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Research article

Phosphorus Response and Use Efficiency in T. Aman Rice Cultivation in Coastal Bangladesh

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A B S T R A C T

Phosphorus (P) is a critical essential mineral nutrient for rice cultivation, particularly in the P-deficient, poorly drained soils of the slightly-saline coastal region of Bangladesh. This study was conducted during the monsoon season (August–December 2020) in Dumki upazila of Patuakhali district to determine the optimum P fertilizer requirement and evaluate P use efficiency (PUE) in T. Aman rice. There were eight P treatments (0, 3, 6, 9, 12, 15, 18, and 21 kg P ha^{-1}), each replicated three times. The results revealed significant improvements in plant height, effective tillers hill^{-1}, grain yield, and total P uptake with rising P levels. The highest grain yield (4.99 t ha^{-1}) and straw yield (6.16 t ha^{-1}) were recorded at 15 kg P ha^{-1}, but the yields were statistically similar with the P rates as low as 9 kg ha^{-1}, which also corresponded with peak agronomic efficiency (AE) and recovery efficiency (RE). Although higher P rates (18 and 21 kg ha^{-1}) marginally increased P uptake, they had no significant improvement of grain yield and led to lower use efficiency indices. Correlation analysis confirmed strong positive relationships between tillering, yield, and P uptake parameters. The findings indicate that 9-12 kg P ha^{-1} is the optimum dose for maximizing yield and PUE in T. Aman rice under slightly-saline coastal conditions of south-central Bangladesh.

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Introduction

Rice (*Oryza sativa* L.) is the principal food item of over half of the global inhabitants that play a pivotal role in sustainable food security, especially in South and Southeast Asia. In Bangladesh, rice occupies approximately 75% of the net cultivable lands and contributes nearly 70% of the daily caloric intake of the population (BBS, 2021). Among the three rice cultivating seasons (Aus, Aman, and Boro) the T. Aman season (transplanted Aman) covers the largest area and significantly contributes to the national rice production (Sume et al., 2023). However, yields in many coastal regions remain suboptimal due to soil salinity, unfavorable environmental condition due to climate change, as well as poor soil fertility and improper nutrient management, particularly of P (Khanam et al., 2020; Jodder et al., 2016; Haque et al., 2025a).

P is second most limiting macronutrient for rice cultivation, especially in flooded and poorly drained soils such as those found in the Ganges Tidal Floodplain of Bangladesh. Although P is essential for root development, tillering, energy transfer, and grain formation, its agronomic effectiveness is often severely constrained by low availability in soil. The efficiency of P is constrained by its high fixation in acidic and alluvial soils, making it unavailable to plants (Fathi & Afra, 2023). Furthermore, the coastal agroecosystems of Bangladesh often experience tidal inundation, fluctuating redox conditions, and low soil organic matter, which collectively affect P solubility, transformation, and uptake (Islam et al., 2024). Consequently, a large proportion of applied P fertilizer remains unavailable to crops, leading to poor PUE.

Improving PUE has emerged as a critical challenge in modern agriculture due to the rising cost of fertilizers, finite global phosphate rock reserves, and growing environmental concerns associated with nutrient losses. Inefficient P use not only increases production costs for resource-poor farmers but also contributes to nutrient accumulation in soils and runoff losses to surface waters, accelerating eutrophication in vulnerable coastal ecosystems (Fixen et al., 2015). In rice-based systems,

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where P recovery by crops is often less than 20%, enhancing PUE is essential for sustaining productivity while minimizing economic and environmental trade-offs (Xiao et al., 2022).

The PUE, which includes AE, RE, and physiological efficiency (PE), provides a comprehensive measure of how effectively applied P is converted into economic yield. Maximizing PUE can reduce production costs, minimize environmental pollution, and increase profitability for resource-poor farmers (Saleque et al., 2006).

In the coastal agroecosystems of Bangladesh, fertilizer management decisions are further complicated by tidal inundation and sediment deposition, which can intermittently supply nutrients while simultaneously altering soil chemical dynamics. As a result, blanket fertilizer recommendations may lead to either under-application, causing yield losses, or over-application, resulting in diminishing yield returns and reduced nutrient efficiency (Haque et al., 2023). This challenge is particularly relevant for T. Aman rice, which is cultivated under prolonged flooded conditions and receives comparatively less research attention than irrigated Boro rice in terms of optimized P management.

Given these constraints and knowledge gaps, there is a clear need for region-specific research to determine optimal P fertilizer rates that maximize both yield and PUE under the unique soil–water dynamics of coastal Bangladesh. Therefore, the present study was undertaken to determine the P fertilizer requirement and evaluate PUE in T. Aman rice (BRRI dhan72) grown in the slightly saline coastal soils of Dumki upazila, south-central Bangladesh. The findings are expected to provide a scientific basis for refining P management strategies aimed at improving productivity, resource-use efficiency, and environmental sustainability in coastal rice-growing areas.

Materials and Methods

Study area and agro-ecological context

The on-farm experiment was undertaken during the T. Aman season (August to December 2020) at Dumki upazila, Patuakhali district, situated in the south-central coastal area of Bangladesh. The region falls within the Ganges Tidal Floodplains (Agro-Ecological Zone 13), characterized by poor drainage, and vulnerability to tidal inundation. The region experiences a subtropical monsoon climate, with high rainfall (approximately 2000 mm annually), mostly concentrated between June and October. Temperatures range from 23°C to 30°C, with relative humidity peaking at 89% during the monsoon (SRDI, 2009; FAO, 1988).

Initial soil properties

Soil sample from 0–15 cm depth was collected before tilling the field to determine baseline physical and chemical properties. The soil was classified as silt loam, with pH 5.71. Electrical conductivity (EC) was 1.61 dS m^{-1} during sample collection, however, during March-April EC value raises to around 3 dS m^{-1}. The soil contains 0.11 % total nitrogen and only 4.5 mg kg^{-1} available P. Soil analysis was done following standard procedure (Page et al., 1982).

Experimental design and treatments

Following randomized complete block design with one factor (P levels), replicated three times the experiment was setup in the farmers' field. Eight P rate treatments were tested: 0 (Control), 3, 6, 9, 12, 15, 18 and 21 kg P ha^{-1}, where the rates indicate the element form of P. Each plot measured 4 m × 3 m, with 1 m spacing between blocks and 30 cm wide bunds around individual plots.

Crop establishment and management

The high yielding T. Aman rice variety, BRRI dhan72 released by the Bangladesh Rice Research Institute was used as the test crop. Twenty eight-day-old seedlings were transplanted maintaining 20 cm × 20 cm spacing in the 12 September 2020. Seedlings were raised traditionally in a nursery bed, and no fertilizers were applied during the seedling stage.

The experimental field was tilled using rotary tiller, following four passes with laddering to ensure uniform leveling and puddling. Labels were placed around each plot to facilitate accurate fertilizer management and data collection.

Fertilizer application

All plots received a uniform basal application of nitrogen (N), potassium (K), sulfur (S), and zinc (Zn) at the rates of 80, 50, 12, and 2 kg ha^{-1}, respectively, based on the Fertilizer Recommendation Guide (FRG, 2018). P was applied as triple super phosphate (TSP) according to treatment specifications. TSP, MoP, gypsum, and zinc sulfate were applied basally, while urea was applied in three equal splits: basal, 15 days after transplanting (DAT), and 32 DAT.

Pest and weed management

The stem borer insect was controlled with spraying *Virtaco* (Chlorantraniliprole + Thiamethoxam) insecticide . The field had naturally minimum weed due to daily tidal submergence from the early vegetative to anthesis stage. However, two weeding was done manually during urea fertilizer topdressing. No fungicides or disease control measures were necessary, as disease incidence was negligible.

Growth and yield data collection

At physiological maturity, five hills were selected randomly from every plot (excluding borders) to measure growth and yield components. Plant height was noted (cm) from bottom to top of the tallest panicle. The **e**ffective tillers $hill^{-1}$ were individually counted from the tillers with at least one filled grain. The number **of g**rains $panicle^{-1}$ were counted from randomly drawn ten panicles and averaged. The 1000-grain weight was m**easured** using an electronic balance.

Yield estimation

The central 6 m² area of each plot was harvested to estimate grain and straw yield. Grain was sun-dried to 14% moisture before weighing. Straw was oven-dried at 62°C for 72 hours to calculate dry matter content. Yield was expressed in t ha^{-1} and adjusted accordingly.

P content and uptake

The grain and straw P content was determined by wet digestion and colorimetric analysis. Plant samples were digested using nitric acid and perchloric acid mixture (3:1 ratio), followed by color development using ammonium vanadate. Total P uptake was computed by multiplying grain or straw yield with corresponding P concentration.

PUE calculations

PUE indices were computed using standard formulas:

$AE = (Y_{Pa} - Y_{P0}) / PR_n$

$RE = (U_{Pa} - U_{P0}) / NR_n$

$PE = (Y_{Pa} - Y_{P0}) / (U_{Pa} - U_{P0})$

Where:

Y_{Pa} = Yield with P application

Y_{P0} = Yield without P (control)

U_{Pa} = P uptake with application

U_{P0} = P uptake in control

PR_n = Rate of P applied

Statistical analysis

All collected data were subjected to analysis of variance (ANOVA) using statistical software "Statistical Tool for Agricultural Research" (STAR-2.0.1). Mean separation test was computed following Duncan's Multiple Range Test at 5% significance level. Correlation coefficients among traits were also calculated to examine inter-relationships between morphological, physiological, and yield parameters using same software.

Results

This section reported the core findings of the paper. For convenience and easy understanding, the findings in growth and yield contributing parameters, grain yield, straw yield and P uptake parameters have been described chronologically. The core findings have been described below under different sub-headings.

Effect of P on growth parameters of rice

The application of P significantly improved plant height and the number of effective tiller hill^{-1} (Table 1). The tallest plant (120.3 cm) was observed in the treatment receiving 15 kg P ha^{-1} (T_6), followed closely by treatments T_7 and T_8. However, plant height found in 12 to 21 kg P ha^{-1} had statistically similar plant height. The lowest height (110.6 cm) was recorded in the control (T_1). Effective tiller production followed a similar trend, with the highest number (10.5 tillers hill^{-1}) observed in T_8 (21 kg P ha^{-1}), which was not statistically different with 15 and 18 kg P ha^{-1} rate. The lowest (5.3 tillers hill^{-1}) tiller production was in the control. A highly significant linear relationship ($R^2 = 0.955$, $p < 0.001$) between P application and tiller number was observed (Figure 1).

Effect of P on yield contributing parameters of rice

Although differences in grain number per panicle and thousand-grain weight were not statistically significant across the treatments (Table 1), they showed slight improvements with P application, especially at moderate rates (9–15 kg P ha^{-1}). The number of grains panicle^{-1} varied from 122 to 129; the highest was in 15 kg P ha^{-1} rate and the lowest was in control treatment. Following similar trend the 1000-grain weight varied from 25.9 g in control treatment to 28.4 g in 15 kg P ha^{-1} rate.

Table 1: Effect of different levels of P on growth and yield components of T. Aman rice (BRRI dhan72)

Treatment	Plant height (cm)	Tillers hill^{-1} (no.)	Grains panicle^{-1} (no.)	Thousand-grain wt. (g)
T_1: P Control	110.6 d	5.3 e	122	25.9
T_2: 3 kg P ha^{-1}	114.5 c	6.6 de	125	27.1
T_3: 6 kg P ha^{-1}	114.8 c	7.4 cd	126	26.9
T_4: 9 kg P ha^{-1}	116.0 bc	8bcd	128	27.5
T_5: 12 kg P ha^{-1}	118.3 abc	8.6bc	128	27.2
T_6: 15 kg P ha^{-1}	120.3 a	9.8ab	129	28.4
T_7: 18 kg P ha^{-1}	118.8 ab	9.4ab	127	28.3
T_8: 21 kg P ha^{-1}	119.1 ab	10.5 a	126	27.3
% CV	1.15	6.21	2.98	3.71
Significance level	**	***	ns	ns
SE (±)	1.10	0.41	3.07	0.82

Note for all tables:
Means with the same letter are not significantly different at 5% level by DMRT
*-Significant at 5% level; **= Significant at 1% level; ***- Significant at 0.1% level; ns-Not significant

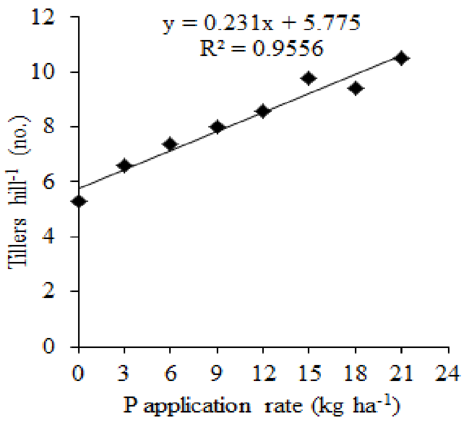

Figure 1: Regression relation between P application rates with production of tiller number per hill (Treatment means, n=8; df-6; **p < 0.001**)

Effect of P application on grain yield of rice

P levels significantly improved grain yield of rice, with maximum yield (4.99 t ha^{-1}) recorded in T_6 (15 kg P ha^{-1}), which was statistically similar to T_5, T_7, and T_8 (Table 2). This suggests that yield response plateaued beyond the recommended dose (15 kg P ha^{-1}), indicating diminishing returns with higher application rates. The control treatment (T_1) recorded the lowest grain yield (4.42 t ha^{-1}), demonstrating the essential role of P in achieving optimum productivity. In the experiment 9-21 kg P ha^{-1} rates had statistically similar grain yields of rice, therefore the higher rates beyond 9 kg P ha^{-1} had little chance to obtain economic benefit from P fertilizer application. Positive correlations were noted between grain yield and both plant height ($r = 0.83$, $p < 0.001$) and effective tillers ($r = 0.76$, $p < 0.001$), highlighting these as key contributors to yield enhancement (Table 4).

Table 2: Effect of different levels of P on grain and straw yield of T. Aman rice (BRRI dhan72)

Treatment	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})
T_1: P Control	4.42 b	5.42 b
T_2: 3 kg P ha^{-1}	4.63 b	5.69 b
T_3: 6 kg P ha^{-1}	4.74 b	5.81 ab
T_4: 9 kg P ha^{-1}	4.84 ab	6.04 a
T_5: 12 kg P ha^{-1}	4.90 a	6.11 a
T_6: 15 kg P ha^{-1}	4.99 a	6.16 a
T_7: 18 kg P ha^{-1}	4.99 a	5.73 ab
T_8: 21 kg P ha^{-1}	4.98 a	5.78 ab
% CV	5.43	9.39
Significance level	**	*
SE (±)	0.134	0.448

Effect of P application on straw yield of rice

Straw yield followed a pattern similar to grain yield. The top most straw yield (6.16 t ha^{-1}) was recorded in T_6, while the control yielded 5.42 t ha^{-1} (Table 2). However, yield gains beyond 15 kg P ha^{-1} were marginal, underscoring the need for economically and environmentally sustainable fertilizer use. Although highest yield was found in 15 kg P ha^{-1} rate, it rather statistically alike with as low as 6 kg P ha^{-1} rate, which indicates necessity of small amount of P in the coastal soils. Straw yield had a significant correlation with increasing grain yield of rice ($r = 0.60$, $p < 0.01$), explaining the necessity of biomass to enhance grain yield of rice.

Effect of P application on P uptake by grain and straw of rice

P content and uptake in grain increased significantly with rising P application (Table 3). However, P content and uptake in straw was not significant. Due to significant uptake by grain the total P uptake was also significantly varied among the treatments. The highest grain P content (0.397%) was noticed in 21 kg P ha^{-1} rate and the lowest was in control treatment (0.299%). In fact, there was a strong linear regression relation of applied P with grain P content ($R^2 = 0.953$, $p < 0.001$; Fig. 2). Although straw P content was not significant but still it was progressively rises with rising of P rates having 0.177% in control treatment and 0.220% in 21 kg P ha^{-1} rate.

Although grain P uptake significantly varied from 13.2 to 19.77 kg ha^{-1} over the treatments, but 12 to 21 kg P ha^{-1} rates had statistically similar grain P uptake. The highest total P uptake (32.51 kg ha^{-1}) was observed in T_8 (21 kg P ha^{-1}), while the lowest (22.79 kg ha^{-1}) was in the control. However, all the treatments beyond 9 kg P ha^{-1} rate had statistically similar total P uptake. The grain P uptake showed a strong positive correlation with grain yield ($r = 0.79$, $p < 0.001$) and total P uptake ($r = 0.93$, $p < 0.001$), suggesting improved nutrient assimilation under adequate P supply (Table 4).

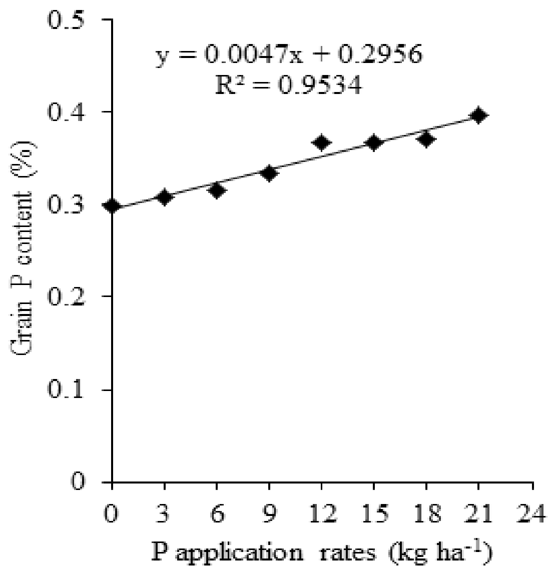

Figure 2: Regression relation between P application rates with grain P content of rice (Treatment means, n=8; df-6; p<0.001)

PUE indices

The study revealed a peak in AE at 3 kg P ha^{-1} (T_2), beyond which AE declined (Fig. 3). This trend reflects the law of diminishing returns, where low application rates yielded higher AE due to balanced nutrient supply without excess fixation or loss.

RE peaked at 12 kg P ha^{-1} rate; then declined (Fig. 4). Similar to AE, the PE also peaked at 3 kg P ha^{-1} rate (Fig. 5). At higher rates (18 and 21 kg P ha^{-1}), RE declined, indicating reduced uptake per unit of applied P, likely due to saturation or soil P fixation. These results underscore the importance of matching fertilizer inputs with crop demand and soil characteristics to optimize PUE.

Correlation among agronomic and P uptake parameters

Significant positive correlations among plant height, tiller number, yield, and P uptake components (Table 4) suggest that P availability influences a wide range of physiological processes. Particularly, strong correlations between grain P uptake and both grain yield ($r = 0.79$) and effective tillers ($r = 0.93$) confirm that P management directly impacts productivity and nutrient cycling in rice systems.

Table 3: Effect of different levels of P on grain and straw P content and uptake of T. Aman rice (BRRI dhan72)

Treatment	Grain P content (%)	Straw P content (%)	Grain P uptake (kg ha^{-1})	Straw P uptake (kg ha^{-1})	Total P uptake (kg ha^{-1})
T_1: P Control	0.299 d	0.177	13.20 d	9.59	22.79 d
T_2: 3 kg P ha^{-1}	0.308 d	0.186	14.24 d	10.58	24.82 cd
T_3: 6 kg P ha^{-1}	0.316 cd	0.209	14.99 cd	12.02	27.01bcd
T_4: 9 kg P ha^{-1}	0.335bcd	0.215	16.19bc	12.92	29.11abc
T_5: 12 kg P ha^{-1}	0.368ab	0.219	18.03ab	13.39	31.41ab
T_6: 15 kg P ha^{-1}	0.368 ab	0.212	17.95ab	13.09	31.04ab
T_7: 18 kg P ha^{-1}	0.372ab	0.217	18.56 a	12.48	31.04ab
T_8: 21 kg P ha^{-1}	0.397 a	0.220	19.77 a	12.74	32.51 a
% CV	4.60	9.32	3.93	12.01	5.86
Significance level	***	ns	***	ns	***
SE (±)	0.012	0.015	0.532	1.19	1.37

Table 4: Correlation matrix between different parameters of rice

Treatment	Plant height	Tillers hill^{-1}	Grains panicle^{-1}	1000-grain wt.	Grain yield	Straw yield	Grain P content	Straw P content	Grain P uptake	Straw P uptake
Tillers hill^{-1}	0.79***									
Grains panicle^{-1}	0.36	0.15								
1000-grain wt.	0.51**	0.38	0.36							
Grain yield	0.83***	0.76***	0.21	0.55**						
Straw yield	0.26	0.36	0.12	0.43*	0.60**					
Grain P content	0.73***	0.87***	0.16	0.22	0.57**	0.09				
Straw P content	0.64***	0.49*	0.20	0.35	0.65***	0.13	0.53**			
Grain P uptake	0.84***	0.93***	0.19	0.36	0.79***	0.29	0.95***	0.63***		
Straw P uptake	0.64***	0.57**	0.22	0.51*	0.83***	0.66***	0.46*	0.83***	0.64***	
Total P uptake	0.83***	0.85***	0.22	0.47*	0.89***	0.50*	0.81***	0.79***	0.93***	0.88***

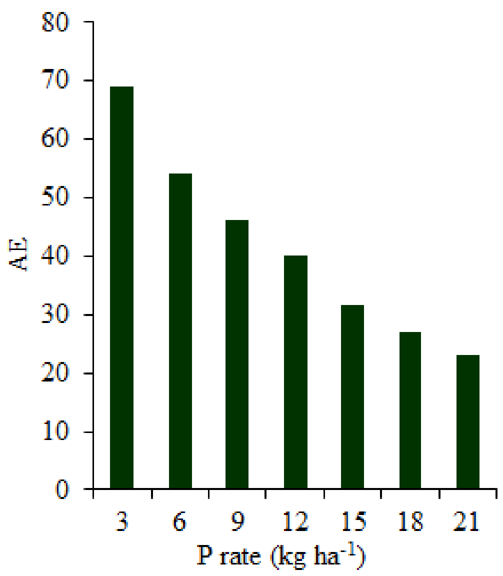

Figure 3: AE (kg grain kg^{-1}P) of P for T. Aman rice at coastal region of Bangladesh

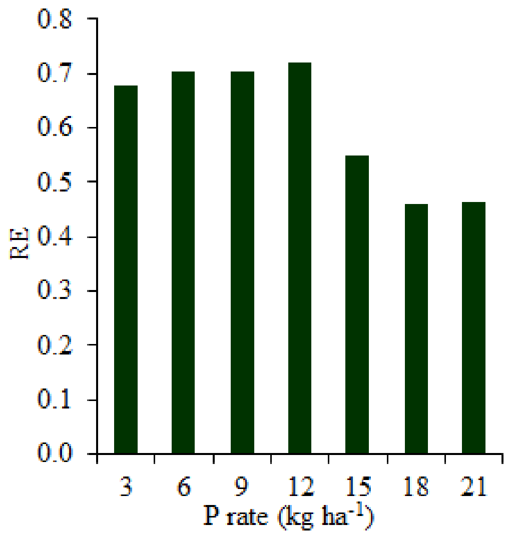

Figure 4: RE (kg P uptake kg^{-1}added P) of P for T. Aman rice at coastal region of Bangladesh.

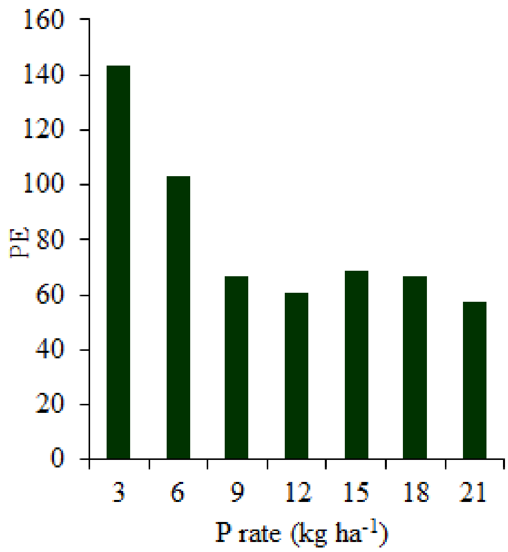

Figure 5: PE (kg grain kg^{-1}P uptake) of P for T. Aman rice at coastal region of Bangladesh.

Discussion

The present study demonstrated that P fertilization significantly influenced growth, yield, P uptake, and PUE in T. Aman rice grown under the slightly-saline coastal conditions of Dumki upazila in Patuakhali district of Bangladesh. These findings are in alignment with earlier research indicating the crucial role of P in rice cultivation, especially under flooded and P-deficient coastal soils (Fageria et al., 2010).

Plant height and effective tillering responded markedly to increasing P levels. The tallest plants and highest tiller numbers were observed at 15–21 kg P ha^{-1}, though no statistically significant differences were found beyond 12 kg P ha^{-1}. This plateau suggests that P response in coastal tidal soils may reach an upper threshold beyond which additional application yields limited physiological benefit (Islam et al., 2024). The strong correlation between tiller number and P application ($R^2 = 0.955$, $p < 0.001$) underscores the role of P in vegetative growth, particularly tiller initiation and survival—an essential determinant of panicle number and eventual yield. Increased P availability is known to promote early root development and enhance cell division, contributing to greater vegetative growth and plant stature (Khan et al., 2023).

The grain yield increased significantly with P application, peaking at 15 kg P ha^{-1} (4.99 t ha^{-1}). However, the yields with 9–21 kg P ha^{-1} were statistically similar, indicating that 9 kg P ha^{-1} could be the economic threshold for P fertilization under these coastal conditions. This finding is particularly relevant for resource-poor farmers, suggesting that applying more than 9 kg P ha^{-1} may not result in proportionate yield gains and could reduce economic return (Fixen et al., 2015). These results contrast slightly with the current recommendation of 15 kg P ha^{-1}, highlighting the need for location-specific fertilizer recommendations.

The higher availability of P from tidal water and silt deposition may contribute to this lower-than-expected optimum P rate, supporting earlier findings regarding nutrient input from tidal submergence (Rahman et al., 2013). However, in the same area upland crops including maize and sunflower shows equal or little bit higher fertilizer requirement than the current recommendation probably due to low soil pH (Haque et al., 2024; 2025b). The positive correlations between grain yield and both plant height ($r = 0.83$, $p < 0.001$) and effective tillers ($r = 0.76$, $p < 0.001$) further reinforce the linkage between P-enhanced vegetative growth and yield potential.

Total P uptake in grain and straw increased with higher P application. However, a significant rise was only observed up to 12 kg P ha^{-1}. Beyond this point, uptake levels plateaued despite increased P application, indicating that physiological P saturation may limit additional uptake. The highest grain P content (0.397%) was found at 21 kg P ha^{-1}, but grain P uptake and total P uptake showed statistical similarity across 12–21 kg P ha^{-1} treatments. This suggests that surplus P input is likely to be lost or immobilized, emphasizing the need for balanced application strategies (Prasad, 2009).

Notably, grain P uptake correlated strongly with both grain yield ($r = 0.79$) and total P uptake ($r = 0.93$), highlighting the role of P assimilation in grain development. The adequate P supply has been reported to be enhanced P translocation from vegetative parts to grains, increasing both yield and grain nutrient content (Khatun et al., 2023; Islam et al., 2024).

The analysis of PUE parameters—AE, RE, and PE—revealed that the highest AE and PE were achieved at 3 kg P ha^{-1}, while RE peaked at 12 kg P ha^{-1}. This inverse relationship between application rate and efficiency highlights the principle of diminishing returns in nutrient management (Vandamme et al., 2018). High application rates (18–21 kg P ha^{-1}) showed reduced RE and AE, likely due to P fixation in coastal soils with low buffering capacity.

These observations stress the necessity of optimizing P rates to balance yield gains with nutrient efficiency. In particular, the findings support the concept of "right rate" under the 4R nutrient stewardship framework—applying the right amount of fertilizer at the right time, source, and place (Fixen et al., 2015).

The findings carry significant implications for sustainable nutrient management in Bangladesh's coastal agroecosystems. Excessive P application not only fails to increase yield but can also contribute to nutrient leaching or accumulation in the environment, exacerbating eutrophication risks. Therefore, an optimum P rate of 9–12 kg ha^{-1} represents an agronomically effective and environmentally prudent threshold for T. Aman rice in slightly-saline, flooded conditions. The strategic P management enhances nutrient use efficiency and supports sustainable intensification in low-input systems (Szymańska et al., 2025).

The P response patterns in this study align with national findings in similar agro-ecological zones, and support international observations in P-deficient, flooded paddy fields (Ferdous et al., 2025; Dobermann & Fairhurst, 2000). However, the lower optimal rate identified here reflects the unique influence of tidal water dynamics in Patuakhali, which necessitates differentiated fertilizer recommendation frameworks.

Conclusion

This study demonstrates that optimizing P management—rather than maximizing P input—is critical for improving both yield and nutrient use efficiency of T. Aman rice in slightly-saline coastal soils of south-central Bangladesh. Although grain yield increased with increasing P rates, the yield response plateaued beyond 9–12 kg P ha^{-1}, while AE, RE and PE declined sharply at higher application levels. This indicates that additional P supply beyond crop demand does not translate into proportional yield gains and instead reduces PUE due to soil P fixation and saturation under flooded coastal conditions. The strong associations among effective tiller production, grain yield, and grain P uptake confirm that P availability primarily enhances yield through improved vegetative growth and efficient P translocation to grains, rather than through continued increases in biomass or P accumulation at higher fertilizer rates. Importantly, moderate P rates (9–12 kg ha^{-1}) achieved near-maximum yield while maintaining superior RE, highlighting this range as the most balanced and sustainable option for coastal rice cultivation. Avoiding excessive P inputs will reduce unnecessary fertilizer costs for farmers, and also help minimize nutrient losses, environmental risks, and long-term P accumulation in coastal agroecosystems. Further long-term studies across different coastal soil types and climatic conditions are recommended to validate and fine-tune the P application threshold for broader adoption.

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Conflict of interest

There is no conflict of interest to declare.

Data availability

All the associated data were included in the manuscript.

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