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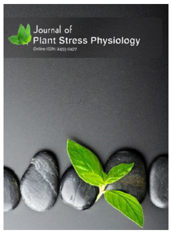

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Evaluation of rice (*Oryza sativa* L.) genotypes for low phosphorus stress tolerance

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ABSTRACT

Phosphorus (P) deficiency is a prime factor limiting rice growth and yield around the globe. Understanding how plants respond to P starvation is very important for breeding varieties with enhanced P uptake and use efficiency. To assess the effect of low P stress on yield and yield contributing traits, an experiment was conducted using six rice genotypes applying two treatments (optimum and deficient P conditions). Data on yield and yield attributing traits *viz.*, days to first flowering (DFF), days to maturity (DM), plant height (PH), number of total tillers/plant (NTTP), number of effective tillers/plant (NETP), panicle length (PL), 100-seed weight (100-SW) and yield per plant (YPP) were recorded. Analysis of variance showed highly significant variation among the genotypes (G), treatments (T) and G × T interaction. When compared with control, a significant reduction in yield and yield attributing traits was observed in most of the studied genotypes in response to low P stress. The highest reduction in YPP was recorded in BRRI dhan78 whereas the lowest reduction was observed in Binadhan-17. Principal component analysis revealed that the first three principal components explained 85.2% of the total variation. Yield per plant (g) showed significant positive correlation with PH, PL, NTTP and NETP whereas it showed significant negative correlation with DFF, DM and 100-SW. Based on stress tolerance indices Binadhan-17, BRRI dhan71 and BRRI dhan79 were categorized as tolerant genotypes and selected for cultivation in P deficient areas and are recommended for the genetic improvement of low P stress tolerance in rice.

KEYWORDS: Phosphorus deficiency, Yield reduction, Principal component, Tolerance indices, Correlation co-efficient

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INTRODUCTION

More than half of the world's population relies on rice to meet their caloric needs, making it one of the most significant and vital cereal crops in the world (Verma *et al.*, 2021). Rice is tightly tied to not only global food security but also economic growth, employment, social stability, and regional peace (Yadev & Kumar, 2018). Rice is an essential and almost non replaceable dietary element of the people of Bangladesh. In Bangladesh, the demand for rice is increasing day by day. With annual population growth of 1.8 million people, every year Bangladesh requires approximately an additional 300,000 metric tons of rice (GAIN, 2013). In recent years, the world's rice production and research have faced unprecedented challenges. Some of the biggest concerns to rice production and food security are decreasing water and arable land availability, the ongoing threat of biotic and abiotic pressures, detrimental consequences of a fast changing climate, nutrient-deficiency in soils etc., (Khush, 2005). To fulfill the increasing demand for food consumption by the population and to assure global food security, rice output must be increased immediately.

Phosphorus (P) is one of the major macronutrients for plant growth and development. It is the second most abundantly required plant nutrient after nitrogen that constitutes many structural components such as nucleic acids (DNA, RNA) of the plant body (Vance *et al.*, 2003; Havlin *et al.*, 2005). It influences a plant from its germination till maturity and is essential for reproduction and protein synthesis (Vance *et al.*, 2003; Malhotra *et al.*, 2018). One of the main obstacles to rice production is soil P deficiency, which impose a substantial impact on rice growth and development by reducing plant growth, reducing root development, decreasing the number of productive tillers, increasing spikelet sterility, delaying flowering, and increasing root elongation and rendering the plants from expressing their full genetic potentials (Kale *et al.*, 2021). It is estimated that about 5.7 billion hectares and almost 50% of rice soils are currently P deficient (Ismail *et al.*, 2007). In Bangladesh around 41% of the cultivated soil contained P below the critical level and 35 % of the soils contained P above the critical level but below the optimum level and the available P of Bangladeshi soils ranged from 2 to 14 ppm with a mean value of 12 ppm (Bhuiyan, 1988; Biswas & Nahar, 2019). The high cost of fertilizers and their limited availability in remote upland areas frequently prevents resource-poor farmers in developing countries from applying P to their deficient fields (Kirk *et al.*, 1998). By 2030, it is anticipated that yearly P fertilizer usage would increase by 20 million tons, and P fertilizer sources are limited (Vance *et al.*, 2003). In addition the cheap sources of phosphates, such as rock phosphate, will be depleted toward the end of the 21st century (Runge-Metzger, 1995; Cordell *et al.*, 2009). Importantly 20 to 30% of the administered P fertilizers are used by cultivating plants; the remainder is quickly immobilized due to fixation and microbial activity. In calcareous soils, the plentiful calcium and magnesium compounds bind inorganic phosphates (Pi), rendering it unavailable to plants. In acidic soils, free iron and aluminum oxides bind to native and applied P (Hinsinger, 2001). On the other hand, excess P added to soil can pollute water resources and contribute to the process of eutrophication. It is therefore essential to minimize the application of P fertilizers by developing cultivars capable of either acquiring P or using P more efficiently to make the crop production systems more sustainable and to minimize problems like eutrophication and slow the depletion of P reserves.

Rice plants adapt to low P in the soil by creating morphological, physiological, biochemical, and molecular modifications for enhanced P-acquisition-efficiency (Pi uptake) and higher internal P-use-efficiency (Tyagi *et al.*, 2012). The quantitative feature of low P tolerance is intricate. As a result, it is possible to design efficient breeding and genetic engineering strategies to produce low P tolerant or P use efficient rice lines. Fortunately, rice germplasm shows large heterogeneity for characteristics related to low soil P tolerance and accompanying rice plant adaptations to low-Pi stress (Wissuwa & Ae, 2001). Although significant progress has been achieved over the last few years on P-deficiency tolerance in plants, the complexity of the traits involved in P-deficiency tolerance and the lack of screening criterion suitable for use in breeding programs have hampered past efforts to develop tolerant high yielding rice varieties. Research related to low P stress tolerance in rice is inexpertly rare in Bangladesh.

Yield is the complex end product of many factors which jointly or singly influence the seed yield. Therefore, considerable attention is needed for the selection of yield and yield-related traits under favorable and P stress conditions. In the advanced breeding program, the degree of association between characters as indicated by the correlation coefficients which help in construction of selection indices has always been a helpful instrument for the selection of desirable characters. Correlation and principal component analysis (PCA) estimate the mutual relationships between various plant characters and determine the component characters on which selection can be based for yield improvement. Breeding rice varieties tolerant to low P has become crucial for future food security due to the diminishing rock phosphate sources and the rising costs of P fertilizers (Yugandhar *et al.*, 2017). One effective approach to enhance the adaptation of rice to P-deficiency is to identify morphological, biochemical and genetic determinants and to incorporate them into a high yielding variety with the aid of molecular markers. Therefore, identification of morphological and biochemical determinants regulating low P stress tolerance at various phases of plant growth and their association studies and selection based on multiple stress tolerance indices will surely speed the progress of breeding in developing nutrient efficient rice varieties. The present investigation was thus aimed (i) to access the phenotypic variability for yield and related traits under low P stress conditions, and (ii) to study the trait association for grain and related traits under low P stress conditions as well as to identify low P tolerant genotypes for future plant breeding program.

MATERIALS AND METHODS

Plant Materials, Experimental Site and Season

The experiment was carried out at the field experimental farm of the Genetics and Plant Breeding (GPB), Bangladesh Agricultural University (BAU), Mymensingh-2202 during T- Aman season, started from 12th July 2019 to 25th November 2019. The experimental area's topography was medium-high land that was a part of Agro-Ecological Zone-9 (Old Brahmaputra Flood Plain). The soil had a sandy loam texture and a pH range of 6.5 to 6.7. The experiment was carried out using six rice varieties/genotypes, *viz.*, Binadhan-17, BRRI dhan49, BRRI dhan71, BRRI dhan78, BRRI dhan79 and Begunipata.

Land Preparation and Seedlings Transplanting

The experiment field was prepared through several ploughing and cross-ploughing and finally laddering to bring the soil correct tilth and leveling. The recommended doses of different chemical fertilizers (50% Urea @ 130 kg/ha, Triple Super Phosphate @ 60 kg/ha, Muriate of Potash @ 85 kg/ha, Gypsum @45 kg/ha, and Zinc sulphate @ 2.5 kg/ha) and Cowdung @ 3 ton/ha was applied during final lend preparation, however, the plot marked for low P stress was prepared by applying all of the fertilizers expect P fertilizer (native soil P was 12.33 ppm). The rest of the Urea was applied in two installments. Half of the Urea was applied 2 weeks after transplanting and rest of the Urea was applied one week before flowering.

Experimental Design, Layout and Seedlings Transplanting

The experiment was conducted following a randomized complete block design (RCBD) with three replications. The unit plot size was 4 m^2 (2 m x 2 m). Twenty-day-old seedlings were transplanted to in the main field. The seedlings transplanted to each plot keeping plant to plant distance 20 cm and row to row distance 25 cm. The distance between two plots was 50 cm.

Intercultural Operation

Different agronomic practices such as weeding and irrigation were done following standard cultivation techniques to ensure better growth of the rice plants. Other intercultural operations were also done whenever necessary.

Data Collection

Data on eight yield attributing traits, such as days to first flowering (DFF), days to maturity (DM), plant height (PH), panicle length (PL), number of total tillers per plant (NTTP), number of effective tillers per plant (NETP), 100-seed weight (100-SW) and yield per plant (YPP) were recorded from ten randomly selected plants per genotype for each replication.

Statistical Analysis

Data recorded for different parameters were compiled and tabulated in proper form for statistical analysis which was carried out in Minitab 17 statistical software package (Minitab Inc. State College, Pennsylvania) and software R, version 3.3.2. The two-way analysis of variance was carried out using Minitab 17 software following RCBD design with two factors in mixed model, in which factors were fixed. Significant difference in treatment means was tested at $P \leq 0.05$ level using Tukey's multiple comparison test. Principal component analysis and phenotypic correlation co-efficient was done using Minitab 17 statistical software.

Calculation of Stress Tolerance Indices

Stress tolerance indices were calculated in grain yield per panicle using following equations:

Stress susceptibility index (SSI) = $(1 - (Ys/Yp))/(1 - (\bar{Y}s/\bar{Y}p))$ (Fischer & Maurer, 1978)

Tolerance Index (TOL) = Yp - Ys (Rosielle & Hamblin, 1981)

Mean productivity (MP) = (Yp + Ys)/2 (Rosielle & Hamblin, 1981)

Stress Tolerance Index (STI) = $(Yp \times Ys)/(\bar{Y}p)^2$ (Fernandez, 1992)

Geometric mean productivity (GMP) = $\sqrt{(Yp)} \times Ys$ (Fernandez, 1992)

Yield stability index (YSI) = Ys/Yp (Gavuzzi *et al.*, 1997)

In the equations above, Ys and Yp stand for the seed yield of genotypes under low P stress (stress) and control (non-stress) circumstances, respectively. Meanwhile, $\bar{Y}s$ and $\bar{Y}p$ stand for the mean seed yield across all genotypes under stress and non-stress situations.

RESULTS

Effect of Low P Stress on Yield-related Traits of Rice Genotypes

The combined analysis of variance results showed that all of the examined traits *viz.*, DFF, DM, PH, PL, NTTP, NETP, 100-SW and YPP were significantly ($p < 0.001$) different across treatments (T) and genotypes (G) (Table 1). In case of treatment (T) x genotype (G) interaction, the character 100-SW (g) showed significant at 0.1% level of probability whereas NETP showed significant at 1% level of probability. The characters, DF, PH, and YPP showed significant at 5% level of probability whereas DM, PL and NTTP showed a non-significant difference due to G x T interaction (Table 1).

Days to first flowering

Under control condition, the maximum number of days required for first flowering was recorded in BRRI dhan49 (94.67 days), whereas the least DFF was recorded in the variety Binadhan-17 (80.67 days). Under low P stress, the highest number of days (98.67 days) required for first flowering was recorded in the variety BRRI dhan79, whereas the least number of days required for DFF (86.00 days) was found in the genotype BRRI dhan71. Low P stress resulted in a significant delayed in DFF (Table 2). The highest delayed in DFF was recorded for the variety Binadhan-17 (8.25%), followed by BRRI dhan79 (5.34%), BRRI dhan71 (5.30%) whereas the lowest delay in DFF was found in BRRI dhan49 (2.81%) (Table 2).

Days to maturity

The variety BRRI dhan49 required the highest number of days (133.33) to mature, whereas, the lowest (114.00) number of days was recorded for Binadhan-17, under control conditions. Under low P stress, the highest number of days (137.67 days) for maturity was recorded for BRRI dhan49, whereas the least number of days (118.67 days) required for Binadhan-17 and BRRI dhan71. Low P stress led to a significant delayed in DM (Table 2). The highest delayed in DM was recorded for the genotype Begunipata (5.05%), followed by BRRI dhan79 (4.39%), Binadhan-17 (4.09%) and the lowest delayed was found for the variety BRRI dhan49 (3.25%) (Table 2).

Plant height (cm)

The highest PH (93.32 cm) was recorded for the genotype BRRI dhan71, whereas, the lowest PH (62.33 cm) was recorded for the genotype Begunipata under control conditions. Similarly, under low P stress, the highest PH (90.63 cm) was recorded in BRRI dhan71, whereas the lowest PH (62.33 cm) was found in the variety Begunipata. Low P stress caused a significant reduction in PH for all the genotypes as compared to control (Table 2). The highest reduction in PH was recorded for the genotype was Begunipata (6.59%), followed by Binadhan-17 (6.47%), BRRI dhan79 (4.75%), BRRI dhan49 (3.47%), BRRI dhan71 (2.88%) whereas the lowest reduction (1.32%) in PH was found in the genotype BRRI dhan78 (Table 2).

Number of total tillers per plant

Under control condition, the highest NTTP (16.00) was recorded in the variety BRRI dhan49, whereas, the lowest (9.67) was recorded for the genotype Begunipata. Under low P stress, the highest NTTP (12.67) was recorded in the

Table 1: Analysis of variance (ANOVA) (mean square) for yield and yield-related traits

Sources of variation	df	DFF	DM	PH (cm)	NTTP	NETP	PL (cm)	100-SW (g)	YPP (g)
Treatment (T)	1	164.694***	220.028***	88.360***	42.2500***	51.3611***	11.1000***	0.117878***	2.11702***
Genotype (G)	5	222.583***	461.961***	823.280***	27.5611***	30.4944***	14.5708***	0.444044***	0.69148***
Replication	2	1.750	0.361	1.666	1.8611	0.8611	0.2095	0.000219	0.14477
G×T	5	3.028*	0.894	2.350*	1.6500	2.3611**	0.7443	0.006898***	0.14081*
Error	22	0.841	0.907	0.846	0.6793	0.5581	0.4892	0.000750	0.04832

*, **and *** indicates significant at 5%, 1% and 0.1% level of probability, respectively. Here, df=degrees of freedom, DFF=days to first flowering, DM=days to maturity, PH=plant height (cm), PL=panicle length (cm), NTTP=number of total tillers/plant, NETP=number of effective tillers/plant, 100-SW=100 seed weight (g), YPP=yield/plant (g)

Table 2: Combined effects of genotype and treatment interaction on yield and yield-related traits of rice. Data represented in the table are the treatment means of three replicates (10 plants per replication).

Genotypes×Treatment	DFF	DM	PH (cm)	NTTP	NETP	PL (cm)	100-SW (g)	YPP (g)
Binadhan-17								
Control	80.67f	114.00h	67.49fg	12.00cde	11.67cde	20.49b-e	2.14f	2.67abc
Low P	87.33de	118.67g	63.12h	11.67cde	11.33de	19.90c-f	2.03g	2.57abc
BRRI dhan49								
Control	94.67bc	133.33cd	72.08de	16.00a	15.67a	18.34f	2.00gh	2.31bcd
Low P	97.33ab	137.67a	69.58ef	12.67bcd	12.33cd	18.16f	1.94h	1.60e
BRRI dhan71								
Control	81.67f	114.67h	93.32a	12.67bcd	12.67bcd	22.37ab	2.32d	2.93ab
Low P	86.00e	118.67g	90.63ab	10.67de	10.67de	20.53b-e	2.24e	2.56abc
BRRI dhan78								
Control	94.33c	131.33de	89.46b	13.67abc	13.67abc	23.54a	2.27de	3.03a
Low P	98.00a	136.33ab	88.28b	11.67cde	11.33de	21.70abc	2.14f	2.06cde
BRRI dhan79								
Control	93.67c	129.00e	77.31c	14.67ab	14.67ab	19.57def	2.49c	2.62abc
Low P	98.67a	134.67bc	73.64d	12.33bcd	12.33cd	18.82ef	2.42c	2.28bcd
Begunipata								
Control	86.67e	118.67g	66.73g	9.67e	9.67e	21.16bcd	2.85a	2.18cde
Low P	90.00d	124.67f	62.33h	6.67f	5.67f	19.67c-f	2.61b	1.75de

Here, DFF=days to first flowering, DM=days to maturity, PH=plant height (cm), PL=panicle length (cm), NTTP=number of total tillers/plant, NETP=number of effective tillers/plant, 100-SW=100 seed weight (g), YPP=yield/plant (g)

genotype BRRI dhan49 whereas the lowest NTTP (6.67) was found for the genotype Begunipata (Table 2). A significant decrease in NTTP in response to low P stress was found, with the highest reduction (31.02%) for the genotype Begunipata, followed by 20.81%, 15.95%, 15.78% and 14.63% for the varieties BRRI dhan49, BRRI dhan79, BRRI dhan71, BRRI dhan78, respectively. The lowest decrease (2.75%) in NTTP was found for Binadhan-17 (Table 2).

Number of effective tillers per plant

The highest NETP (15.67) was recorded in the genotype BRRI dhan49, whereas the lowest number (5.67) was recorded for the genotype Begunipata under control conditions. Under low P stress condition the maximum NETP (12.33) was recorded in the genotype BRRI dhan49 and BRRI dhan79 whereas the minimum NETP (5.67) was found for the genotype Begunipata (Table 2). Imposition of low P stress resulted in a significant decrease in NETP in all the studied genotypes as compared to control. The highest reduction in NETP was recorded in the genotype Begunipata (41.36%), followed by BRRI dhan49 (21.31%), BRRI dhan78 (17.11%), BRRI dhan79 (15.95%), BRRI dhan71 (15.78%) and the lowest reduction in NETP was recorded in the genotype Binadhan-17 (2.91%) (Table 2).

Panicle length (cm)

Under control condition the highest PL (23.54 cm) was recorded for the genotype BRRI dhan78, whereas the lowest (18.16 cm) was recorded for the genotype BRRI dhan49. Under low P stress conditions, the highest PL (21.70 cm) was recorded for the variety BRRI dhan78, whereas the lowest PL (18.16 cm) was found for the variety BRRI dhan49 (Table 2). Low P stress led to a significant reduction in PL, as compared to controls, the highest reduction (8.22%) was for variety BRRI dhan71 followed by BRRI dhan78 (7.82%), Begunipata (7.04%), BRRI dhan79 (3.83%), Binadhan-17 (2.87%). The least reduction (0.98%) in PL was recorded for the genotype BRRI dhan49 (Table 3).

100-seed weight (g)

Maximum 100-SW (2.85 g) was recorded for the genotype Begunipata, whereas, the minimum (1.94 g) was recorded in the genotype BRRI dhan49 under control condition the. Under low P stress condition, the maximum 100-SW (2.61 g) was recorded in the genotype Begunipata, whereas, the minimum (1.94 g) was found in the variety BRRI dhan49 (Table 2). A significant reduction in 100-SW was observed in response to low P stress, the maximum reduction (8.42%) was

Table 3: Principal components (PCs) for eight yield and yield-related traits in six rice genotypes from principal component analysis with Eigen vectors (loadings) of the first three PCs

Variables	PC1	PC2	PC3
DFF	0.375	-0.360	0.407
DM	0.410	-0.350	0.368
PH (cm)	0.189	0.388	0.488
NTTP	0.512	0.192	-0.221
NETP	0.504	0.219	-0.190
PL (cm)	-0.102	0.451	0.478
100-SW (g)	-0.353	-0.002	0.375
YPP (g)	0.074	0.556	-0.080
% Variation explained	37.1%	33.1%	15%
ANOVA for PC scores			
T (*p* value)	<0.001	<0.001	<0.001
G (*p* value)	<0.001	<0.001	<0.001
T×G (*p* value)	0.012	0.193	0.061

T=Treatment, G=Genotypes, T×G = Treatment –Genotype interaction, *p*=Probability of statistical significance. Here, DFF=days to first flowering, DM=days to maturity, PH=plant height (cm), PL=panicle length (cm), NTTP=number of total tillers/plant, NETP=number of effective tillers/plant, 100-SW=100 seed weight (g), YPP=yield/plant (g)

recorded in the genotype Begunipata followed by 5.73%, 5.14%, 3.45% and 3.00% for the varieties BRRI dhan78, Binadhan-17, BRRI dhan71, BRRI dhan49, respectively. The least reduction (2.81%) was recorded in the variety BRRI dhan79 (Table 2).

Seed yield per plant (g)

Under control condition, the highest YPP 3.03 (g) was recorded in the variety BRRI dhan78, whereas, the lowest 1.60 (g) was recorded in the variety BRRI dhan49. Under low P stress, the highest YPP (2.57 g) was recorded for the variety Binadhan-17, whereas, the lowest (1.60 g) was found in the genotype BRRI dhan49. Imposition of low P stress resulted in a significant decrease in YPP for all the genotypes when compared to control (Table 2). The highest reduction in YPP was recorded for the variety BRRI dhan78 (32.01%), followed by BRRI dhan49 (30.73%), Begunipata (19.72%), BRRI dhan79 (12.98%), BRRI dhan71 (12.63%), however, the lowest reduction was recorded for the genotype Binadhan-17 (3.75%) (Table 2).

Principal Component Analysis

The PCA results of eight seed yield and yield-related traits, and their relative contributions towards the total genetic divergence is presented in Table 3. Data were considered in each component with Eigen values more than 1, as it determines a minimum 10% of the variation Brejda *et al.* (2000). In the present study, three components indicated Eigen values of greater than one. The first three PCs with Eigen values explained 85.2% of the total variation among 6 rice genotypes for the 8 quantitative traits studied. PCA revealed that PC1 accounted for more than 37% of total variance where NTTP had the highest positive loadings (0.512) followed by NETP (0.504), DM (0.410), DF (0.375), PL (0.189) and YPP (0.0.074). The PC2 accounted for more than 33% of total variance whereby YPP (0.556), PL (0.451), PH (0.388), NETP (0.219), and NTTP (0.192) exhibited the highest positive loadings and DF (-0.360) showed the highest negative loading, followed by DM (-0.350) and 100-SW (-0.002). The PC3 accounted for 15% of the total variance whereby PH showed highest positive loading (0.488) and NTTP showed the highest negative loading (-0.221) (Table 3).

Estimation of Correlation Coefficient among Yield and Yield-related Traits

The Pearson correlation coefficient among the yield and yield-attributing morphological traits that attribute the yield is available in Table 4. Days to maturity showed significant positive correlation with DFF (0.977**). Panicle length (cm) showed significant positive correlation with PH (0.590**) whereas it showed a non-significant negative correction with DFF and DM. Plant height had positively non-significant correlation with DFF and DM. A significant positive correction was also found between NTTP and DM (0.344*) whereas NTTP showed a non-significant negative correction with PL and positive correction with DFF and PH. Number of effective tillers per plant showed a positive correlation with PH (0.344*) and NTTP (0.982**), whereas, it showed a non-significant negative correction with PL. 100-Seed weight showed a significant negative correlation with NTTP (-0.492**) and NETP (-0.451**), whereas, it showed non-significant positive correlation with PL. Finally, YPP showed significant positive correction with PH (0.482**), PL (0.551**), NTTP (0.415*) and NETP (0.450**), whereas, it showed significant negative correlation with DF (-0.416*) and DM (-0.435**) and a non-significant negative correction with 100-SW (Table 4).

Stress Tolerance Indices based on Seed Yields of Six Rice Genotypes obtained from Control and Low P Stress

Different stress tolerance indices of rice genotypes that were estimated from yields in normal and low P stress conditions are presented in Table 5. The highest MP value was recorded in BRRI dhan71 (2.75) followed by Binadhan-17 (2.62), BRRI dhan78 (2.54), BRRI dhan79 (2.45), Begunipata (1.97) and the lowest was found in BRRI dhan49 (1.96). The highest GMP value in the variety BRRI dhan71 (2.74) followed by Binadhan-17 (2.62), BRRI dhan78 (2.49), BRRI dhan79 (2.45), Begunipata (1.96) and the lowest in the genotype BRRI dhan49 (1.92). The highest value for TOL was observed in the genotype BRRI dhan78 (0.97) followed by BRRI dhan49 (0.70), Begunipata (0.43), BRRI dhan71 (0.37), BRRI dhan79 (0.34) and the lowest was observed in genotype Binadhan-17 (0.10). The highest SSI was obtained in the genotype BRRI dhan78 (1.73), followed by BRRI dhan49 (1.65), Begunipata (1.07), BRRI dhan79 (0.70), BRRI dhan71 (0.68) and the lowest was found in genotype Binadhan-17 (0.20). Maximum STI value was obtained in BRRI dhan71 (1.09) followed by Binadhan-17 (1.00), BRRI dhan78 (0.90), BRRI dhan79 (0.87), Begunipata (0.56) and the lowest in the variety BRRI dhan49 (0.54). The highest YI was obtained in the variety Binadhan-17 (1.20) and BRRI dhan71 (1.20), followed by BRRI dhan79 (1.07), BRRI dhan78 (0.96), Begunipata (0.82) and the lowest was recorded in the variety BRRI dhan49 (0.75).

Table 4: Simple phenotypic correlation coefficient among different yield and yield-related traits rice genotypes

Traits	DFF	DM	PH (cm)	PL (cm)	NTTP	NETP	100-SW (g)
DM	0.977**						
PH (cm)	0.023	0.054					
PL (cm)	-0.311	-0.312	0.590**				
NTTP	0.280	0.344*	0.295	-0.051			
NETP	0.261	0.320	0.344*	-0.014	0.982**		
100-SW (g)	-0.166	-0.263	-0.116	0.210	-0.492**	-0.451**	
YPP (g)	-0.416*	-0.435**	0.482**	0.551**	0.415*	0.450**	-0.021

*and **indicates significant at and 5% and 1% level of probability, respectively. Here, DFF=days to first flowering, DM=days to maturity, PH=plant height (cm), PL=panicle length (cm), NTTP=number of total tillers/plant, NETP=number of effective tillers/plant, 100-SW=100 seed weight (g), YPP=yield/plant (g)

Table 5: Stress tolerance indices for rice genotypes, estimated from yields obtained from control and low P stress conditions

Genotypes	MP	GMP	TOL	SSI	STI	YI
Binadhan-17	2.62	2.62	0.10	0.20	1.00	1.20
BRRI dhan49	1.96	1.92	0.70	1.65	0.54	0.75
BRRI dhan71	2.75	2.74	0.37	0.68	1.09	1.20
BRRI dhan78	2.54	2.49	0.97	1.73	0.90	0.96
BRRI dhan79	2.45	2.45	0.34	0.70	0.87	1.07
Begunipata	1.97	1.96	0.43	1.07	0.56	0.82

Here, SSI=Stress Susceptibility Index, TOL=Stress Tolerance, MP=Mean Productivity, STI=Stress Tolerance Index, GMP=Geometric Mean Productivity, and YI=Yield Index

DISCUSSION

In Bangladesh, 65% of agricultural land experiences soil fertility decline (Egashira *et al.*, 2003) and promotion of intensification of rice cultivation due to population pressure has caused a gradual reduction in soil fertility. High yielding varieties that require excess synthetic fertilizer are also responsible for poor soil health. So, it is a first-hand challenge to agriculture to keep rice production stable in such nutrient deficient soil. It is estimated that, more than 80% of P applied as fertilizer is clogged with soil particles, rendering it unavailable for adequate plant growth (Nadira *et al.*, 2014). Rice production is seriously constrained when soil is deprived of essential plant nutrients like P (Ismail *et al.*, 2007). In addition, a delay in maturity, high sterility, as well as poor grain quality is also noticeable symptoms under P deficiency (Dobermann & Fairhurst, 2000). In the current study, efforts were made to find out the effects of low P stress on seed yield and yield-related traits in six rice genotypes. The association among characters was also studied by correlation coefficient analysis. Principal component analysis was also used to explore the variability of the studied characters and genotypes, respectively. Low P stress tolerance indices were also estimated to identify the tolerant genotypes.

Effect of Low P Stress on Yield-related Traits of Rice Genotypes

The flowering of rice is a complex process, which is regulated by many internal and external factors, which interact and restrict each other. Delayed in flowering and ripening is a common consequence of low P stress in rice. Results of the present study also showed that all of the genotypes showed a significant delayed in flowering and ripening, however, minimum delayed in DFF and DM was recorded in the variety was recorded BRRI dhan49 whereas maximum delayed were observed in Binadhan-17 (Table 2). Similar to our results delayed in flowering and maturity were also reported in rice (Atakora *et al.*, 2015; Ye *et al.*, 2019; Kale *et al.*, 2020; Kavitha *et al.*, 2022), which could be a plant adaptive mechanism for effective/increased phosphorus acquisition and utilization (Nord & Lynch, 2008). Since low gibberellin levels have been shown to delay flowering and P levels were positively correlated with gibberellin levels (Blazquez *et al.*, 1998), the delayed flowering caused by low-P level could be achieved by gibberellin signaling (Jiang *et al.*, 2007).

Plant height was found to decrease in response to low P stress. The highest PH reduction was noted in the Begunipata whereas the lowest was the lowest was recorded in BRRI dhan78 which could be another adaptive mechanism that helps the plant to acquire more P for growth and maintenance, thus reducing the cell growth (Cancellier *et al.*, 2012). Similar to our results, decrease in PH in response to low P stress has also been found by others (Kale *et al.*, 2020; Kavitha *et al.*, 2022; Miriyala *et al.*, 2022). Increased root growth relative to shoot under low P stress was associated with increased sucrose concentration in roots, and thus possibly resulted from assimilates liberated by shoot growth inhibition which eventually reduced the PH (Luquet *et al.*, 2005). Additionally, under low P stress, PH was found to decrease due to decrease in RuBP pool size and insufficient ATP synthesis as well as consequently to a decrease in photosynthetic C assimilation and ultimately plant growth becomes stunted (Pieters *et al.*, 2001; Havlin *et al.*, 2005).

The NTTP and NETP are the most important traits that contribute to yield of plants. Low P stress considerably decreased the NTTP and NETP in the majority of the investigated genotypes in the current study; Begunipata experienced the maximum reduction, while Binadhan-17 experienced the lowest reduction (Table 2). A similar result of decreasing in NTTP and NETP was also reported by others (Fageria *et al.*, 2011; Fageria & Knupp, 2013; Atakora *et al.*, 2015; Deng *et al.*, 2020; Kale *et al.*, 2021; Miriyala *et al.*, 2022; Basavaraj *et al.*, 2022) and thus the number of tillers can be used as one of the criteria to evaluate low soil P tolerance in rice. Extensive root systems and robust seedlings are promoted by P. Plants grown on P deficient soils appear stunted with dark green leaves due to anthocyanin accumulation, suppressed root development, and reduced tillering (Doberman & Fairhurst, 2000). Number of total tillers per plant is reduced due to decline in leaf biomass and changes in the photosynthetic process under low P stress. Tiller abortion rate increased when plants were exposed to low P condition as a result number of effective tillers/plant also reduced.

In addition to the above traits, PL, 100-SW and YPP were also found to decrease significantly (Table 2) in response to low P stress. Importantly, maximum decrease of these traits was observed the genotypes Begunipata, BRRI dhan49 and BRRI dhan78. In contrast, minimum decrease was observed in the varieties Binahdan-17, BRRI dhan71 and BRRI dhan79 as compared to control (Table 2). In accordance with our results, decrease in PL, 100-SW and YPP in rice in response low P stress was also reported by other researchers (Kale *et al.*, 2020; Basavarag *et al.*, 2022; Kavitha *et al.*, 2022; Miriyala *et al.*, 2022). Phosphorus is a constituent of nucleic acids, phospholipids and it also participates in the processes of energy production and enzyme activation (Marschner, 2012). Phosphorus limitation adversely affects crop yield and quality. Low P stress causes various physiological alterations, such as disruption of membranes, impaired biomolecules and high-energy molecules formation, nutrient imbalance, differences in enzyme activation/inactivation and lower cell division activity and impairment of metabolic functions and increase energy investment (Balyan & Singh, 2005; Havlin *et al.*, 2005; Razaq *et al.*, 2017). Lower yield observed under low P stress may be due to reduced photosynthetic efficiency because adequate concentrations of P are important to maintain high rates of photosynthesis to fill the developing seeds (Usuda & Shimogawara, 1991; Rychter *et al.*, 2005). However, few varieties showed a less decrease in yield and yield attributing traits under low P stress conditions probably due to their higher P uptake or P utilization efficiency (Kale *et al.*, 2020).

Principal Component Analysis

To assess morphological variation and establish a genetic link among genotypes, PCA analysis has been applied to many crops. It evaluates each element's importance and contribution to overall variation. While each coefficient of proper vectors represents the level of contribution of every original variable with which each PC is related, it can be used to quantify the independent influences of a specific attribute on the overall variance. The higher the coefficient, regardless of the sign, the more effective it will be in discriminating between varieties. In the present study, PCA indicated three PCs with Eigen values more than unity and accounted for 85.2% of the total variance in the data (Table 3). PC1 and PC2 differentiated those genotypes having higher NTTP, PH, NETP, DFF and DM and YPP. In PC2, the genotypes were differentiated according to the positive and negative values of the traits. However, the negative values only suggest the direction of the correlation between the component and the variable. In PC3, PH, PL, DFF, 100-SW and DM exhibited highly positive loading and thus it differentiated the genotypes with good vegetative growth having more seed grain. Therefore selection of traits via the traits that contribute to maximum variability through three major PCs would be rewarding. Similar amount of cumulative variance with three major CPs was also reported by Basavaraj *et al.* (2022).

Correlation Coefficient among Yield and Yield-related Traits

Correlation analysis sheds light on the relationship between grain yield and other qualities and aids plant breeders in formulating suitable selection strategies for improving multiple attributes simultaneously. Results from the phenotypic correlation coefficients (Table 4) revealed that YPP had a positive and significant correlation with PH, PL, NTTP and NEPT, indicating the importance of these traits for increasing yields. Similar to our results, significant positive correction between PH, PL, NTTP and NEPT with YPP were also reported by others under control (Emi *et al.*, 2021) and low P stress conditions (Basavaraj *et al.*, 2022). The significant and positive associations between these characters suggested that an additive genetic model was less affected by environmental fluctuation. Thus direct selection of these traits could be ideal criteria for higher grain yield under low P stress conditions. Positive and significant correlations were also found for NTTP with DM, which indicated that late maturing variety has more vegetative growth as well as more tillering; increasing number of total tillers substantially increase the number of effective tillers; DM with DFF indicating that those varieties which having early flowering tendency will mature earlier. These results agreed with those of previous workers (Ratna *et al.*, 2015). Positive, but non-significant associations were for 100-SW with PL; NETP with DFF and DM; NEPT with DFF and PH; PH with DFF and DM were also recorded. Positive and non-significant correlation referred information of inherent relation among the pairs of combinations. Similarly few non-significant relations were also observed among the traits. The negative and non-significant association referred a complex linked of relation among the pair of combinations.

Stress Tolerance Indices

For the purpose of identifying tolerant genotypes tested under abiotic stress conditions, a number of indices had been developed. Recently, low P tolerance in rice was also evaluated using these indices (Swamy *et al.*, 2019; Manoj *et al.*, 2023). Based on the contribution of the specific trait, the stress indices were grouped into two categories; tolerant indices (MPI, MRP, REI, STI, and DTE) and susceptible indices (TOL and SSI). Several selection criteria are proposed for selecting genotypes, with consideration to plant yield, based upon their performances under normal and low P stress environments. The SSI study (Table 5) demonstrated that genotype BRRI dhan78 had the highest value, whereas the lowest value was recorded for the genotype Binadhan-17. Higher values of SSI indicate higher sensitivity to and a greater reduction in yield under low P stress conditions (Guttieri *et al.*, 2001). In contrast, lower values indicate a lower susceptibility to low P stress. Therefore, based on SSI, Binadhan-17 genotype could be considered as tolerant genotypes. Results of the TOL index showed that the variety BRRI dhan78 had the highest TOL value with the lowest value obtained by the genotype Binadhan-17. A low TOL index value indicates higher tolerance to low P stress (Khodarahmpour *et al.*, 2011). Selections made on this criterion are specific for genotypes with low yield potential under non-stress conditions and better yield potentials under stress conditions (Fernandez, 1992). So, this criterion does not help us to separate genotypes yielding well under stress conditions, from genotypes yielding well under both stress and unstressed conditions. Based on the result of MP, the genotype BRRI dhan71 had the highest value followed by Binadhan-17, BRRI dhan78, BRRI dhan79 and Begunipata. It was reported that a positive correlation was present between MP and Ys (stressful environment), therefore, selection based on MP will improve average yields under both stress and non-stress conditions (Rosielle & Hamblin, 1981). Therefore, high MP can be used in the genotype selection process. A higher STI value for a genotype in a stressful environment means higher stress resilience and greater yield potential (Fernandez, 1992). The variety BRRI dhan71 followed by Binadhan-17 and BRRI dhan78 genotypes that have higher values of STI, indicate their tolerance to low P stress. The study of GMP showed that the genotype BRRI dhan71 had the highest value. Based on this index, genotypes with higher values were considered tolerant and had high yields under both normal and stress conditions (Khodarahmpour *et al.*, 2011). In the present study, YI discriminated the genotypes Binadhan-17, BRRI dhan71 and BRRI dhan79 as the most tolerant genotypes. YI was particularly relevant to differentiate tolerant and sensitive varieties under low P conditions. According to our results, low P significantly reduced the seed yield of some genotypes, while others were tolerant to low P stress. This indicates that sufficient genetic variability was present for low P tolerance among the genotypes studied. Based upon the stress tolerance indices it was found that Binadhan-17, BRRI dhan71, and BRRI dhan79 were potential low P stress tolerant genotypes as they performed well under low P stress conditions.

CONCLUSION

The current study showed that the genetic material under inquiry had significant phenotypic variability under both control and stressful circumstances. Imposition of low P stress resulted in a significant decrease in yield and yield-related traits, however, the varieties Binadhan-17, BRRI dhan71, and BRRI dhan79 showed a lower decrease of the morphological yield attributing traits under P stress. PCA indicated that NTTP, NETP, DM, DFF, PH and YPP are the most important characters contributing to the total genetic divergence. Correlation analysis revealed that YPP showed positive and significant correlation with PH, PL, NTTP and NETP. Based on stress tolerance indices Binadhan-17, BRRI dhan71 and BRRI dhan79 were categorized as tolerant genotypes. However, more study utilizing these genotypes under different agro-climatic conditions is required to investigate the further insights for developing low P stress tolerant rice variety.

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