et al.* (2024)
Forage teosinte (2 seasons, 3 cuts)	Nanoparticle urea (NPU), urea milled to below 30 nm	50% of N as NPU foliar suspension (100 mg L^{-1}) + 50% of N as bulk urea (BU) top-dressed; N applied in three equal doses (2 weeks after sowing and after the first and second cuts)	100% N as BU (280 kg N ha^{-1}, 46% N)	Fresh yield, plant height and stem diameter similar to 100% BU; crude protein 66.10 g kg^{-1}. Supports 50% partial substitution under these conditions; laboratory-made NPU, not a commercial product.	Salama & Badry (2020)
Bt cotton	Nano nitrogen	Reduced soil N + foliar nano nitrogen [AUTHORS TO INSERT soil N reduction, nano dose, number and timing of sprays from the original article]	100% conventional N [AUTHORS TO INSERT dose]	Improved plant height, sympodial branches, leaf area index, dry matter and seed cotton yield; the comparison reported is with the control, so equivalence to the full conventional dose should be confirmed from the original article.	Gousia *et al.* (2024)
Forage sorghum	Nano-urea + nano-DAP	Integrated foliar nano-urea and nano-DAP schemes [AUTHORS TO INSERT doses, soil fertilizer level and timing from the original article]	Conventional fertilizer rates [AUTHORS TO INSERT]	Positive growth and yield responses reported; supports partial substitution, but quantitative results should be added from the original article.	Ahari *et al.* (2024)

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