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Role of nano urea and nano DAP in integrated nutrient management: A review

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ABSTRACT

Global agriculture has experienced a dramatic evolution, resulting in a huge surge in the use of synthetic mineral fertilizers, which have caused significant ecological consequences, soil degradation, and reduced nutrient use efficiency (NUE). The integrated use of mineral, organic and biological sources of nutrients in a systematic way is integrated nutrient management (INM), and it aims to balance all the sources of nutrients to achieve soil health and productivity. In recent years, new nano-urea and nano-diammonium phosphate (nano-DAP) fertilizers, which are highly reactive and slow-release substitutes for conventional bulk fertilizers, have been developed in the field of nanotechnology. This review critically collates the experimental evidence of 39 peer-reviewed papers to assess the agronomic, physiological, economic and environmental effects of applying nano-fertilizers in INM practices. Conjoint field trials showed that foliar application of nano-urea (4 mL/L) and nano-DAP (2–2.5 mL/L) at critical vegetative stages did not reduce but significantly improved the vegetative growth, chlorophyll content, dry matter and yield of various field crops such as wheat, pearl millet, potato, sorghum, blackgram and groundnut when compared with the Recommended Dose of Fertilizers (RDF). The ultra-small particle size (typically 20–50 nm, up to ~100 nm) of the nano-formulations allows rapid penetration through the cuticle and stomata, reducing losses via volatilization, leaching and fixation in the soil. Moreover, the integration of nano-fertilizer enhances the biological health of soil by promoting the growth of microbial populations (bacteria, fungi and actinomycetes) and enzyme activity. Synchronized INM treatments lower bulk-fertilizer, labor and transportation costs on an economic basis, resulting in higher benefit-cost ratios (B:C). However, there are a number of critical research gaps, such as a considerable "yield penalty" noted when solid nitrogenous fertilizers are totally replaced by foliar applications of nano-urea in some vegetable cropping systems (e.g., okra) and a high risk of soil nutrient mining when basal solid fertilizer rates are insufficient. The review underscores the importance of multi-season and long-term field trials under varying soil-climatic conditions for developing application criteria for nano-fertilizers under sustainable agriculture conditions.

Keywords: *Nano-urea and DAP, Integrated Nutrient Management (INM), Nutrient Use Efficiency (NUE), Soil Microbiological Health, Sustainable Agriculture.*

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1. Introduction

Traditional crop production intensive use of bulk mineral fertilizers such as prilled urea and conventional diammonium phosphate (DAP) is due to the macro-element requirement of nitrogen (N) and phosphorus (P) (Chamuah *et al*., 2023a; Saud *et al*., 2022). Bulk fertilizers have established themselves as a means to ensure food security worldwide, but their overuse and misuse have led to significant environmental issues (Aanoor *et al*., 2023; Dayal *et al*., 2025). These losses lead to significant environmental issues such as soil acidification, nitrate

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contamination of groundwater, eutrophication of water bodies, high N_2O greenhouse-gas emissions, and higher costs to farmers for soil application (AL-Tameemi *et al*., 2019; Rezk *et al*., 2021; Priyanshi *et al*., 2025; Reddy *et al*., 2022). To address these environmental and economic impacts, researchers in agriculture have developed Integrated Nutrient Management (INM) strategies, which involve proper application of chemical mineral fertilizers, organic manures (farmyard manure, vermicompost and compost) and biofertilizers for ensuring soil fertility and plant nutrient requirements without compromising soil health in the long term (Saud *et al*., 2022; El-Henawy *et al*., 2018; Samruthi *et al*., 2020). Seedling root dipping and foliar spraying of nano-fertilizers prevent nutrient binding/immobilization in the soil and nutrient losses via soil mediated pathways and promote delivery of the nutrient to metabolic sinks of plants at nanoscale (1–100 nm) with high surface reactivity and large specific surface area, similar to physiological nutrient absorption kinetics (Acharya *et al*., 2023; Balachandar *et al*., 2023; Chamuah *et al*., 2023a; Dalapati *et al*., 2025; Kumar Mandal *et al*., 2023; Sharma *et al*., 2022). Despite the theoretical benefits reported, the effectiveness of multi-crop field trials (MFTs) varies greatly (Chandrakar *et al*., 2025; Kumar Mandal *et al*., 2023). Therefore, based on the experiment-based literature, the available evidence was critically summarised and the actual potential, limitation and risks of the use of nano-urea and nano-DAP in modern INM strategies were evaluated.

2. Review Methodology

This review compiles 39 peer-reviewed field studies published from 2018–2026. The studies were published in journals such as the International Journal of Plant & Soil Science, International Journal of Environment and Climate Change, Journal of Scientific Research and Reports, Plant Archives, Biological Forum An International Journal, The Pharma Innovation Journal, Agricultural Science Digest, Journal of the Indian Society of Coastal Agricultural Research, Environment, Biodiversity and Soil Security, and the Journal of Experimental Agriculture International, in addition to one Research Square preprint. The trials were carried out mainly in India and involved wheat, pearl millet, potato, sorghum, blackgram, groundnut, cabbage, maize, onion, rice, tea and related crops.
Inclusion criteria: Studies were only retained if they provided results for field-based (and not just laboratory or pot-culture) agronomic, physiological, nutrient-uptake, soil-health, or economic outcomes of foliar-applied and/or seed/seedling-applied nano-urea and/or nano-DAP treatments, compared within an integrated or comparative nutrient-management design (e.g., a conventional-fertilizer treatment or an unfertilized control treatment).
Data synthesis: Quantitative outcomes (growth attributes, yield and nutrient uptake, soil parameters, benefit–cost ratios and environmental indicators) were retrieved and synthesized narratively. Treatments combining reduced levels of conventional fertilizer with nano-urea or nano-DAP were emphasized, as these are the integrated nutrient management (INM) treatments most frequently reported in the literature.
Limitations of the evidence base: This review does not include a formal, reproducible literature-search protocol (databases searched, exact search strings, and date limits), and none is reported here. There was also no definite division between independently funded trials and those sponsored by a manufacturer. A number of studies used IFFCO-brand nano-urea or nano-DAP, but use of the product does not by itself indicate manufacturer funding, and no explicit funding-source statement identifying commercial sponsorship was found in the papers reviewed. This uncertainty is acknowledged rather than resolved: the evidence available is not sufficient to classify trials by funding source, and no such classification is attempted here. The synthesis is accordingly based on the published field evidence available, but its conclusions are limited by the absence of a documented, reproducible search process and by incomplete funding transparency in the underlying literature.

3. Nano-Fertilizers and their contribution to Integrated Nutrient Management

In the conventional mode of fertilizer application, the synthetic fertilizers are broadcast or drilled into the soil and subsequently break down, releasing very high concentrations of ionic nutrients (Reddy *et al*., 2022). In such cases, nutrients are given out at large rates when compared to the biological absorbing capacity of the young root system, causing high environmental losses. Nano-fertilizers, however, are formulated to release the nutrients slowly (Releasing nutrient over 40-50 days as compared to 4-10 days for conventional fertilizers) (Rezk *et al*., 2021)

3.1 Physical Mechanisms Underlying Nano-Fertilizer Effectiveness

Nano-Fertilizer effectiveness can be attributed to a number of physical mechanisms. There are several physical mechanisms that contribute to the effectiveness of Nano-Fertilizers. The efficacy of nano-urea, nano-DAP applied as foliar sprays is mainly due to three interconnected physical mechanisms:

- Particle Size & Stomatal Entry: IFFCO liquid nano-urea is of particle size 20-50 nm (Baboo, 2021, as cited in Kumar Mandal *et al*., 2023). Stomatal pores are much bigger than this so the nanoparticles can penetrate the stomatal pores, leaf cuticle during foliar spraying (Sharma *et al*, 2022).

- High surface area/volume ratio: The surface area of Nano-urea is around 10,000 times higher than that of granular urea (Baboo, 2021, as cited in Kumar Mandal *et al*., 2023). This large surface area is proposed to increase particle reactivity and to accelerate the assimilation of the particles in the plant, but this is a proposed mechanism and not directly demonstrated for nano-urea/nano-DAP specifically.
- Controlled kinetics and phloem mobility: after being absorbed by the epidermal cells, it is proposed that nanoparticles travel through the apoplastic and symplastic pathways, including phloem movement, to reach active sink tissues, avoiding soil-binding reactions that hinder the conventional fertilizer movement (Dalapati *et al*., 2025).

For both nano-urea and nano-DAP, no specific studies were found that directly confirmed the pathway of foliar application to translocation in phloem. This pathway was mentioned as proposed (not confirmed) in other studies reviewed, where nano-CaO in groundnut and nanoparticles in wheat phloem tissue were reviewed. In an INM system, these mechanisms are being used agronomically by using lower rates of conventional soil fertilizer (usually 50-75% of the recommended rate of nitrogen and phosphorus) during early crop growth stages and using nano-urea or nano-DAP in foliar application during the active vegetative stages to achieve the maximum physiological efficiency in the utilization of soil nutrient (Chandrakar *et al*., 2025; Pandey *et al*., 2025; D. Singh *et al*., 2023).

3.2 Digital and AI-Assisted Application of Nano-Fertilizers

Accurate, location and stage appropriate delivery is a key part to unlocking the potential of nano-urea and nano-DAP in INM, and this is being done more and more with digital and AI based solutions than by calendar spray. Unmanned-aerial-vehicle (UAV) or satellite multispectral/hyperspectral vegetation indices can be used to estimate the nitrogen status of crop plants at the field scale at the appropriate time by training machine-learning or deep-learning models using multispectral/hyperspectral images (Chlingaryan *et al*., 2018). This information, together with variable-rate spraying (VRS) equipment, such as different drone-mounted sprayers, can be used to optimize the dose, timing and spatial placement of nano-fertilizers within a single field, targeting areas of N or P deficiency identified by the remote-sensing-derived crop status data, instead of applying a blanket rate (Toscano *et al*., 2024). In theory this would minimize the risks of under- or over- application (yield losses and risks of soil nutrient mining and yield loss respectively as described in Sections 5.2 and 7.2) of foliar nano-fertilizers and would help address the crop and region-specific dosing questions raised in Section 10. However, none of the 39 studies reviewed here tested nano-urea or nano-DAP application specifically using AI, remote-sensing- or drone technology; this is therefore not a current application but a direction that is being prioritized for future research.

3.3 Nano Urea in Integrated Nutrient Management

In this regard, the use of Nano Urea in Integrated Nutrient Management is being encouraged. In conventional systems, top-dressing with nitrogen is very susceptible to volatilization loss and leaching loss of N as NH_4^+ and NO_3^- ions (Sharma *et al*., 2022; D. Singh *et al*., 2023). Based on field evidence, the following successful nano-urea INM treatments are highlighted: 50% RDN as basal conventional urea and 50% RDN as two applications of nano-urea at 30 and 50 DAS gave the highest wheat grain production (36.35 q/ha) in the field trial conducted at Ayodhya, Uttar Pradesh, as compared to 34.50 q/ha in 100% RDN (conventional urea) (D. Singh *et al*., 2023). In sandy soil, the growth and yield of pearl millet (*Pennisetum glaucum L*.) was significantly improved by application of 100% RDN along with two foliar applications of nano-urea (4 mL/L) at 30 and 45 DAS as compared to lower N levels under Kharif season (Sharma *et al*., 2022). On potato, 50% of the recommended dose of nitrogen as granular urea and 100% as liquid nano-urea applied in two foliar sprays led to 6.9% higher yield compared to 100% RDF and 8 days earlier maturity in the lower Gangetic plains of West Bengal (Dutta, 2022). The grain yield (3,375kg/ha) and dry-matter production (14,481kg/ha) were significantly more with 50% N as neem coated urea and 50% N as liquid nano-urea with full dose of soil applied P and K than in the control (Balachandar *et al*., 2023). For onion (*Allium cepa L*.), application of 0.4% nano-urea with 75% recommended dose of NPK fertilizer produced 336.40 q/ha of onion yield as compared to 331.39 q/ha with 100% recommended dose of NPK fertilizer (Dubey *et al*., 2023).

3.4 Nano DAP in Integrated Nutrient Management

Liquid nano-DAP (8% N, 16% P, w/v) has been evaluated to achieve the greatest recovery of phosphorus and the least granular DAP soil application. The efficiency of P use by soil is ~18-20% (Rezk *et al*., 2021; Acharya *et al*., 2023), as it easily combines with calcium ions in alkaline/neutral soils and iron/aluminium oxides in acid soils. When applied as a foliar spray or as seedlings through dipping, Nano-DAP is not affected by this soil-fixation effect. From field investigations, the following important findings: Among the seeds, black gram (Vigna mungo L.) recorded the highest yield (1240 kg/ha) as statistically similar with two foliar spray treatments of liquid nano-DAP (2 mL/L) at 25 & 40 DAS (1219 kg/ha) and 25 DAS (1216 kg/ha) respectively (Chandrakar *et al*., 2025). Pandey *et*

al. (2025) noted that the use of 50 % RDF of N and P along with two spray applications of nano-urea and nano-DAP (20 and 40 DAS) led to significantly higher production of grains and total uptake of plant nutrients. The application of 50 per cent of recommended conventional N and P fertilizer and 10 mL/L nano-DAP as seed treatment with two foliar applications of 2.5 mL/L nano-DAP at 35 and 50 DAS gave the highest pod yield of 2410 kg/ha of groundnut (*Arachis hypogaea L*.) compared with other treatments as observed by Dalapati *et al*. (2025). This treatment was statistically similar or better than the conventional mineral-fertilizer treatment (2390 kg/ha). Seedling root dipping with 5 mL/L and foliar application of nano-DAP (2 mL/L at 25–30 DAT) together with 40 kg P/ha (reduced soil-P application) significantly improved head compactness, leaf chlorophyll and wrapper leaves in cabbage (*Brassica oleracea var. capitata*) (Chamuah *et al*., 2023a).

4. Effects on Crop Growth and Yield

Effect on crop growth and yield In general, Nano-fertilizers have been reported to exhibit a positive influence on growth and yield of major agronomic crops under INM systems whereas the magnitude of the effect varies across various crops, growth stages and application regimes; in certain cropping systems like okra and tea, the yields obtained with the use of Nano-fertilizers were not different than conventional full fertilizer application (Y. K Singh *et al*, 2023).

4.1 Growth Attributes

Experimental results show significant enhancements in a number of growth parameters: Nano-urea or nano-DAP + partial dose of conventional basal fertilizer shows a constant effect of tall plants as compared to other treatments. The plant height of black gram under 75% RDP + foliar nano-DAP was found to be 45.44 cm which is statistically at par with 100% conventional RDF (47.07 cm) (Chandrakar *et al*., 2025). Leaf Area Index (LAI) and canopy cover: Nano-nitrogen foliar treatment helps to create a high and active leaf area. Two sprays of nano-urea caused more number of sub-branches and terminal leaves in potato leading to higher photosynthetic efficiency of plants which led to more interception of solar energy (Dutta, 2022; D. Singh *et al*., 2023). The highest LAI at harvest was obtained with STCR based N in the form of urea (50%) plus two times foliar applications of nano-urea in paddy (Aanoor *et al*., 2023). Dry-matter accumulation with wheat treated with 75% RDN + PK + 2 sprays of nano-urea was 725.24 g/m² while it was 715.57 g/m² in 100% conventional RDF (Priyanshi *et al*., 2025).

4.2 Yield Attributes and Yield Penalties

For groundnut, phosphorus uptake and rate of net CO_2 fixation was increased with nano-DAP, which subsequently increased the enzymatic activity and improved root growth, nodule formation, pod count and yield by 69% over the unfertilized control (Dalapati *et al*., 2025). But, scientific studies have revealed that 100% replacement of bulk fertilizers with 100% nano-fertilizers is not always a blessing in terms of increased crop production, it can even lead to considerable crop losses: Under field trials conducted on okra cultivation in heavy textured coastal soil of West Bengal, Kumar Mandal *et al*. (2023) reported that complete replacement of soil nitrogen with foliar application of nano-urea led to a significant loss in yield (18.5–41.2% depending on the treatment). The poor nitrogen availability from foliar nano-urea application alone was found to be inadequate for okra, which has a very early growth cycle needing high level of solid mineral reserves in the root zone, leading to less marketable yield and stunted plants. Constraints on Tea growth (Khan *et al*., 2026): Foliar nano-urea application at 300–400mL/acre promoted the active shoot vegetative growth, and conventional RDF application in the soil produced the highest total yield. Foliar nano-urea application can provide N only and not help meet the needs of other macro and micronutrients.

5 Nutrient Uptake and Nutrient Use Efficiency

Higher chemical reactivity and physical losses in soil with lower recovery rates of traditional nitrogenous and phosphatic fertilizers. The advantage of using nanotechnological fertilizers is that through the specific physiology action, nutrient uptake will be enhanced and the nutrient use efficiency will also be improved (Patil *et al*., 2020).

6 Nutrient concentrations and plant uptake

The application of 50% RDF for N and P along with 100% RDF for K with two foliar spray of nano-urea and nano-DAP yielded the highest grain N (3.20%), P (0.54%) and K (0.68%) levels than 100% conventional RDF and absolute control (Pandey *et al*., 2025). Uptake allocation: Synced Conventional - Nano Application T6; 50% Recommended dose of N&P + 100% Recommended dose of K + Two foliar sprays of Nano Urea and Nano DAP optimized N and P uptake. The 100% conventional RDF soil treatment had the highest total vegetative (straw) uptake of N, P and K. This indicates that use of solid mineral fertilizer in the soil promotes vegetative growth, while use of foliar nano-fertilizer promotes reproductive growth (Pandey *et al*., 2025).

7 How Nutrient Use Efficiency is improved

No volatilization and soil fixation of urea: Direct foliar application of nano-urea eliminates volatilization and soil fixation which is a major advantage over soil application (Chamuah *et al*., 2023a; Reddy *et al*., 2022). In case of phosphorus, the particle size of the Nano-DAP (25-50nm) does not react with calcium, iron or aluminium in the soil, and is moved to active growth centres more quickly (Pandey *et al*., 2025). Slow and extended bio-available activity: Nano-fertilizer substrates provide nutrient availability slowly and steadily over 40–50 days which corresponds to the physiological requirements of plants. The slow-release nature of this fertilizer ensures a steady supply of nutrients and prevents sudden nutrient bursts that can happen with conventional fertilizers that are highly soluble (Rezk *et al*., 2021; AL-Tameemi *et al*., 2019; D. Singh *et al*., 2023).

8 Soil Fertility and Soil Health impacts

The maintenance and improvement of long-term soil health is one of the primary objectives of INM. Based on research, synthesizing Nano-fertilizer into soil system generates definite physical, chemical and biological responses.

8.1 Physical and Chemical Properties

The basic chemical and physical characteristics of the soil are not affected significantly by either foliar application of nano-urea or foliar application of nano-DAP through short duration field trials: Single season field trial conducted in post-harvest soil of blackgram and groundnut showed that there was no significant difference between soil RDF and nano-fertilizer treatment in soil pH and EC (Dalapati *et al*., 2025). After cultivation, soil pH was not significantly altered in paddy after using nano-fertilizer treatments (from 6.98 to 7.20) as compared to heavy granular urea treatment which caused localized soil acidification (Aanoor *et al*., 2023). Soil physical structure: There was no significant difference in bulk density, particle density and organic-carbon fractions after integration of foliar nano-urea or nano-DAP (Pandey *et al*., 2025).

8.2 The Risk of Soil Nutrient Mining

One of the major challenges identified by Kumar Mandal *et al*. (2023) was soil nutrient mining, which is a critical risk associated with using foliar nano-fertilizers instead of granular fertilizers. In okra field experiment in West Bengal, the post-harvest available soil nitrogen under T5 (complete replacement of granular soil N by foliar application of nano urea) recorded 92.4 kg/ha of soil N which was lower than both the complete fertilizer (T2, 138.6 kg/ha) and the unfertilized control (T1, 77.0 kg/ha). Foliar sprays also provide only a portion of the total N requirement of the crop, so that soil N reserves will be utilized for the remaining needs, and thus some soil-N depletion will occur if foliar nano-fertilizer is the sole source of N.

8.3 Soil Biological Properties

It is not expected that nano-fertilizers would significantly affect the physical properties of soil but it has beneficial effects on the biological properties of soil: Application of recommended dose conventional fertilizer along with foliar nano-urea resulted in increased microorganisms (bacteria, fungi and actinomycetes) in rhizosphere (Aanoor *et al*., 2023). This biological stimulation is believed to be due to better vegetative growth and root development which results in a greater production of organic root exudates in the rhizosphere. The SMBC, and growth of phosphorus-solubilizing bacteria (PSB) significantly improved in groundnut-growing acid Inceptisols under the application of Nano-DAP at 10 mL/L (Dalapati *et al*., 2025; Sahu *et al*., 2023). Increased nutrient solubility in the rhizosphere (Aanoor *et al*., 2023; Saud *et al*., 2022).

9 Nutrient Management in Organic Farming

Liquid nano-fertilizers are well suitable for use with organic manures and bio-organic formulations (El-Henawy *et al*., 2018): Application of 100% of N as foliar nano-urea along with 100% of the target dose of the STCR-N with Bio-Organic Fertilizer (50% vermicomposting, 35% rice-husk biochar and 15% rock phosphate inoculated with beneficial microbes) showed significant improvements in both the grain and straw production of direct wet-seeded rice. This results in organic–mineral associations which reduce the nitrogen leaching and ensure appropriate nutrient availability throughout the growth (Saud *et al*., 2022). Neem-coated urea (NCU) along with foliar nano-urea application at critical tillering and pre-flowering periods of sorghum was found to be excellent in vegetative growth, dry-matter production and grain yield as the solid basal NCU was able to meet early vegetative N requirement of the crop and foliar nano-urea was able to supply direct N to leaves (Balachandar *et al*., 2023). Good

compatibility of groundnut with native rhizobia was observed in the case of groundnut treated with nano-DAP (10 mL/L) seed treatment and foliar sprays, resulting in increased root nodulation, nodule N content and N-fixation efficiency (Dalapati *et al*., 2025)

10 Economic and Environmental Implications

Accessibility to farmer adoption of nano-fertilizers depends on the economic viability and environmental sustainability of the integration at the farmer level (Chamuah *et al*., 2023a, 2023b; Y. K. Singh *et al*., 2023).

10.1 Economic aspects

Empirical economic studies reveal that the applications of nano-fertilizers in INM system could be helpful in reducing the cost of cultivation and enhancing the profitability: Reduced cultivation and handling costs: One 500 mL bottle of liquid nano-urea may be used in place of 1 bag of prilled urea, according to the manufacturer's literature, but this is not true on a nutrient-content basis. The absolute content of N in a 500 mL bottle of IFFCO nano-urea is approximately 4% N by weight and yields about 20 g N while a 45 kg bag of prilled urea (46% N) yields about 20.7 kg N – a 1000fold difference in the absolute N content. Kumar Mandal *et al*. (2023) caution that this claim could mislead the farmers to the effect that they can replace fertilizers with nano-urea; in fact, the advantage of the nano-urea is that it reduces the transport, storage and labour requirement required because of its smaller physical volume and the fact that it can be used to supplement the recommended soil-N dose. Using liquid nano-urea instead of conventional chemical N rate by 50% saved around Rs. in potato cultivation. It has reduced input cost by 17,800 per hectare and increased yield by 6.9% and maturity date by 8 days compared to full conventional RDF (Dutta, 2022). These highest B:C ratios were achieved in wheat in 75% NPK and single foliar spray of nano-urea at 30 DAS in Kanpur, Uttar Pradesh (B:C 2.22) and under a 50:50 conventional-urea/nano-urea top-dressing regime in Ayodhya, Uttar Pradesh (B:C 1.42) (D. Singh *et al*., 2023; Y. K. Singh *et al*., 2023). Groundnut: Fully conventional treatment (100% soil applied N and P, no seed treatment, no foliar application) recorded the lowest B:C ratio (2.07) followed by the treatment with 50% of the standard N and P dose along with seed treatment (nano-dap 10 mL/l) and two foliar sprays (nano-dap 2.5 mL/l at 35 and 50 DAS), which recorded the highest B:C ratio (2.19). The B:C ratio was found to be lower in this case (1.40–1.41) as compared to (2.33–2.47) in zero–two sprayings due to no significant difference in yield and increment in the input cost in blackgram when spray was used at three times the recommended rate (Chandrakar *et al*., 2025).

Summary Table of Reviewed Field Trials

Summary table built directly from the cited papers' own treatment tables, with a Cost/Economics column added wherever the source reports B:C ratio or cost data.

Crop	Location	Treatment (best nano regime)	Result vs. 100% RDF / control	Yield difference	Source
Wheat	Ayodhya, U.P.	50% RDN basal urea + 50% RDN as 2 nano-urea top-dressings (30, 50 DAS)	36.35 vs 34.50 q/ha (100% conv. urea)	5.40%	D. Singh *et al*. (2023)
Wheat	Kanpur, U.P.	75% NPK + 1 nano-urea foliar spray (30 DAS); B:C 2.22 vs 2.20 (100% NPK)	B:C +0.02	B:C +0.9%	Y. K. Singh *et al*. (2023)
Wheat	Kanpur region, U.P.	75% RDN+PK + 2 foliar sprays 4 mL/L nano-urea (40, 60 DAS)	725.24 vs 715.57 g/m² dry matter (100% RDN+PK)	+1.4% (dry matter)	Priyanshi *et al*. (2025)
Pearl millet	Rajasthan (sandy soil, Kharif)	100% RDN + 2 foliar sprays nano-urea (4 mL/L, 30 & 45 DAS)	Significantly increased plant height, dry matter, chlorophyll, and grain/straw N, P and K content over control and single-spray treatments	Growth/nutrient content ↑	Sharma *et al*. (2022)

Potato	Lower Gangetic Plains, West Bengal	50% RDN granular urea + full N as nano-urea (2 foliar sprays)	+6.9% vs 100% RDF; 8 days earlier maturity; ₹17,800/ha saved	+6.9%	Dutta (2022)
Sorghum		50% N as neem-coated urea + 50% N as nano-urea + full soil P,K	3,375 kg/ha grain, 14,481 kg/ha dry matter under this treatment		Balachandar *et al*. (2023)
Onion		0.4% nano-urea (30 & 60 DAT) + 75% NPK RDF	336.40 vs 331.39 q/ha (100% NPK RDF)	1.50%	Dubey *et al*. (2023)
Blackgram		100% RDF (control) vs 2 nano-DAP foliar sprays (2 mL/L, 25 & 40 DAS)	1,240 kg/ha (100% RDF) vs 1,219 / 1,216 kg/ha (nano-DAP, statistically similar)	−1.7% / −2.0% (n.s.)	Chandrakar *et al*. (2025)
Blackgram		50% RDF N&P + 100% RDF K + 2 foliar sprays nano-urea + nano-DAP (T6)	This treatment (T6) was significantly associated with higher grain yield than the other five treatments		Pandey *et al*. (2025)
Groundnut	East & S.E. Coastal Plain, Odisha (rabi 2023–24, single season)	50% conv. N,P + seed treatment 10 mL/L nano-DAP + 2 foliar sprays 2.5 mL/L (35, 50 DAS)	2,410 vs 2,390 kg/ha pod yield (100% conv.); B:C 2.19 vs 2.07 (100% conv.)	+0.8% yield; +5.8% B:C	Dalapati *et al*. (2025)
Cabbage	Jorhat, Assam	Seedling root-dip 5 mL/L + foliar nano-DAP 2 mL/L (25–30 DAT) + 40 kg P/ha	Improved head compactness (29.88 vs 24.43 control), chlorophyll and wrapper leaves vs. RDF	See source (%)	Chamuah *et al*. (2023a)
Okra	Coastal West Bengal (Kharif 2022)	1/3 N nano-urea (T5, full nano) vs 100% RDF soil N,P,K (T2)	Yield reduction −41.2% (T5) vs T2; N2O 1.71 vs 2.85 mg/m²/day; NO_3^- 0.74–0.85 vs 1.22 mg/L	−41.2% (yield penalty)	Kumar Mandal *et al*. (2023)
Tea	Northern Bangladesh	Foliar nano-urea 300–400 mL/acre vs conventional soil RDF	Conventional RDF gave highest total yield; nano-urea aided shoot growth only	Lower than RDF (qualitative)	Khan *et al*. (2026)

11 Environmental Sustainability

There are several environmental benefits of foliar application of Nano-fertilizer, such as reducing chemical losses (Sharma *et al*., 2022): The N2O flux was reduced to 0.79–1.71 mg/m²/day with the foliar nano-urea application as compared to the conventional soil application of prilled urea of 2.85 mg/m²/day in a field experiment with okra (Kumar Mandal *et al*., 2023). Nitrate (NO_3^-) concentration of the leachate was also found to be lower under the nano-urea treatments (0.74–0.85 mg/L) as compared to the fully recommended conventional fertilizer dose (1.22 mg/L) in the same trial (Kumar Mandal *et al*., 2023). The environmental benefits were proven in one okra test in the coastal West Bengal area and may not be considered to extend to other crops and areas without proper testing.

12 Research Gaps and Future Perspectives

Although the literature demonstrates benefits of integrating nano-fertilizers into INM frameworks, important research gaps remain:

1. Longevity of nanoparticles: Long-term impacts of nanoparticle accumulation in soil, plant tissues and agricultural food webs are not well known (Acharya *et al*., 2023; Priyanshi *et al*., 2025). Extensive testing is needed to determine toxicity to beneficial soil microorganisms, earthworms and humans (Acharya *et al*., 2023; El-Henawy *et al*., 2018).
2. Crop-specific and regional standardization: Optimal concentration, timing and integration ratio of nano-fertilizers with conventional fertilizers differ significantly by crop physiology, soil properties and climate. Guidance for different crops and agro-climatic zones is required (Chandrakar *et al*., 2025; Khan *et al*., 2026; Pandey *et al*., 2025).
3. Soil mining and nutrient exhaustion: Long-term monitoring of nutrient stocks under reduced conventional soil-fertilizer application is needed to avoid soil nutrient exhaustion (Kumar Mandal *et al*., 2023).
4. Application machinery and standardization: Standardization of droplet size, surfactant incorporation and leaf retention under field conditions is necessary to optimize retention and minimize spray drift (Chandrakar *et al*., 2025; Sahu *et al*., 2023).

13 Conclusion

A critical review was carried out of the empirical evidence available on the use of liquid nano-urea and nano-DAP in Integrated Nutrient Management (INM) systems (Priyanshi *et al*., 2025; Chandrakar *et al*., 2025). Both applications of foliar nano-urea (4 mL/L) and/or nano-DAP (2–2.5 mL/L) with a lower rate of conventional mineral fertilizer (typically 50–75% of RDF) could decrease the application of conventional solid chemical fertilizer by 25 to 50% in several reviewed cropping systems, and under optimized spray frequency, improved profitability (Chandrakar *et al*., 2025; Y. K. Singh *et al*., 2023); in the one trial on which measurements were made, lower N2O flux and nitrate leachate (Kumar Mandal *et al*., 2023) were associated with this decrease in conventional solid chemical fertilizer. The environmental and economic benefits noted in Section 5.2 and 7.2, and the use of short duration, many single-season trials as the basis for the evidence base (Section 7.1) should not be extrapolated to all crops and regions without additional and longer term confirmation. To realize the full potential of nanotechnology in sustainable precision agriculture, optimized recommendations for foliar application of nano-fertilizers need to be developed for specific crops and regions on the basis of long-term, multi-location field experiments.

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15 Abbreviation

Abbreviation	Full Form
B:C	Benefit-Cost Ratio
DAS	Days After Sowing
DAT	Days After Transplanting
GHG	Greenhouse Gas
INM	Integrated Nutrient Management
LAI	Leaf Area Index
N	Nitrogen
Nano-DAP	Nano-Diammonium Phosphate
NCU	Neem-Coated Urea
NUE	Nutrient Use Efficiency
P	Phosphorus
PSB	Phosphorus Solubilizing Bacteria
RDF	Recommended Dose of Fertilizers
RDN	Recommended Dose of Nitrogen
RDP	Recommended Dose of Phosphorus
SMBC	Soil Microbial Biomass Carbon
STCR	Soil Test Crop Response

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