Annals of Bangladesh Agriculture
Journal homepage: gau.edu.bd/aba

ORIGINAL ARTICLE

Improving rice productivity and profitability through efficient use of nitrogen and phosphorus fertilizers

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ARTICLE INFO.

Keywords:

rice, nutrient use efficiency, economic benefit.

Received : 13 October 2025
Revised : 13 November 2025
Accepted : 24 December 2025
Published : 05 January 2026

Citation:

Ferdous, J., G. Akther, M. A. Hoque and T. S. Hoque. 2026. Improving rice productivity and profitability through efficient use of nitrogen and phosphorus fertilizers. *Ann. Bangladesh Agric.* 29(2): 157-174

ABSTRACT

Nitrogen (N) and phosphorus (P) are essential for rice production, and diammonium phosphate (DAP), which supplies both N and P may provide agronomic and environmental advantages relative to urea. We evaluated seven fertilization strategies in BRRI dhan49: control (T_1), urea at N rate but no P (T_2), DAP at the N rate (T_3), urea at N rate + TSP at P rate (T_4), DAP at the P rate (T_5), no N and no P (T_6), and DAP at P rate + urea at N rate (T_7). Treatments were assessed for growth, yield, nutrient uptake, and post-harvest soil fertility. Fertilization significantly affected all parameters. T_7 produced the highest plant height (94.7 cm) and grain yield (5.65 t ha^{-1}), followed by T_4 (93.9 cm; 5.12 t ha^{-1}). Relative to the control, T_7 increased grain yield by 41% and total plant N uptake by ~75%, and it delivered the highest values for key yield components (panicle length, tillers $hill^{-1}$, and filled grains $panicle^{-1}$). Post-harvest soils under T_7 and T_4 showed elevated organic C, total N, and available P, indicating improved fertility. Profitability analysis identified T_7 as the most lucrative fertilized option (net return 5.08×10^6 Tk ha^{-1}) and T_5 as the most cost-efficient (BCR 3,825) due to minimal input cost. Collectively, a regimen combining basal DAP with split urea applications enhances yield, nutrient uptake, and soil fertility while maintaining strong economic performance in BRRI dhan49.

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https://doi.org/10.3329/aba.v29i2.84947
ISSN 1025-482X (Print)/2521-5477 (Online)

Introduction

Rice (*Oryza sativa* L.) is a staple food crop for nearly half of the global population and plays a critical role in food security and economic development, particularly in Asia. As the third-largest producer and consumer of rice, Bangladesh relies heavily on this crop, which contributes approximately 18% to the national GDP (Mamun *et al.*, 2021; Manzoor *et al.*, 2006). Enhancing rice productivity is essential to meet the growing food demand, and among the various agronomic inputs, fertilizer application remains one of the most influential factors in increasing yield potential (Alam *et al.*, 2009). Nitrogen (N), phosphorus (P), and potassium (K) are the three primary macronutrients fundamental to plant growth. Among these, N and P are especially critical due to their involvement in key physiological and biochemical processes. Nitrogen is essential for vegetative growth, chlorophyll production, and grain yield formation, while P plays a central role in energy transfer, nucleic acid synthesis, root development, and early crop establishment (Dick, 2011; Zhang and Raun, 2006; Ma *et al.*, 2022). As a result, balanced and efficient fertilization strategies that enhance nutrient use efficiency (NUE) while minimizing environmental losses are necessary for sustainable rice cultivation.

Urea is the mostly used nitrogenous fertilizer in Bangladesh. However, its NUE is relatively low—typically around 35–40% with substantial N losses occurring through volatilization, leaching, and denitrification, especially under tropical conditions (Khalil *et al.*, 2003; Sun *et al.*, 2012). In response to these challenges, several N-saving technologies have been developed, such as the use of urea super granules (USG), controlled-release fertilizers, and nitrification/urease inhibitors (Spiertz, 2010). However, widespread adoption of USG is limited due to the high labor requirements for deep placement. Phosphorus fertilizers such as triple super phosphate (TSP), single super phosphate (SSP), and di-ammonium phosphate (DAP) are integral components of nutrient management in rice production systems. Among these, DAP stands out due to its dual nutrient content, supplying 18% N and 46% P_2O_5, thereby offering a strategic advantage as a compound fertilizer. Its potential to simultaneously meet crop demands for both N and P positions as a promising alternative to the conventional practice of applying urea and TSP separately. However, despite its agronomic relevance and commercial availability, limited research has addressed the comparative performance of DAP in place of discrete N and P sources under the specific agro-ecological and management conditions of Bangladeshi rice-based systems. Recognizing the need for more integrated and efficient fertilization strategies, this study was undertaken to examine the agronomic effectiveness and environmental implications of replacing urea and TSP with DAP. The investigation specifically aimed to: (i) compare the efficiency of DAP and urea as N sources in rice cultivation, and (ii) evaluate the feasibility of utilizing DAP as a combined source of N and P, in lieu of conventional urea and TSP applications.

Materials and Methods

Experimental site and initial soil properties

The experiment was conducted during the late monsoon to early winter season i.e., Aman season (July–November 2023) at Soil Science Field Laboratory, BAU. The experimental site is located at 24.70°N latitude and 90.50°E longitude, with an elevation of 18 meters above sea level. The field lies on medium-high land, classified as non-calcareous dark grey floodplain soil, and falls under the Old Brahmaputra Floodplain zone. The area experiences a subtropical climate, marked by high temperatures and moderate to heavy rainfall during the kharif season (April to September), and cooler temperatures during the rabi season (October to March). The physicochemical properties of soil are given in the table 1.

Experimental design and treatments

The experiment followed a Randomized Complete Block Design (RCBD) with 3 blocks (replications), each divided into 7 treatment plots, totaling 21 plots (3 × 7). Each plot measured 4 m × 2.5 m, with 50 cm drains separating the blocks. The test crop was BRRI dhan49, a high yielding variety of Aman season. Forty-day-old seedlings were transplanted at 25 cm × 15 cm spacing, with three healthy seedlings per hill. The experiment comprised seven treatment combinations designed to evaluate the effects of different nitrogen (N) and phosphorus (P) fertilizer sources and application strategies on rice cultivation. The treatments were as follows: T_1 served as the control with no supply of N, P, K, S, or Zn fertilizers. T_2 involved N application from urea in three splits without any phosphorus supplied through TSP. T_3 received N from di-ammonium phosphate (DAP) in three splits. T_4 included N from urea along with P from TSP. In T_5, both N and P were supplied from DAP at a rate equivalent to the required phosphorus dose, with no additional nitrogen provided. T_6 was devoid of both N and P applications. Finally, T_7 combined N and P from DAP with additional N from urea applied in two splits. According to the Fertilizer Recommendation Guide (FRG, 2018), N, P, K, sulfur (S), and

Table 1 Physicochemical properties of the Experimental Field

Characteristics	Value
pH (Soil: water =1: 2.5)	6.48
Organic matter (%)	1.81
CEC (me $100g^{-1}$ soil)	12.56
Total N (%)	0.173
Available P (ppm)	6.08
Exchangeable K (meq. 100 g^{-1} soil)	0.142
Available S (mg Kg^{-1})	13.75

Table 2. Fertilizer doses according to treatments

Treatments	Fertilizer dose(kg/ha)					
	Urea	DAP	TSP	MoP	Gypsum	$ZnSO_4$
T1	0	0	0	0	0	0
T2	196	0	0	20	22.2	4.95
T3	0	500	0	20	22.2	4.95
T4	196	0	40	20	22.2	4.95
T5	0	40	0	20	22.2	4.95
T6	0	0	0	20	22.2	4.95
T7	180	40	0	20	22.2	4.95

Here, T_1: control (no fertilizer), T_2: N from urea (3 split; No supply of P by TSP), T_3: N from DAP (3 split), T_4: N from urea + P from TSP, T_5: NP from DAP (No additional N) at P rate, T_6: no supply of N or P, T_7: NP from DAP + N from urea (2 split). Means with the same letters within the same column do not differ significantly.

zinc (Zn) were applied at rates of 90, 8, 10, 4, and 1 kg ha^{-1}, respectively, using urea, DAP, TSP, MoP, gypsum, and zinc sulfate. All fertilizers, except urea, were applied as a basal dose during final land preparation before transplanting. Urea was applied in three equal top-dressings: at 15, 30 (active tillering), and 50 (panicle initiation) days after transplanting. Intercultural practices like gap filling, weeding, and pest control were carried out as needed throughout the growing period. The nutrient inputs are detailed in Table 2.

Harvesting and sample analysis

The crop was harvested on 22 Nov 2023 at full maturity. The crop was cut at the ground level and plot wise crop was bundled separately and brought to the threshing floor. Then harvested crop was threshed separately. Grain and straw yields were recorded plot wise and expressed as t ha^{-1} on 14% moisture basis. Five hills were randomly selected from each plot at maturity to record yield contributing characters like plant height, number of tillers $hill^{-1}$, panicle length, number of grains $panicle^{-1}$ and 1000-grain weight. Plant samples collected from the field experiment were analyzed for N, P, K, and S contents. Grain and straw samples were dried in an oven at about 65 ^{0}C for 48 hours and then ground in a grinding mill to pass through a 20 mesh sieve. The methods followed in plant analyses (grain and straw) were as follows. The samples were ground and analyzed for N, P, K and S contents following standard methods (H_2SO_4 digestion for N and HNO_3-$HClO_4$ digestion for P, K & S) in the Department of Soil Science. Nitrogen was measured by distillation with 40% NaOH, followed by titration with 0.01 N H_2SO_4. Phosphorus was estimated using a spectrophotometer after color development with Barton solution. Potassium was analyzed with a flame photometer at 880 nm wavelength, while sulfur content was determined turbidimetrically using a spectrophotometer at 420 nm wavelength after adding acid seed and turbidimetric solutions.

Collection, preparation and analysis of soil samples

Soil samples were collected at a depth of 15 cm from the surface. The initial soil samples were collected before fertilizer application to the experimental field. Samples were taken by means of auger after removing weeds, plant, stubbles etc. The composite sample was air dried, ground and sieved through a 20 mesh sieve and stored in a plastic bag for physical and chemical analysis. The organic matter content was calculated by multiplying the percent organic carbon with the van Bemmelen factor 1.724 by following Walkley and Black (1947). The total nitrogen was determined by semi-micro Kjeldahl method. Soil Available P was extracted with 0.5 M $NaHCO_3$ (Olsen P; pH ≈ 8.5; soil:solution = 1:20) by shaking for 30 min and filtering. Phosphate in the extract was quantified by the molybdate–ascorbic acid ("blue") method at 880 nm against KH_2PO_4 standards. Concentrations are reported on an oven-dry basis as mg P kg^{-1} soil (Olsen *et al*., 1954).

Total P in soil was determined after HNO_3–$HClO_4$ digestions to a clear solution, with phosphate quantified by the same molybdate–ascorbic acid colorimetry at 880 nm. For reporting, total P was expressed as kg P ha^{-1}.

Calculation

The following formula was used to calculate the amount of N:

$$\% N = \frac{(T\text{-}B) \times N \times 0.014 \times 100}{S}$$

Where,

T = Sample titration value (mL) of standard H_2SO_4, B = Blank titration value (mL) of standard H_2SO_4, N = Strength of H_2SO_4, S = Weight of soil sample in gram

Yield was calculated using the following formula:

Yield (ton per hectare) = grain yield per plot (kg) ×10000/plot size×1000

Nutrient uptake was calculated as follows:

$$\text{Nutrient Uptake (kg N ha}^{-1}\text{)} = \frac{\text{Dry matter yield} \times \text{Nutrient content} \times 1000}{100}$$

Units

Dry matter yield= t ha^{-1}, N, P, K and S content= %, Nutrient uptake = kg ha^{-1}

Economic analysis

Net Return (Tk/ha):

Net Return = Grain Yield Value (Tk/ha) − Fertilizer Cost (Tk/ha)

Benefit-Cost Ratio (BCR):

BCR=Grain Yield Value (Tk/ha) / Fertilizer Cost (Tk/ha)

In this calculation, the price of urea, TSP and DAP were 27, 27 and 21 tk/kg were used.

Statistical analysis

The collected data were analyzed statically by F- test to examine the treatment effect and the mean differences were adjudged by Duncan's Multiple Range Test (DMRT) (Gomez and Gomez, 1984) and ranking was indicated by letters.

Results

Yield contributing parameters

The growth and yield attributes of BRRI dhan49 were significantly influenced by the application of different fertilizer treatments, as summarized in Table 3. Plant height varied markedly among treatments, ranging from 67.5 cm in the control (T_1) to 94.7 cm in T_7. The tallest plants were observed in T_7, followed closely by T_4 (93.9 cm), while the

Table 3. Effect of nitrogen and phosphorus from different chemical sources on yield contributing characters of BRRI dhan49

Treatment	Plant height (cm)	No. of total tillers/hill	No. of effective tiller/hill	Panicle length (cm)	No. of filled grain/ panicle	No. of unfilled grain/ panicle	Thousand grain weight (g)
T1	67.5 ± 1.03 b	14.6 ± 0.99	12.0 ± 0.23 b	12.3 ± 0.58 c	122 ± 2.50 c	12.7 ± 0.86 a	21.4 ± 0.52
T2	90.9 ± 0.33a	15.3 ± 0.71	13.5 ± 0.63 ab	21.4 ± 0.26 a	154 ± 3.17 b	12.3 ± 0.47 a	22.3 ± 0.31
T3	93.5 ± 1.37 a	16.2 ± 0.91	14.3 ± 0.30 a	21.7 ± 0.62 a	158 ± 2.74 b	12.1 ± 1.70 a	21.9 ± 0.39
T4	93.9 ± 0.68 a	14.8 ± 1.28	13.2 ± 0.86 ab	22.1 ± 0.31 a	176 ± 0.67 a	11.8 ± 1.30 a	21.5 ± 0.47
T5	74.6 ± 2.53 b	13.0 ± 1.05	11.8 ± 0.71 b	16.6 ± 1.64 b	145 ± 0.90 b	12.4 ±1.34 a	21.0 ± 0.44
T6	74.8 ± 2.14 b	14.7 ± 0.11	13.1 ± 0.20 ab	16.3 ± 0.53 b	129 ± 4.82 c	10.3 ± 1.46 a	21.1 ± 0.49
T7	94.7 ± 2.01 a	16.3 ± 0.39	14.7 ± 0.38 a	22.0 ± 0.31 a	181 ± 4.02 a	9.2 ± 0.97 b	21.5 ± 0.10
Level of sig.	**	ns	*	**	**	**	ns

*significant at 5% level of probability, ** means 1% level of probability. T_1: control (no fertilizer), T_2: N from urea (3 split; No supply of P by TSP), T_3: N from DAP (3 split), T_4: N from urea + P from TSP, T_5: NP from DAP (No additional N) at P rate, T_6: no supply of N or P, T_7: NP from DAP + N from urea (2 split). Means with the same letters within the same column do not differ significantly.

shortest plants were found in T_1, which was significantly lower than all other treatments. This suggests that the application of DAP, particularly in combination with urea, enhanced plant height compared to the sole application of urea. Similarly, the number of effective tillers per hill ranged from 12.0 to 14.7, with the highest number recorded in T_7, which was statistically at par with T_2, T_3, and T_4. The lowest number of effective tillers was observed in T_1, reflecting the negative impact of nutrient omission. Panicle length also varied significantly among treatments, ranging from 12.3 cm to 22.1 cm. The longest panicles were observed in T_4, followed by T_2, T_3, and T_7, all of which were statistically similar, while the shortest panicle length was found in the control treatment (T_1). The number of filled grains per panicle ranged from 122 to 181, with T_7 producing the highest number, statistically comparable to T_4. These two treatments (T_4 & T_7) outperformed the others, including T_1, T_2, T_3, T_5, and T_6, which were statistically similar but inferior. In terms of unfilled grains per panicle, only T_7 showed a statistically significant difference from the other treatments, with the overall range being 9.2 to 12.7 grains. The 1000-grain weight of BRRI dhan49 varied slightly between 21.4 g and 22.3 g across treatments; however, no statistically significant differences were observed, indicating that grain weight was not markedly affected by the different fertilizer treatments.

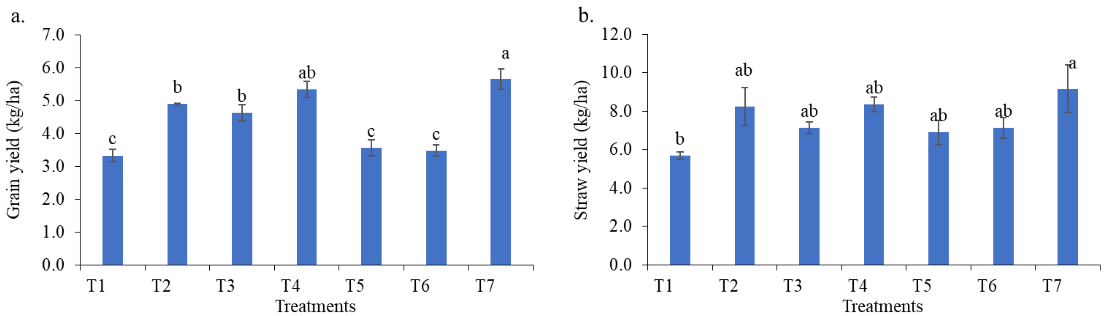

Fig. 1. Effects of nitrogen and phosphorus from different chemical sources on (a) grain and (b) straw yield of BRRI dhan49; Here, T_1: control (no fertilizer), T_2: N from urea (3 split; No supply of P by TSP), T_3: N from DAP (3 split), T_4: N from urea + P from TSP, T_5: NP from DAP (No additional N) at P rate, T_6: no supply of N or P, T_7: NP from DAP + N from urea (2 split). Bar represents standard errors of mean and with different letters vary significantly to each other.

Table 4. Effect of chemical fertilizers on N and P uptake by BRRI dhan49

Treatments	N (kg ha^{-1})		P (kg ha^{-1})	
	Grain	Straw	Grain	Straw
T1	22.8 ± 0.09 g	36.9 ± 0.01 d	7.74 ± 0.00 f	1.20 ± 0.05 c
T2	31.6 ± 0.01d	27.7± 0.00 f	6.26 ± 0.00 g	1.38 ± 0.01 b
T3	33.2 ± 0.01 c	39.9 ± 0.01 c	11.4 ± 0.00 c	1.54 ± 0.05 b
T4	38.8 ± 0.01 b	42.1 ± 0.00 b	15.7 ± 0.01 a	2.26 ± 0.31 a
T5	27.2 ± 0.00 f	25.5 ± 0.01 g	8.15 ± 0.00 e	2.24 ± 0.02 a
T6	21.4 ± 1.9 g	31.9 ± 0.00 e	9.91 ± 0.01 d	1.45 ± 0.18 b
T7	41.1 ± 0.00 a	51.4 ± 0.00 a	14.4± 0.02 b	2.87 ± 0.83 a

***= significant at 0.1% level of probability. Here, T_1: control (no fertilizer), T_2: N from urea (3 split; No supply of P by TSP), T_3: N from DAP (3 split), T_4: N from urea + P from TSP, T_5: NP from DAP (No additional N) at P rate, T_6: no supply of N or P, T_7: NP from DAP + N from urea (2 split). Means with the same letters within the same column do not differ significantly.

Table 5. Effect of chemical fertilizers on K and S uptake by BRRI dhan49

Treatments	K (kg ha^{-1})		S (kg ha^{-1})	
	Grain	Straw	Grain	Straw
T1	36.3 ± 0.02 f	55.4 ± 0.02 g	1.35 ± 0.01 d	2.85 ± 0.02 e
T2	39.0 ± 0.02 e	93.8 ± 0.00 c	1.39 ± 0.01 d	4.47 ± 0.01 b
T3	46.9 ± 0.01 b	88.1 ± 0.01 d	1.52 ± 0.01 c	3.57 ± 0.03 c
T4	55.6 ± 2.00 a	99.0 ± 0.03 b	1.53 ± 0.02 c	3.53 ±0.03 c
T5	41.6 ± 0.01 d	56.2 ± 0.00 f	2.05 ± 0.02 b	2.28 ± 0.01 f
T6	44.6 ± 0.01 c	77.6 ± 0.02 e	1.34 ± 0.02 d	2.98 ± 0.01 d
T7	55.2 ± 1.08 a	108.7 ± 0.00 a	2.34 ± 0.00 a	7.08 ± 0.01 a

***= significant at .1% level of probability. Here, T_1: control (no fertilizer), T_2: N from urea (3 split; No supply of P by TSP), T_3: N from DAP (3 split), T_4: N from urea + P from TSP, T_5: NP from DAP (No additional N) at P rate, T_6: no supply of N or P, T_7: NP from DAP + N from urea (2 split). Means with the same letters within the same column do not differ significantly.

Grain yield

The grain yield of BRRI dhan49 responded significantly due to various treatments ranged from 3.33 to 5.65 t ha^{-1}. All the treatments showed higher grain yield over control (Fig. 1a). Grain yield was found higher in T_7 which was statistically dissimilar to all the treatments, except T_4. Treatments $T_{2,}$ T_3 and T_4 showed grain yield with no significant differences among each other. Treatments $T_{1,}$ T_5 and T_6 also revealed similar characteristic in their grain yield pattern with each other.

The treatment T_7 had 41% and 38% higher grain yield over T_1 and T_6, again 16% and 18% higher than T_2 and T_3, respectively.

Straw yield

Different types of nitrogen and phosphorus sources treatments showed significant differences on straw yield of BRRI dhan49 (Fig. 1b). The straw yield obtained from different treatments ranged from 5.68 to 9.17 t ha^{-1}. The straw yield was higher in T_7 which was statistically different to the T_1 but similar with other treatments.

Effect of treatments on nutrient uptake

Significant variations were observed in the uptake of nitrogen (N), phosphorus (P), potassium (K), and sulfur (S) by both grain and straw of BRRI dhan49 rice in response to different fertilizer treatments, as presented in Tables 4 and 5. Nitrogen uptake by grain and straw was highest in T_7 (41.1 kg ha^{-1} and 51.4 kg ha^{-1}, respectively), while the lowest uptake was recorded in T_6 (21.4 kg ha^{-1} for grain) and T_5 (25.46 kg ha^{-1} for straw). Each treatment exhibited statistically significant differences, and T_7 resulted in a 75% increase in grain N uptake over the control (T_1). Phosphorus uptake by grain and straw was maximized in T_4 (15.7 kg ha^{-1} and 2.26 kg ha^{-1}, respectively), whereas the lowest grain P uptake was found in T_2 (6.26 kg ha^{-1}). For straw P uptake, treatments T_2, T_3 and T_6 were statistically similar, while T_4, T_5 and T_7 formed another statistically similar group. Compared to T_1, grain P uptake was enhanced by 49% in T_4. Potassium uptake by grain was highest in T_4 (55.6 kg ha^{-1}) and T_7 (55.2 kg ha^{-1}), which was statistically similar to each other, while the greatest K uptake by straw occurred in T_7 (108.7 kg ha^{-1}). The lowest K uptake by both grain and straw was recorded in the control treatment T_1 (36.3 and 55.4 kg ha^{-1}, respectively), with all treatments differing

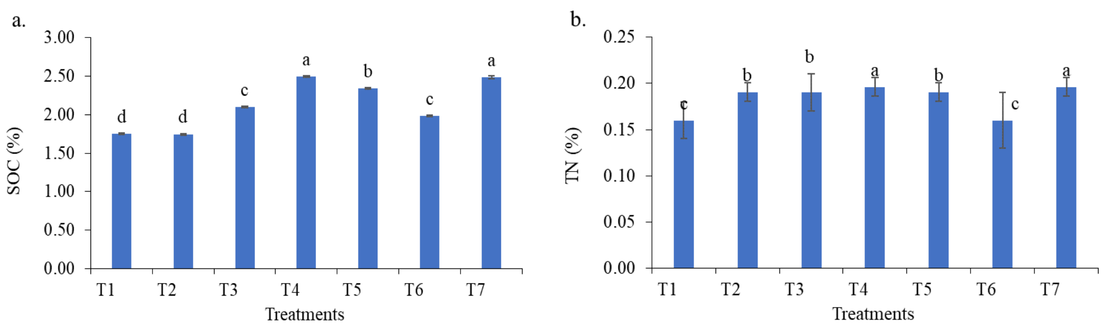

Fig. 2. Effects of chemical fertilizers on SOC and total TN of post-harvest soil; Here, T_1: control (no fertilizer), T_2: N from urea (3 split; No supply of P by TSP), T_3: N from DAP (3 split), T_4: N from urea + P from TSP, T_5: NP from DAP (No additional N) at P rate, T_6: no supply of N or P, T_7: NP from DAP + N from urea (2 split). Bar represents standard errors of mean and with different letters vary significantly to each other.

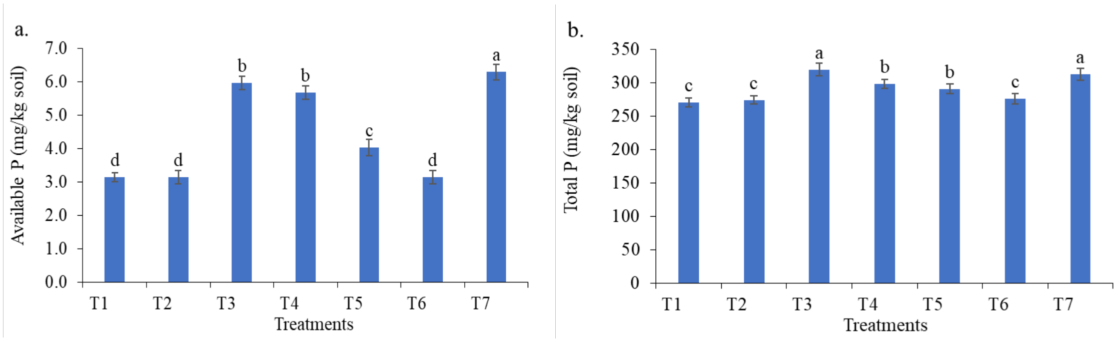

Fig. 3. Effects of chemical fertilizers on (a) soil available phosphorus (SAP) and (b) soil total phosphorus (STP); Here, T_1: control (no fertilizer), T_2: N from urea (3 split; No supply of P by TSP), T_3: N from DAP (3 split), T_4: N from urea + P from TSP, T_5: NP from DAP (No additional N) at P rate, T_6: no supply of N or P, T_7: NP from DAP + N from urea (2 split). Bar represents standard errors of mean and with different letters vary significantly to each other.

significantly. Grain K uptake increased by 34–35% in T_4 and T_7 relative to T_1. Sulfur uptake also varied significantly across treatments, with T7 showing the highest uptake in both grain (2.34 kg ha^{-1}) and straw (7.08 kg ha^{-1}). The lowest S uptake by grain was observed in T_6 (1.34 kg ha^{-1}), and treatments T_1, T_2, and T_6 were statistically similar, as were T_3 and T_4. These findings highlight the positive influence of combined application of DAP and urea, particularly in T_7, on enhancing nutrient uptake efficiency in rice.

Post-harvest Soil Parameters

Soil organic carbon and total nitrogen

Significant differences among the treatments were found on post-harvest analysis of soil for SOC and TN. Treatment T_7 being

Table 6. Economic Performance of Different Treatments Based on Fertilizer Costs, Grain Yield, Net Returns, and Benefit-Cost Ratios (BCR)

Treatment	Fertilizer Cost (Tk/ha)	Grain Yield Value (Tk/ha)	Net Return (Tk/ha)	BCR
T1	0	2995655	2995655	∞
T2	5292	4581344	4576052	865.71
T3	10500	4158507	4148007	396.05
T4	6372	4797781	4791409	752.95
T5	840	3212737	3211897	3824.69
T6	0	3125901	3125901	∞
T7	5700	5085235	5079535	892.15

Here, T_1: control (no fertilizer), T_2: N from urea (3 split; No supply of P by TSP), T_3: N from DAP (3 split), T_4: N from urea + P from TSP, T_5: NP from DAP (No additional N) at P rate, T_6: no supply of N or P, T_7: NP from DAP + N from urea (2 split). Means with the same letters within the same column do not differ significantly.

similar with T_4 was found to contribute more in the accumulation of SOC than other treatments and the lowest was found in T_1 and T_2 significantly (Fig. 2a). Urea and DAP showed a similar effect on TN accumulation, as observed in T_2, T_3, and T_5 (Fig. 2b). A significant variation in treatments for TN accumulation was found, where T_1 and T_6 had similar rate of TN and T_7 along with T_4 had the higher TN.

Soil total and available phosphorus

Different sources of P addition had significant effect on the soil total and available P (Fig 3a and 3b). The addition of DAP or TSP remarkably increased soil P content than soils with no supply of P sources. The maximum value of available P (6.3 mg/kg) was observed in T_7 due to the addition of DAP, followed by T_4 (5.67 mg/kg) and the minimum was (3.14-3.15 mg/kg) in T_1, T_2 and T_6. Similarly, the total P was higher (320 mg/kg) in T_3, being similar with T_7 (312 mg/kg) and lower value was in T_1 (271 mg/kg soil). Addition of DAP increased P availability by 9% over the TSP.

Cost benefit of fertilizer use

The profitability analysis of seven treatments (T_1 to T_7) revealed significant differences in economic efficiency (Table 6). Treatments T_1 and T_6, which incurred no fertilizer costs, achieved net returns equal to their grain yield values of 2,995,655 Tk/ha and 3,125,901 Tk/ha, respectively, with infinite benefit-cost ratios (BCR). Among the treatments that utilized fertilizers, T_7 demonstrated the highest profitability, producing a grain yield value of 5,085,235 Tk/ha, a net return of 5,079,535 Tk/ha, and a BCR of 892.15. Similarly, T_5 achieved the highest BCR of 3,824.69 due to its minimal fertilizer cost of 840 Tk/ha, highlighting its cost-efficiency despite a moderate grain yield value of 3,212,737 Tk/ha. There, T_4 and T_2 also performed well, yielding net returns of 4,791,409 Tk/ha and 4,576,052 Tk/ha, with BCRs of 752.95 and 865.71, respectively. In contrast, T_3 showed the highest fertilizer cost of 10,500 Tk/ha, and a relatively low BCR of 396.05 was recorded which suggesting diminished profitability despite its grain yield value of 4,158,507 Tk/ha. These findings underscore that higher fertilizer costs do not necessarily translate to higher profitability, as evidenced by T_7 achieving superior economic returns with a moderate fertilizer cost. Overall, T_7 emerged as the most profitable treatment, combining high grain yield and reasonable input costs, while T_5 demonstrated that minimal input costs can achieve exceptional cost-efficiency, emphasizing the potential for optimized resource use in enhancing agricultural profitability.

Discussion

Yield components

Nitrogen and phosphorus source and combination significantly influenced the growth and productivity of BRRI dhan49. The combined application of urea and DAP (T_7) gave consistently higher values than single-source treatments because basal P from DAP and split-applied N from urea maintained a sustained nutrient supply in the root zone. Plant height reached 94.7 cm under T_7, in line with reports that DAP + urea produces the tallest plants and that height generally increases with greater N and P inputs (Saleem *et al*., 2024; Amare *et al*., 2019). Mechanistically, P via its role in ATP and energy transfer—supports cell division and elongation, promoting taller plants (Khan *et al*., 2023). Tiller production also responded strongly: the highest tillers hill^{-1} (15) occurred under T_7, consistent with robust N effects on tillering (e.g., 27.6 tillers at 150 kg N ha^{-1}; Yoseftabar, 2012) and with P-driven stimulation of root growth and tiller initiation (Panhwar *et al*., 2011). Panicle length increased with N fertilization and with combined N×P relative to no-N/P controls (Bahmanyar and Mashaee, 2010). Reproductive performance reflected this improved nutrition. The maximum grains panicle^{-1} (181) occurred in T_7, where DAP was applied at land preparation and urea was split during crop growth, ensuring nutrient availability through flowering and grain filling. Prior studies similarly show positive effects of basal P on filled grains and synergistic N×P effects on grain number (Ismunadji & Uexküll, 1974; Shi *et al*., 1990); for comparison, 300 kg urea ha^{-1} yielded 147.5 grains panicle^{-1} versus 111.8 under farmers' practice (Karim *et al*., 2019). These advantages translated into yield: T_7 (NP from DAP + supplemental N from urea) produced the highest grain and straw yields (5.60 and 9.17 t ha^{-1}, respectively), whereas the lowest grain yield (3.33 t ha^{-1}) and straw yield (5.68 t ha^{-1}) were recorded in the control (T_1) and the DAP-only at P rate (T_5), respectively. Yield gains tracked N supply via greater biomass accumulation, longer panicles, and higher panicle density (Bahmaniar and Ranjbar, 2007). Agronomically, splitting urea into 2–3 applications reduces losses and synchronizes N supply with crop demand, while DAP improves P availability, leaf area, light-use efficiency, and carbohydrate partitioning to grains—thereby increasing thousand-grain weight and overall yield (Al-Khuzai and Al-Juthery, 2020; Zhang *et al*., 2003). Consistent with this mechanism, DAP + urea has raised yield by ~45% over the control in independent studies (Shwe *et al*., 2019). Overall, combining basal DAP with well-timed split urea applications optimizes yield-contributing traits and maximizes BRRI dhan49 productivity.

Nutrient content and uptake

The results showed that the uptake and accumulation of various nutrients, including N, K and S in grain and straw, were significantly increased with application of urea and DAP fertilizers combindly. In case of rice grain and straw, the highest N uptake result was found in treatment T_7. Again, in case of P uptake by grain and straw, highest result was found in treatment T_4 (N from urea + P from TSP) as plant uptake more phosphorus from TSP fertilizer. Compared to nitrogen fertilizer alone, combined application of nitrogen and phosphorus enhanced grain yield and nitrogen uptake by stimulating root growth, which in turn reduced soil NO_3^- accumulation (Wen *et al*., 2016). When PU fertilizer was applied with the tested phosphorus fertilizers, PU with DAP gave the higher NUE than with TSP. The combination of phosphorus fertilizers with urea and USG resulted in higher phosphorus use efficiency (PUE) compared to the application of phosphorus fertilizer alone (Shwe *et al.*, 2019). It showed that application of N fertilizer without P fertilizer or application of P fertilizer without N fertilizer cannot get the better nutrient use efficiency. Zheng *et al*, 2023 reported that increased plant growth required both N and P that are mutually synergistic effects result in growth stimulation and enhanced nutrient uptake. Combined use of nitrogen and phosphorus from urea and DAP fertilizers can stimulate plants to consume and gradually accumulate N, P, K and S nutrient content in their bodies, thereby ultimately achieving optimum growth and productivity (Dash *et al.*, 2015).

Soil parameters

The post-harvest soil analysis revealed significant effects of treatment combinations on SOC, TN, and P levels. These findings highlight the critical role of balanced nutrient management in sustaining soil fertility and productivity.

Soil organic carbon (SOC) and total nitrogen (TN)

The SOC levels were highest in T_7 and T_4, indicating that treatments combining both N and P inputs can enhance organic carbon accumulation. This improvement can be attributed to increased biomass production and subsequent organic matter return to the soil, as well as improved microbial activity due to balanced nutrient availability (Xu *et al.*, 2021). Proper and balanced application of nitrogen and phosphorus fertilizers is key to improving their efficiency and promoting better crop growth, soil organic matter, and overall soil health (Solomon and Saddiq, 2019). The lowest SOC levels in T_1 and T_2 suggested the importance of P in complementing N inputs to sustain organic carbon storage. The TN levels followed a similar trend, with T_7 and T_4 showing the highest accumulation. The addition of DAP (T_7) or TSP (T_4) likely improved N retention by facilitating better nutrient uptake and reducing losses through leaching or volatilization (Liang *et al.*, 2018). This finding aligns with reports that balanced fertilization optimizes nutrient cycling and minimizes nutrient losses (Zhang *et al.*, 2020). In contrast, T_1 and T_6 (no N or P supply) had the lowest TN levels, underscoring the adverse effects of nutrient omission on soil N-P reserves. Immediately the application of urea, it undergoes hydrolysis to produce ammonium by ammonification process for moving to further processes such as nitrification, denitrification but in case of DAP there is no need of ammonification since N is already present in ammonium form, so within short time the possibility of N loss is high from DAP than from urea. However, interestingly, the similar TN levels observed in T_2 (urea), T_3 (DAP), and T_5 (NP from DAP at P rate) indicate that both urea and DAP effectively supply N but irrespective to nutrient source, retention of N residue is limited for next crop. In line with our result, it was also supported by Ferdous *et al* (2023) that N is highly volatile nutrient.

Soil total and available phosphorus (P)

The treatments significantly affected both total and available P levels, the highest available P observed in T_7. The addition of DAP in T_7 and T_3 led to the greatest increase in available P, while T_4 (P from TSP) also showed elevated P levels. This confirms the efficacy of DAP and TSP as reliable P sources for enhancing soil P availability. The substantial increase in total P (2–11% over control) in treatments receiving external P inputs aligns with findings by Wako *et al*. (2024), who reported that P supplementation replenishes soil P reserves and ensures long-term fertility. The lowest P levels in T1 (control), T_2 (urea only), and T_6 (no N or P supply) highlight the depletion of soil P in the absence of external inputs. This aligns with previous studies indicating that continuous cropping without P supplementation accelerates soil P exhaustion, limiting crop productivity (Gupta *et al.*, 2020).

The results emphasized the importance of balanced nutrient application in maintaining soil health. The T_7, which combined urea and DAP inputs for N and P sources, proved most effective in improving SOC, TN, and P levels. This treatment likely benefited from synergistic effects of N and P, optimizing nutrient availability and uptake. On the other hand, treatments with limited or no P inputs, such as T_1, T_2, and T_6, demonstrated poor soil fertility outcomes, indicating the risks of P omission. In contrast the higher P in post harvest soil may be due to the high rate application of P source. Finally, it can be concluded that, both combinations, such as urea and DAP and urea and TSP were effective in crop production. The DAP supplied both N and P but urea was used only for N and TSP for P. Therefore, the application of DAP at required P rate and rest of the N from urea will be beneficial for both economically and environmentally.

Conclusion

The findings of this study suggest that DAP, with its dual nutrient composition, is an efficient and cost-effective alternative to conventional fertilizers such as urea and TSP. Its ability to improve crop productivity while maintaining long-term soil fertility makes it an environmentally sustainable option for farmers. Finally, the combined use of DAP and urea represents a highly effective fertilization strategy for maximizing rice yield, nutrient use and soil fertility. This approach not only ensures sustainable crop production but also addresses key economic and environmental challenges in agriculture. Future research should focus on evaluating the long-term impacts of these fortification strategies under diverse agro-ecological conditions to refine recommendations for widespread application.

Supplementary Materials

The data supporting the findings of this study are archived at the respective institutions of the authors. Access to the data is available upon reasonable request and subject to approval by the data owners.

Acknowledgements

Bangladesh Agricultural University, Mymensingh

Conflict of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Author Contributions

Conceptualization, Md. Anamul Hoque and Tahsina Sharmin Hoque; methodology, Gufrana Akter and Jannatul Ferdous; software, Jannatul Ferdous; validation, Md. Anamul Hoque, Tahsina Sharmin Hoque and Jannatul Ferdous; resources, Md. Anamul Hoque; data curation, Jannatul Ferdous and Gufrana Akter; writing—preparation of the initial draft, Jannatul Ferdous; writing, review and editing, Md. Anamul Hoque and Tahsina Sharmin Hoque; visualization, Jannatul Ferdous; supervision, Md. Anamul Hoque and Tahsina Sharmin Hoque; project administration, Md. Anamul Hoque; revenue acquisition, Md. Anamul Hoque. All authors have reviewed the manuscript in its current form and given their approval.

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