Bangladesh Rice Journal 29 (1), 2025

BRJ

Contents lists available at Banglajol

Bangladesh Rice Journal

journal homepage: www.banglajol.info/index.php/BRJ

Sustainable Rice Fertilization: Can Nano-Urea and Nano-Diammonium Phosphate Reduce Nitrogen and Phosphorus Inputs without Yield Penalties in Bangladesh?

M N Islam[1*], M Iqbal[1], S M M Islam[1], A T M S Hossain[1], T P Suvo[1], A Islam[1], M R Islam[1]

[1]Soil Science Division, Bangladesh Rice Research Institute, Gazipur, Bangladesh

A R T I C L E I N F O

Keywords:
Agro-ecological zone
Nano-fertilizer
Prilled urea
Recommended fertilizer dose

A B S T R A C T

Efficient fertilizer management is essential for sustaining rice productivity in Bangladesh while lowering production costs and minimizing environmental risks. This study examined whether liquid nano-urea (LNU) and liquid nano-diammonium phosphate (LND) could partially replace conventional prilled urea and diammonium phosphate (DAP) without yield penalties. Field experiments were conducted across six agro-ecological zones during the Boro 2022–23 and 2023–24 seasons, using randomized complete block designs with three replications. In the LNU experiment, various N rates and foliar sprays of nano-formulations were tested, whereas in the LND experiment, different P rates and foliar sprays of nano-formulations were evaluated. In 2022–23 at Gazipur, applying 66% of the recommended dose of prilled urea (RDPU) plus foliar LNU achieved yields (6.55 t ha^{-1}) statistically comparable to 100% RDPU (7.00 t ha^{-1}), saving 34% of urea. Multi-location trials in 2023–24 confirmed that yields from 66% RDPU with LNU often matched those from 100% RDPU, particularly in Gazipur, Cumilla, Habiganj, and Rajshahi. In Habiganj, two foliar sprays of LNU with 50% RDPU produced yields equivalent to those of 66% RDPU alone, indicating a potential to save 16% of urea. No significant yield differences were observed among LND treatments, and plots without phosphorus fertilization yielded similarly to those with 100% recommended P. This suggests that residual soil P supported crop growth during a single season, although long-term P omission could risk soil depletion. Overall, nano-urea enabled yield maintenance with up to one-third lower urea inputs, reducing input dependency and supporting national food security goals. Strategic use of 50% recommended P, with or without nano-DAP, may offer a sustainable pathway for phosphorus management in rice systems. However, long-term soil health impacts, economic feasibility, and farmer adoption dynamics require further investigation before large-scale recommendations can be made.

1. Introduction

Rice (*Oryza sativa* L.) remains one of humanity's most consequential crops, supplying a large share of daily calories across Asia and substantial portions of Africa and Latin America. Globally, rice occupies on the order of 160–165 million hectares and contributes roughly one-fifth of dietary energy supply, with Asia accounting for ~90% of both production and consumption (UN FAO, 2025). These figures

* Corresponding author at: Soil Science Division, Bangladesh Rice Research Institute, Gazipur, Bangladesh.
E-mail address: nazrulag@gmail.com (M N Islam)

https://doi.org/10.3329/brj.v29i1.90847

underscore the centrality of rice to food security and livelihoods, particularly under rising demand and climatic stressors. The productivity gains achieved since the Green Revolution have depended heavily on mineral fertilizers, especially nitrogen (N) and phosphorus (P). Yet, agronomic and environmental inefficiencies remain large. Classic syntheses and subsequent global assessments indicate that nitrogen recovery efficiency in cereals often hovers near ~30–40%, implying that the majority of applied N is lost to the environment via volatilization, leaching, runoff, and denitrification (Islam et al., 2013a and 2013b; Raun et al., 2002; Islam et al., 2018). These losses erode farmer profitability and contribute to downstream pollution and greenhouse-gas (GHG) emissions (Islam et al., 2024; Islam et al., 2025). Likewise, global analyses report phosphorus use efficiency in cereals to be commonly below 20–25%, with large fractions of applied P becoming soil-fixed or transported to aquatic systems, thereby intensifying eutrophication risks and highlighting long-term concerns over finite phosphate rock resources (Yu et al., 2021).

The environmental externalities of current fertilizer paradigms are particularly salient in rice systems. The overutilization of synthetic fertilizers results in economic burdens and contributes to the escalation of pollution in soil, water, and the atmosphere. Nano fertilizers, engineered nutrient carriers or nano-scaled nutrient formulations designed to enhance delivery, uptake, and synchrony with crop demand have emerged as a promising (if still maturing) frontier. Reviews synthesize several hypothesized advantages: (i) high surface area and reactivity that improve solubility and mobility; (ii) potential for controlled or slow release; (iii) enhanced foliar absorption through stomatal or cuticular pathways; and (iv) opportunities for targeted delivery that reduce off-site losses. These features could, in principle, allow partial substitution of conventional urea and phosphate fertilizers while maintaining yields and improving NUE/PUE (Jakhar et al., 2022).

Within this space, nano-urea and nano-diammonium phosphate (nano-DAP) have attracted intense interest because they align directly with the dominant macronutrient constraints in rice. Field experiments and early multi-site trials from South Asia report that foliar nano-urea applied at critical growth stages can sustain grain yields while enabling reductions in conventional prilled urea (PU), and that nano-DAP may increase P uptake efficiency and yield components relative to equal or reduced doses of bulk DAP (Reddy et al., 2025; Sweety et al., 2024). However, the evidence base is heterogeneous across crops, seasons, and sites; and study designs vary in replication, formulation chemistry, and comparators, which complicates cross-study inference. In addition, nutrient uptake and use efficiency vary depending on plant genotypes, water management and the characteristics of fertilizers (Islam et al., 2015 and 2016; Rahman et al., 2014; Islam et al., 2023).

Recent controlled and field studies illustrate both the promise and the caveats. For nitrogen, a two-year field study comparing granulated vs. nano-urea in wheat and rice at the ICAR-IARI farm in New Delhi reported improvements in NUE metrics and comparable yields at reduced N input in nano-urea regimes, though effects were context-dependent and not uniformly superior in all environments, underscoring the need for season- and site-specific validation (Reddy et al., 2025). For phosphorus, several investigations have evaluated nano-formulated DAP and nano-hydroxyapatite (nHA) as more labile P sources. Some studies in rice and upland cereals document improved P uptake, photosynthetic performance, and yield with nano-P foliar sprays or seedling dips under reduced soil-applied P, while materials-science work on nHA suggests enhanced bioavailability with potential co-benefits for reducing metal(loid) mobility in flooded soils (Sahoo et al., 2024; Xiong et al., 2018). At the same time, reviews caution that nanoparticle–soil–microbe interactions are complex; benefits can be formulation-specific, and standardized efficacy and safety testing is still evolving.

Stepping back to the global challenge of nutrient management, the need for innovation in fertilizer technologies is widely recognized across both agronomic and policy domains. A recent Sustainable Agriculture review highlights novel fertilizers, including nano-formulations, as part of a broader portfolio to improve NUE and reduce losses, while emphasizing rigorous, independent evaluation, transparent labelling, and life-cycle assessment before widescale promotion (Maaz et al., 2025). In parallel, global cropland phosphorus budgets and systems analyses published in high-impact venues stress that raising PUE is essential both for resource security and for water-quality protection, given non-renewable phosphate rock reserves and the prevalence of harmful algal blooms in P-enriched watersheds (Zou et al., 2022). For countries such as Bangladesh—one of the world's largest rice producers—the intersection of food security goals, fertilizer import bills, and environmental limits makes the case for higher efficiency particularly compelling. But the question is fundamentally global: can nano-enabled N and P fertilization deliver equivalent or higher yields at lower input rates across diverse ecologies (from monsoonal lowlands to irrigated deltas and subtropical uplands), while also offering credible reductions in loss pathways (NH_3 volatilization, NO_3^- leaching, runoff) and supply-chain risks (e.g., P price shocks)?

In Bangladesh, where smallholder farmers often rely on excessive fertilizer use to achieve yield targets, the adoption of nano-urea and nano-DAP could significantly reduce fertilizer use and production costs while sustaining or improving rice productivity. However, limited field-based research has been conducted to evaluate their effectiveness under the diverse agroecological conditions of Bangladesh. Policymakers need credible cost–benefit analyses that incorporate subsidy structures and potential import substitutions for N and P fertilizers. The present study contributes to this agenda by examining whether nano-urea and nano-DAP can reduce nitrogen and phosphorus inputs without yield penalties under rice-growing conditions reflective of South Asia, particularly Bangladesh. By rigorously testing nano-urea and nano-DAP within this broader systems frame, we can more credibly judge their role in a diversified toolkit for resilient, climate-compatible rice intensification worldwide.

2. Materials and methods

2.1. Experimental site and season

Field experiments were conducted during the Boro 2022-23 season in Gazipur (AEZ 28) and the Boro 2023–24 season across six representative agro-ecological zones (AEZs) of Bangladesh: Gazipur (AEZ 28), Cumilla (AEZ 19), Habiganj (AEZ 20), Sonagazi (AEZ 18), Rajshahi (AEZ 11) and Satkhira (AEZ 13). These sites were selected to capture the diversity of soil properties, climatic conditions, and cropping patterns that characterize the country's major rice-growing regions. Bangladesh has a humid subtropical climate characterized by a monsoon season from May to October and a dry season from November to May. It receives approximately 2000 mm of rainfall annually, with an average temperature around 25 ˚C (Islam et al., 2025; Islam et al., 2024; Mainuddin et al., 2021). About 82–83% of this rainfall occurs during the wet season, from May to October (Mainuddin et al., 2021). Boro rice is grown during the dry season, which heavily relies on irrigation. In Boro 2022-23, LNU was tested at the BRRI farm in Gazipur using BRRI dhan89 as the test variety. In Boro 2023-24, trials were conducted at BRRI farms in Gazipur, Cumilla, Habiganj, Satkhira, Sonagazi, and Rajshahi, with BRRI dhan100, BRRI dhan74, BRRI dhan104, BRRI dhan89, BRRI dhan107, and BRRI dhan102 used as test varieties, respectively. Soil samples (0–15 cm depth) were collected prior to ploughing at each site to determine baseline soil characteristics, including pH (Glass electrode method), organic carbon (Walkley and Black wet digestion method), total nitrogen (Micro-Kjeldahl method), and available phosphorus (Modified Olsen method), following the procedures described by Saha et al. (2016). The soil pH ranged from slightly acidic in Habiganj (pH 5.6) to slightly alkaline in Satkhira (pH 7.9) and Rajshahi (pH 7.5), with variable organic carbon (0.90–1.32%), total nitrogen contents (0.09–0.13%), and available phosphorus (13-35 mg kg^{-1}).

2.2 Experimental design and layout

A randomized complete block design was employed with three replications at each location. The individual plot size was 20 m^2 (4.0 m × 5.0 m), with 30 cm bunds separating adjacent plots to prevent the movement of water and fertilizer. Treatment details are presented in Tables 1 and 2. The experiment was designed to assess the potential of nano-urea and nano-DAP (experimental formulations) to partially replace prilled urea and conventional diammonium phosphate (DAP) without affecting yield.

Table 1
Treatment combinations of liquid nano-urea (LNU) trial at different locations, Boro 2022-23 and 2023-24.

Boro 2022-23	Boro 2023-24
T_1: 66% recommended dose of prilled urea (RDPU) at basal and active tillering	T_1: 50% recommended dose of prilled urea (RDPU) at basal
T_2: 66% RDPU (33% at basal and 33% at active tillering) + two foliar sprays of LNU (at max. tillering and one week before flowering)	T_2: 50% RDPU at basal + two foliar sprays of LNU (at max. tillering and one week before flowering)
T_3: 100% RDPU (33% at basal + 34% at active tillering + 33% at max. tillering)	T_3: 33% RDPU at basal + 33% RDPU at active tillering
T_4: 100% RDPU (33% at basal + 34% at active tillering + 33% at max. tillering) + two foliar sprays of LNU (max. tillering and one week before flowering)	T_4: 33% RDPU at basal + 33% RDPU at active tillering + two foliar sprays of LNU (at max. tillering and one week before flowering)
	T_5: 100% RDPU (33% at basal + 34% at active tillering + 33% at max. tillering)

Table 2
Treatment combinations of liquid nano-DAP (LND) trial at different locations, Boro 2023-24.

Boro 2023-24
T_1 : 50% of the recommended doses of P (RDP) at basal
T_2 : 50% RDP at basal + one foliar spray of LND at 20-25 DAT
T_3 : Root dipping of seedlings with LND + 50% RDP at basal + one foliar spray of LND at 20-25 DAT
T_4 : 50% RDP at basal + two foliar sprays of LND at 20-25 DAT and 45-55 DAT
T_5 : Root dipping of seedlings with LND + 50% RDP at basal + two foliar sprays of LND at 20-25 DAT and 45-55 DAT
T_6 : 100% RDP at basal

The recommended dose of fertilizers was based on the Fertilizer Recommendation Guide (Hossain et al, 2024), varying slightly across sites according to soil fertility status. The recommended dose of N was 174 kg ha^{-1} for the Boro season in all locations. The dose of LNU/LND was 1235 ml ha^{-1}, and the solution concentration was 4 ml L^{-1} of water.

2.3. Crop management

Two to three seedlings were transplanted per hill with a spacing of 20 cm by 20 cm. Urea fertilizer was administered in three equal doses at the basal stage, during maximum tillering, and at panicle initiation. The full dose of P, K, S, and Zn was applied during final land preparation using TSP, MoP, gypsum, and zinc sulphate. Liquid nano-urea was sprayed as a foliar at maximum tillering and one week before flowering. Liquid nano-DAP was applied by seedling root dipping before transplanting and as a foliar spray at 20–25 and 45–50 days after transplanting (DAT). Other agronomic practices, including weed and pest management, were implemented following BRRI recommendations.

Rice was harvested at physiological maturity from a central 5 m^2 area (125 hills) in each plot to determine grain yield. The grains were winnowed, sun-dried, and adjusted to a standard 14% moisture content, with yields expressed in t ha^{-1}.

2.4. Statistical analysis

Grain yield data were analyzed using STAR 2.0.1 software (IRRI, Philippines). A randomized complete block design (RCBD) was used for the analysis of variance (ANOVA), and treatment means were compared using Tukey's Honest Significant Difference (HSD) test at the 5% significance level.

3. Results

In the Boro 2022-23 season, urea fertilizer application had a significant impact on rice grain yield (Table 3). The lowest yield of 5.74 t ha^{-1} was recorded with the application of 105.6 kg N ha^{-1} (66% RDPU, T_1), which was significantly lower than other treatments. However, spraying LNU alongside 66% RDPU (T_2) increased the grain yield to 6.55 t ha^{-1}, marking a 14% improvement over T_1. The highest yield of 7.00 t ha^{-1} was obtained with the application of 160 kg N ha^{-1} (100% RDPU, T_3), which was statistically similar to T_2 (66% RDPU + LNU). The LNU treated plot with reduced dose (66%) of prilled urea (T_2) yielded higher net benefits of 198663 Tk ha^{-1}, compared to the similar doses of prilled urea (PU) treated plot (T_1) of 180522 Tk ha^{-1}. However, the highest net benefit (214786 Tk ha^{-1}) was found in T_3 (100% of RDPU) treatment (Table 6).

Table 3
Effect of liquid nano-urea (LNU) on the grain yield of BRRI dhan89 at BRRI farm, Gazipur, in Boro 2022-23.

Treatment	Grain yield (t ha^{-1})
T_1 : 66% recommended dose of prilled urea (RDPU) at basal and early tillering	5.74 c
T_2 : 66% RDPU (33% at basal and 33% at early tillering) + two foliar sprays of LNU (at max. tillering and one week before flowering)	6.55 ab
T_3 : 100% RDPU (33% at basal + 34% at early tillering + 33% at max. tillering)	7.00 a
T_4 : 100% RDPU (33% at basal + 34% at early tillering + 33% at max. tillering) + two foliar sprays of LNU (max. tillering and one week before flowering)	6.48 b
Level of significance	**
CV	3.8

In the Boro 2023-24 season, the effects of LNU on rice yield are presented in Table 4. In Gazipur, Cumilla, Habiganj and Satkhira sites, 100% of RDPU (T_5) gave the highest grain yield, which was statistically similar to T_3 (66% of RDPU) and T_4 (two foliar sprays of LNU along with 66% of RDPU). So, it indicates that 66% of RDPU is sufficient for obtaining optimum rice yield. However, in the Habiganj site, the T_3 treatment (66% of RDPU) gave a statistically identical yield to the T_2 (two foliar sprays of LNU along with 50% of RDPU) treatment. This indicates that LNU may save 16% of prilled urea without sacrificing rice yield in the Boro season. A significant yield difference between the T_1 (50% of RDPU) and T_2 (two foliar sprays of LNU along with 50% of RDPU) treatments in Cumilla and Habiganj sites also indicates that the foliar spray of LNU might have positive effects on rice yield in the Boro season. In contrast, no yield difference was found between the T_1 and T_2 treatments in the Gazipur, Satkhira and Rajshahi sites. In Rajshahi, the highest grain yield was obtained from T_5 (100% RDPU), which was statistically similar to T_4 (two foliar sprays of LNU with 66% RDPU), indicating that LNU could reduce prilled urea use by 34% without yield loss. Notably, no significant yield differences among treatments were observed at the Sonagazi site. Moreover, the highest net benefit (218446-258726 Tk ha^{-1}) was found from the recommended dose of prilled urea (T_5) in all locations except in Satkhira (Table 6).

Table 4
Effect of liquid nano-urea (LNU) on the grain yield of rice in Boro 2023-24.

Treatment	Grain yield (t ha^{-1})					
	Gazipur (BRRI dhan 100)	Cumilla (BRRI dhan74)	Habiganj (BRRI dhan104)	Satkhira (BRRI dhan89)	Rajshahi (BRRI dhan102)	Sonagazi (BRRI dhan107)
T_1	5.71 b	5.71 c	6.04 c	4.11 b	5.19 c	7.55
T_2	6.17 b	6.81 b	6.61 b	4.41 b	5.26 c	7.71
T_3	6.77 a	7.68 a	6.89 ab	6.46 a	6.20 b	7.49
T_4	7.05 a	7.79 a	6.70 ab	6.02 a	6.96 ab	7.65
T_5	7.12 a	8.39 a	7.19 a	6.18 a	7.47 a	7.90
Level of significance	**	***	**	***	***	NS
CV	3.84	5.60	4.13	6.31	6.85	3.74

Means with the same letter are not significantly different. NS = non-significant at 5% level of significance. T_1: 50% recommended dose of urea (RDU) at basal; T_2: 50% RDU at basal + two foliar spray of LNU (at max. tillering and one week before flowering); T_3: 33% RDU at basal + 33% RDU at active tillering; T_4: 33% RDU at basal + 33% RDU at active tillering + two foliar spray of LNU (at max. tillering and one week before flowering); T_5: 100% RDU (33% at basal + 34% at active tillering + 33% at max. tillering).

The effects of LND on rice yield are presented in Table 5. There were no significant variations in rice yield among the treatments at any location. No yield difference between the treatments of 50% (T_1) and 100% (T_6) recommended dose of P fertilizer in the Boro season was observed.

Table 5
Effect of liquid nano-DAP (LND) on the grain yield of rice in Boro 2023-24.

Treatment	Grain yield (t ha^{-1})		
	Habiganj (BRRI dhan104)	Rangpur (BRRI dhan102)	Rajshahi (BRRI dhan107)
T_1	7.20	7.37	6.27
T_2	7.09	7.63	6.82
T_3	7.19	7.33	6.63
T_4	7.26	7.34	6.68
T_5	7.31	7.26	7.12
T_6	7.42	7.67	7.14
Level of significance	NS	NS	NS
CV	3.53	2.13	8.73

T_1: 50% of recommended doses of P (RDP) at basal; T_2: 50% RDP at basal + one foliar spray of LND at 20-25 DAT; T_3: Root dipping of seedlings with LND + 50% RDP at basal + one foliar spray of LND at 20-25 DAT; T_4: 50% RDP at basal + two foliar spray of LND at 20-25 DAT and 45-55 DAT; T_5: Root dipping of seedlings with LND + 50% RDP at basal + two foliar spray of LND at 20-25 DAT and 45-55 DAT; T_6: 100% RDP at basal.

Table 6
Economic analysis of liquid nano-urea (LNU) for Boro rice cultivation in 2022-23 and 2023-24.

Treatments	Net Benefit (Tk ha^{-1})						
	2022-23	2023-24					
	Gazipur	Gazipur	Cumilla	Habiganj	Satkhira	Rajshahi	Sonagazi
T_1	180522	181142	182742	193342	128292	166042	246092
T_2	198663	189363	209633	204913	130953	161423	244503
T_3	214786	212002	240912	217692	198182	195202	242442
T_4	192927	213863	237683	205313	178203	210893	240463
T_5	-	218446	258726	223486	186086	229596	251106

Total variable cost includes the price of fertilizer, labor cost for fertilizer application and additional products and by-products, as other costs were similar in all treatments. Urea = 27 Tk kg^{-1}, TSP = 27 Tk kg^{-1}, MoP = 20 Tk kg^{-1}, Gypsum = 20 Tk kg^{-1}, Zinc = 350 Tk kg^{-1}, liquid nano-urea = 1700 Tk/500 ml (3.4 Tk/ml), price of paddy = 30 Tk kg^{-1}, price of straw = 5 Tk kg^{-1}, laborer wage = 500 Tk day^{-1}, five additional laborers/ha were required for fertilizer application and five for spraying of LNU, four additional laborers were required for one ton additional products and by-products. In Boro 2022-23, T_1 = 66% recommended dose of prilled urea (RDPU) at basal and early tillering; T_2 = 66% RDPU (33% at basal and 33% at early tillering) + two foliar sprays of LNU (at max. tillering and one week before flowering); T_3 = 100% RDPU (33% at basal + 34% at early tillering + 33% at max. tillering); T_4 = 100% RDPU (33% at basal + 34% at early tillering + 33% at max. tillering) + two foliar spray of LNU (max. tillering and one week before flowering). In Boro 2023-24, T_1 = 50% recommended dose of urea (RDU) at basal; T_2 = 50% RDU at basal + two foliar spray of LNU (at max. tillering and one week before flowering); T_3 = 33% RDU at basal + 33% RDU at active tillering; T_4 = 33% RDU at basal + 33% RDU at active tillering + two foliar spray of LNU (at max. tillering and one week before flowering); T_5 = 100% RDU (33% at basal + 34% at active tillering + 33% at max. tillering).

4. Discussion

The present study demonstrates that nano-urea, when strategically integrated with conventional fertilizer management, can sustain rice yields in some AEZ of Bangladesh, while reducing nitrogen (N) fertilizer inputs. This finding has profound implications for sustainable intensification in Bangladesh and other rice-based systems worldwide, where rising input costs, environmental degradation, and climate variability are pressing concerns. However, nano-DAP might not respond positively to increasing rice production.

One of the most compelling outcomes was the ability of nano-urea to maintain yields at up to 33% lower prilled urea input. This aligns with previous research indicating that foliar-applied nano-fertilizers enhance nutrient use efficiency by bypassing soil-related losses such as volatilization, leaching, and denitrification (Reddy et al., 2025). Plant growth and yield responses depend on various climatic conditions (Islam et al., 2022). Nitrogen losses from conventional urea in flooded rice systems are particularly high, often exceeding 50–70% of applied N (Coskun et al., 2017). By directly supplying N to the leaves in nano-form, uptake efficiency is substantially increased, thereby explaining the observed equivalence in yield between reduced-dose treatments and the full recommended dose (Jakhar et al., 2022; Reddy et al., 2025).

The absence of significant yield differences between the 100% RDPU treatment and reduced RDPU (66%) with nano-urea (Table 4) indicates that Bangladesh can achieve food security goals with lower input dependency. Similar results were reported in India, where the Indian Council of Agricultural Research (ICAR) validated that nano-urea could replace 25–30% of conventional urea without yield penalties across several crops, including rice and wheat (Upadhyay et al., 2023). Likewise, trials in Africa and Southeast Asia have confirmed comparable yield sustainability under reduced inputs when nano-fertilizers are integrated (Khundi et al., 2025). This finding is particularly relevant for Bangladesh, where fertilizer imports constitute a significant portion of the agricultural subsidy budget, and price volatility has strained both government and farmers (Alam, 2018). By enabling substantial fertilizer savings, nano-urea adoption can reduce the financial burden while maintaining production, thereby aligning with Sustainable Development Goal (SDG) 2 of ending hunger and promoting sustainable agriculture.

For phosphorus, the observation that Boro rice yields did not differ significantly between phosphorus-omitted plots and those receiving the full recommended dose of DAP (Table 5) suggests that phosphorus omission in a single season might not necessarily reduce rice yield. In the context of Bangladesh, this phenomenon is likely attributable to residual soil phosphorus accumulation from previous fertilization, which may often sustain rice production even in the absence of fresh P inputs. In Bangladesh, it is indicated that the critical soil P threshold—as measured by Olsen P—is approximately 10 mg kg^{-1}; soils above this level typically show limited yield response to additional P fertilization (Hossain et al., 2024). This implies that in soils with phosphorus levels exceeding this critical value, rice plants may extract sufficient P from the soil legacy pool, negating the need for seasonal fertilizer in the short term. Further, phosphorus availability in wetland (paddy) soils—such as those under Boro cultivation—is often enhanced due to reductive dissolution of soil Fe and Al compounds, which frees sorbed phosphorus and increases its plant availability (Choudhury et al., 2007). This environmental mechanism might further bolster soil-derived P supply, thereby diminishing the immediate response to additional DAP application.

However, it is essential to interpret these findings within a broader agronomic and environmental context. Continued omission of P fertilizer over multiple seasons—especially in high-extraction cropping systems like intensively managed Boro rice—could eventually deplete residual P pools, leading to deficiencies and yield decline. Therefore, even if an individual season shows no significant yield gap between treatments, P fertilization remains crucial for long-term soil fertility maintenance and sustained productivity. Phosphorus legacies and soil redox dynamics may buffer rice yield against short-term P omission in highly fertilized Bangladeshi soils. Yet, for sustainable management, phosphorus inputs must still be adjusted over time in response to soil P trends, crop demand, and environmental considerations. Therefore, either a reduced application of P fertilizer at 50% of the recommended dose or the combined use of foliar-applied nano-DAP with 50% of the recommended dose may serve as suitable strategies for sustainable rice production.

Excessive N and P application has long been associated with negative environmental externalities, including greenhouse gas (GHG) emissions, eutrophication, and soil degradation (Gaihre et al., 2018; Xia et al., 2020). In flooded rice systems, urea-derived N is a major source of nitrous oxide (N_2O) and methane (CH_4), potent greenhouse gases (Bhuiyan et al., 2021). By improving NUE, nano-urea reduces the potential for excess N losses, thereby lowering the environmental footprint of rice production. Phosphorus over-application has also led to the accumulation of residual P in soils, increasing the risk of runoff into water bodies and contributing to harmful algal blooms (Ngatia and Taylor, 2018). By reducing the reliance on bulk P fertilizers, nano-DAP provides a pathway to more precise nutrient management and mitigates such risks. Therefore, the current results not only support economic sustainability but also environmental stewardship.

The efficiency of nano-urea and nano-DAP is linked to their smaller particle size, higher surface area, and greater solubility, which enhance absorption and translocation within the plant (Nongbet et al., 2022). In the case of nano-urea, direct foliar absorption allows for immediate assimilation, especially during critical growth stages such as tillering and panicle initiation, when N demand peaks (Namasharma et al., 2023; Nongbet et al., 2022). Similarly, nano-DAP applied during early vegetative and reproductive stages likely enhances P availability for root development, tiller production, and grain filling. From the present study, site-specific variability in yield response was observed. Nano-urea performed particularly well in Gazipur and Rajshahi soils with lower organic matter and N. This aligns with findings by Belyaeva et al. (2024), who showed that NUE gains are more pronounced under conditions of high N losses.

While the study highlights the potential of nano-urea and nano-DAP in rice production, several limitations remain and warrant further investigation. Firstly, the long-term effects of nano-fertilizers on soil health are not fully understood. Emerging research suggests that these materials may alter microbial communities and soil enzyme activities—factors vital for nutrient cycling and soil function (Zhang et al., 2024). Secondly, the economic viability of nano-formulations at scale requires careful evaluation. Although their precise delivery mechanisms seem promising, the costs associated with large-scale production, distribution, and regulatory approval remain uncertain, and real-world supply chains have yet to be tested. Equally important is understanding farmer perceptions and adoption behavior. Recent studies indicate that smallholder farmers are hesitant to adopt innovations perceived as risky or costly unless clear benefits are demonstrated, with access to extension services and credit playing critical roles in adoption decisions (Kule et al., 2025). Finally, the environmental fate and potential toxicity of nano-fertilizers must be rigorously monitored; unintended soil or water contamination could negate their agronomic advantages (Kekeli et al., 2025). Addressing these knowledge gaps is crucial for ensuring that nano-fertilizers become a safe, economical, and widely adopted component of sustainable agriculture.

Moreover, combining nano-fertilizers with complementary practices such as conservation agriculture, alternate wetting and drying (AWD), and precision agriculture technologies can amplify benefits. For example, AWD reduces methane emissions while improving water-use efficiency; integrating nano-urea under AWD could create synergistic effects for both yield and environmental outcomes. Similarly, precision tools such as drone-based foliar sprays could further enhance the effectiveness of nano-fertilizer delivery.

5. Conclusion

This study provides compelling evidence that nano-urea can play a transformative role in sustainable rice production in different locations of Bangladesh and other rice-growing regions worldwide. By partially substituting conventional prilled urea with foliar-applied nano-urea, it is possible to reduce nitrogen inputs without compromising grain yield. The results highlight that nano-urea can effectively replace up to one-third of prilled urea in some locations, while the efficacy of nano-DAP is still mysterious. These findings align with the broader goals of resource-efficient agriculture, offering a pathway to improved farm profitability and reduced dependence on fertilizer imports. Despite these promising outcomes, several caveats remain. LNU may not be economically viable, as it demonstrated a lower net benefit compared to the recommended doses of prilled urea. Long-term effects of nano-fertilizer application on soil microbial health, nutrient cycling, and environmental safety require further research. Additionally, socio-economic factors such as farmer awareness, adoption behaviour, and affordability at scale must be carefully addressed through participatory trials, extension programs, and policy support.

References

Alam, M. A. U. (2018). The effect of the 'subsidy on fertilizer'on food prices in Bangladesh and policy options. Journal of Economics and Sustainable Development, 9, 200-208.

Belyaeva, O., Ward, G., Wijesinghe, T., Chen, D., & Suter, H. (2024). Influence of soil organic matter, fertiliser formulation and season on fertiliser nitrogen use efficiency in temperate pastures. Nutrient Cycling in Agroecosystems, 129(1), 133-150.

Bhuiyan, M. S. I., Rahman, A., Kim, G. W., Das, S., & Kim, P. J. (2021). Eco-friendly yield-scaled global warming potential assists to determine the right rate of nitrogen in rice system: A systematic literature review. Environmental Pollution, 271, 116386.

Choudhury, A. T. M. A., Kennedy, I. R., Ahmed, M. F., & Kecskés, M. L. (2007). Phosphorus fertilization for rice and control of environmental pollution problems. Pakistan Journal of Biological Sciences, 10(13), 2098-2105.

Coskun, D., Britto, D. T., Shi, W., & Kronzucker, H. J. (2017). Nitrogen transformations in modern agriculture and the role of biological nitrification inhibition. Nature plants, 3(6), 1-10.

Gaihre, Y. K., Singh, U., Islam, S. M. M., Huda, A., Islam, M. R., Sanabria, J., Satter, M.A., Islam, M.R., Biswas, J.C., Jahiruddin, M. & Jahan, M. S. (2018). Nitrous oxide and nitric oxide emissions and nitrogen use efficiency as affected by nitrogen placement in lowland rice fields. Nutrient Cycling in Agroecosystems, 110(2), 277-291.

Hossain, M. B., Jahiruddin, M., Chowdhury, M. A., Naser, H. M., Anwar, M. M., Islam, A., Haque, M. A., Alim, M. A., Hossain, G. M. A., Islam, M. A., Hossain, A., Satter, M. A., & Alam, F. (2024). Fertilizer Recommendation Guide-2024. Bangladesh Agricultural Research Council (BARC), Farmgate, Dhaka-1215, Bangladesh. https://apps.barc.gov.bd/fertilizer_recommendation/FRG%20English%2030.10.2024.pdf

Islam, M. N., Bell, R. W., Barrett-Lennard, E. G., & Maniruzzaman, M. (2025). Shallow drains and straw mulch alleviate multiple constraints to increase sunflower yield on a clay-textured saline soil I. Effects of decreased soil salinity, waterlogging and end-of-season drought. European journal of agronomy, 162, 127416.

Islam, M. N., Bell, R. W., Barrett-Lennard, E. G., & Maniruzzaman, M. (2022). Growth and yield responses of sunflower to drainage in waterlogged saline soil are caused by changes in plant-water relations and ion concentrations in leaves. Plant and Soil, 479(1), 679-697.

Islam, M. N., Alam, F., Saha, P. K., Shah, A. L., Islam, A., & Biswas, J. C. (2015). Effect of magic growth on rice yield. Bangladesh Rice Journal, 19(2), 91-97.

Islam, M. N., Islam, A., & Biswas, J. C. (2016). Genotypic variations in modern rice and nitrogen use efficiency. International Journal of Agricultural Papers, 1(2), 27-35.

Islam, M. N., Rahman, M. M., Mian, M. J. A., Barua, R., & Kamal, A. M. (2013a). Leaching loss of NPKS in silty soil under alternate wetting and drying condition. Eco-friendly Agriculture Journal, 6(04), 67-71.

Islam, M. N., Rahman, M. M., Mian, M. J. A., Barua, R., & Kamal, A. M. (2013b). Leaching loss of NPKS in the Old Brahmaputra Floodplain soil under continuous standing water condition. Eco-friendly Agriculture Journal, 6(04): 63-66

Islam, S. M. M., Gaihre, Y. K., Islam, M. N., Jahan, A., Sarkar, M. A. R., Singh, U., Islam, A., Al Mahmud, A., Akter, M., & Islam, M. R. (2024). Effects of integrated nutrient management and urea deep placement on rice yield, nitrogen use efficiency, farm profits and greenhouse gas emissions in saline soils of Bangladesh. Science of the Total Environment, 909, 168660.

Islam, S. M. M., Gaihre, Y. K., Islam, M. N., Suvo, T. P., Sander, B. O., Habib, M. A., Islam, A., Nayak, S., Singh, U., Hasegawa, T., & Islam, M. R. (2025). Reducing greenhouse gas emissions and improving rice yield: The influence of cultivars, soil salinity, and nitrogen management. Science of The Total Environment, 997, 180192.

Islam, S. M. M., Gaihre, Y. K., Biswas, J. C., Jahan, M. S., Singh, U., Adhikary, S. K., Satter, M. A., & Saleque, M. A. (2018). Different nitrogen rates and methods of application for dry season rice cultivation with alternate wetting and drying irrigation: Fate of nitrogen and grain yield. Agricultural Water Management, 196, 144-153.

Islam, S. M. M., Gaihre, Y. K., Islam, M. R., Islam, A., Singh, U., & Sander, B. O. (2023). Effects of integrated plant nutrition systems with fertilizer deep placement on rice yields and nitrogen use efficiency under different irrigation regimes. Heliyon, 9(12).

Jakhar, A. M., Aziz, I., Kaleri, A. R., Hasnain, M., Haider, G., Ma, J., & Abideen, Z. (2022). Nano-fertilizers: A sustainable technology for improving crop nutrition and food security.

NanoImpact, 27, 100411.

Kekeli, M. A., Wang, Q., & Rui, Y. (2025). The role of nano-fertilizers in sustainable agriculture: Boosting crop yields and enhancing quality. Plants, 14(4), 554.

Khundi, Q., Jiang, Y., Sun, Y., & Rui, Y. (2025). Nanofertilizers for Sustainable African Agriculture: A Global Review of Agronomic Efficiency and Environmental Sustainability. Nanomaterials, 15(5), 390.

Kule, E. K., Obia, A., Agole, D., Okello, D. M., & Odongo, W. (2025). Farmer perceptions and their implications for adoption of sustainable agricultural intensification practices. Discover Sustainability, 6(1), 210.

Maaz, T. M., Dobermann, A., Lyons, S. E., & Thomson, A. M. (2025). Review of research and innovation on novel fertilizers for crop nutrition. npj Sustainable Agriculture, 3(1), 25.

Mainuddin, M., Karim, F., Gaydon, D. S., & Kirby, J. M. (2021). Impact of climate change and management strategies on water and salt balance of the polders and islands in the Ganges delta. Scientific reports, 11(1), 7041.

Namasharma, S., Pahari, A., Banik, A., Pal, S., Sana, M., Pal, S., & Banerjee, H. (2023). Impact of foliar applied nano-urea on growth, productivity and profitability of hybrid rice (*Oryza sativa* L.). Oryza, 60(3), 464-472.

Ngatia, L., & Taylor, R. (2018). Phosphorus eutrophication and mitigation strategies. In H. Ohtake, & S. Tsuneda (Eds.), Phosphorus-recovery and recycling (pp. 45-61). InTech, Rijeka, Croatia.

Nongbet, A., Mishra, A. K., Mohanta, Y. K., Mahanta, S., Ray, M. K., Khan, M., Baek, K.H., & Chakrabartty, I. (2022). Nanofertilizers: a smart and sustainable attribute to modern agriculture. Plants, 11(19), 2587.

Rahman, M. S., Islam, M. N., Hassan, M. Z., Islam, S. A., & Zaman, S. K. (2014). Impact of water management on the arsenic content of rice grain and cultivated soil in an arsenic contaminated area of Bangladesh. Journal of Environmental Science and Natural Resources, 7(2), 43-46.

Raun, W. R., Solie, J. B., Johnson, G. V., Stone, M. L., Mullen, R. W., Freeman, K. W., Thomason, W.E., & Lukina, E. V. (2002). Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. Agronomy Journal, 94(4), 815-820.

Reddy, K. S., Shivay, Y. S., Kumar, D., Pooniya, V., Prasanna, R., Mandi, S., Nayak, S., Baral, K., Alekhya, G., & Borate, R. B. (2025). Relative performance of granulated and nano urea on productivity and nitrogen use efficiency of wheat–rice sequence. Plant Nano Biology, 11, 100131.

Saha, P. K., Islam, S., Islam, M. N., Biswas, J. C., & Haque, M. M. (2016). Soil plant nutrient status under intensive rice-farming systems in unfavorable eco-systems of Bangladesh. International Journal of Chemical and Pharmaceutical, 2(2), 1-13.

Sahoo, B. R., Dash, A. K., Mohapatra, K. K., Mohanty, S., Sahu, S. G., Sahoo, B. R., Prusty, M., & Priyadarshini, E. (2024). Strategic management of nano-fertilizers for sustainable rice yield, grain quality, and soil health. Frontiers in Environmental Science, 12, 1420505.

Sweety, R., Boominathan, P., Senthil, A., Jegadeeswari, D., & Kumar, G. P. (2024). Nano-diammonium phosphate enhances grain yield by modulating gas exchange traits and nutrient use efficiency in rice. Plant Science Today, 11(sp4).

UN FAO. (2025). Our World in Data. “Production: Crops and livestock products” [original data]. Food and Agriculture Organization of the United Nations. Retrieved August 19, 2025 from https://archive.ourworldindata.org/20250731-180103/grapher/rice-production.html

Upadhyay, P. K., Dey, A., Singh, V. K., Dwivedi, B. S., Singh, T., GA, R., Babu, S., Rathore, S.S., Singh, R.K., Shekhawat, K., & Shukla, G. (2023). Conjoint application of nano-urea with conventional fertilizers: An energy efficient and environmentally robust approach for sustainable crop production. Plos one, 18(7), e0284009.

Xia, Y., Zhang, M., Tsang, D. C., Geng, N., Lu, D., Zhu, L., Igalavithana, A. D., Dissanayake, P. D., Rinklebe, J., Yang, X., & Ok, Y. S. (2020). Recent advances in control technologies for non-point source pollution with nitrogen and phosphorous from agricultural runoff: current practices and future prospects. Applied Biological Chemistry, 63(1), 8.

Xiong, L., Wang, P., Hunter, M. N., & Kopittke, P. M. (2018). Bioavailability and movement of hydroxyapatite nanoparticles (HA-NPs) applied as a phosphorus fertiliser in soils. Environmental Science: Nano, 5(12), 2888-2898.

Yu, X., Keitel, C., & Dijkstra, F. A. (2021). Global analysis of phosphorus fertilizer use efficiency in cereal crops. Global Food Security, 29, 100545.

Zhang, H., Zheng, T., Wang, Y., Li, T., & Chi, Q. (2024). Multifaceted impacts of nanoparticles on plant nutrient absorption and soil microbial communities. Frontiers in plant science, 15, 1497006.

Zou, T., Zhang, X., & Davidson, E. A. (2022). Global trends of cropland phosphorus use and sustainability challenges. Nature, 611(7934), 81-87.