Proceedings of the Pakistan Academy of Sciences:
B. Life and Environmental Sciences 55 (2): 55–64 (2018)

ISSN: 2518-4261 (print), ISSN 2518-427X (online)

Pakistan Academy of Sciences

Research Article

Differential Performance of Wheat Genotypes for Grain Yield, Phosphorus Uptake and Utilization at Low and High Phosphorus Levels

Muhammad Abbas*, Muhammad Irfan, and Javaid Ahmed Shah

Soil and Environmental Sciences Division, Nuclear Institute of Agriculture (NIA), Tando Jam

Abstract: A pot experiment was conducted to test grain yield response and phosphorus use efficiency (PUE) in 10 wheat genotypes at low (10 mg P kg^{-1} soil) and high (40 mg P kg^{-1} soil) soil phosphorus (P) levels. The genotypes differed significantly ($P < 0.05$) for grain yield, P uptake and P efficiency indices at each P level. Phosphorus stress factor (PSF) varied between 0.15 and 30.1%, signifying the differential P responsiveness of the wheat genotypes. Each parameter was assigned an index score of 1, 2, or 3 for its low, medium, or high grade of performance at each P level. Furthermore, the genotypes were grouped into six categories based on their grain yield and total P uptake at low P level. Genotypes EST-28/11 and MSH-3 with high grain yield (8.42 and 7.95 g pot^{-1}) and high P uptake (38.0 and 30.9 mg P pot^{-1}), and NIA-Sunder with high grain yield (8.33 g pot^{-1}) but medium P uptake (23.9 mg P pot^{-1}) at low P level can be selected for P deficient soils. Genotypes EST-28/11, MSH-3 and NIA-Sunder also attained high total index scores (25, 23 and 23) at low P level. Such type of categorization will aid in breeding programs for improving nutrient use efficiency.

Keywords: Phosphorus efficiency index, Phosphorus utilization, Plant nutrition, Wheat genotype.

1. INTRODUCTION

Phosphorus (P) deficiency is a major constraint to crop productivity on more than 30% of the world's cultivated soils [1] and about 5 to 15% of yield losses are attributed to the deficiency of this nutrient [2]. In case of Pakistan, P deficiency has been reported on more than 90% of soils. High pH and calcium carbonate contents impart P fixing properties to the Pakistani soils which entail into low recovery (15-20% only) of applied P fertilizers [3]. Inorganic P fertilizers are manufactured from mined rock phosphate (RP) which is a limited and non-renewable resource, and expected to deplete by the end of this century [4]. Diminishing RP reserves, geographical concentration of RP in only very few countries of the world, low recovery and high prices of P fertilizers, and environmental pollution due to P losses warrant the global stakeholders to come up with multi-dimensional and sustainable strategies to resolve this problem [5]. The development of crop cultivars that uptake and/or utilize P more efficiently on P deficient soils seems a sustainable alternative to the conventional high input approach [6]. Cultivation of P efficient crops will significantly improve the efficiency of P fertilizers and decrease the cost of production as well as environmental deterioration. Genotypic variation for P efficiency has been reported in many crops like rice [7], barley [8], Brassica [9], wheat [6] and cotton [10] which can be exploited to uphold the productivity of P impoverished agricultural systems.

Phosphorus efficiency in any crop can be improved by the screening and categorization of existing germplasm for growth and yield performance in low P medium. Such type of classification will lead to the identification of genotypes that can be effectively grown on soils with variable P contents. Some researchers have classified the crop genotypes based on their biomass production and P utilization [6, 11] and

Received, March 2017; Accepted, June 2018
* Corresponding Author: Muhammad Abbas; alimadad51214@gmail.com

identified two categories for each of efficiency and response, i.e. i) efficient and responsive, ii) efficient but non-responsive, iii) inefficient but responsive, and iv) inefficient and non-responsive. However, the usefulness of such classification was challenged by Aziz et al. [12] as no sharp distinction between efficiency as well as response groups could be made. A cultivar may be categorized as efficient or inefficient if it has mean value slightly higher or lower than the population mean. Contrarily, Gill et al. [13] proposed nine different classes of wheat cultivars by employing metroglyph technique with three categories viz., low, medium and high of efficiency and responsiveness each. Such type of classification was very effective and could accommodate a wide range of medium efficient or responsive cultivars between low and high extremes.

Wheat, the staple food of Pakistan, is being sown on more than 9 million hectares annually, with production of about 25 million tons [14]. It contributes to 1.9 % of GDP of the country and 9.6 % of the value addition in agriculture. A major chunk of production cost of wheat crop is associated with P fertilizer inputs. According to NFDC [15], wheat crop accounts for 50% of annual P fertilizer consumption in Pakistan. In this perspective, improvement in P use efficiency of wheat crop alone can significantly affect P fertilizer demand in future. The current study was, therefore, undertaken to evaluate the growth and yield response of 10 wheat genotypes at low and high P levels in soil.

2. MATERIALS AND METHODS

Seeds of 10 wheat genotypes were collected from Plant Breeding and Genetics Division, Nuclear Institute of Agriculture (NIA), Tando Jam. Genotypes included nine advanced wheat lines (AA-V1, AA-V2, AA-V3, MSH-3, MSH-5, BWQ-4, EST-28/11, EST-29/9, ESW-9525) and one cultivar (NIA-Sunder). Soil was collected from the experimental field of NIA, Tando Jam. It was air-dried, crushed to pass through a 2 mm sieve and subsequently filled in plastic pots of 10 kg capacity (25 cm diameter and 30 cm depth). The soil used in the pot experiment was clay loam in texture (with 21.7, 42.2 and 36.1% sand, silt and clay, respectively), non-saline (EC_e = 2.1 dS m^{-1}), alkaline (pH = 7.9) with 12.5% $CaCO_3$, 0.73% organic matter, 0.081% Kjeldahl N, and 3.7 and 180 mg kg^{-1} AB-DTPA (ammonium bicarbonate - diethylene triamine penta acetic acid) extractable P and K, respectively.

The experiment was laid-out in a completely randomized design with factorial combination of 10 wheat genotypes and two phosphorus levels in three replicates. Two P levels, i.e. 10 mg P kg^{-1} soil (20 kg P ha^{-1}, low P) and 40 mg P per kg^{-1} soil (80 kg P ha^{-1}, high P) were established with triple super phosphate (TSP). These levels of P were adopted from Wang et al. [16]. A basal dose of 40 mg N kg^{-1} was adjusted with urea in all pots. An additional 40 mg N kg^{-1} was supplied to each pot at tillering (after 30 days of sowing) and booting stage (after 60 days of sowing) of the crop to reach total amount of nitrogen 120 mg N kg^{-1} soil (240 kg N ha^{-1}). All pots received 40 mg K kg^{-1} soil (80 kg K ha^{-1}) in the form of sulfate of potash (SOP). Before seed sowing, a basal dose of urea and all of TSP and SOP were mixed well into the soil.

Ten seeds were sown in each pot, and at two-leaf stage the seedlings were thinned to maintain only five similar sized plants. Pots were irrigated with reverse osmosis (RO) water as and when required. At maturity, plants were harvested and separated into grain and straw by manual threshing. Grain and straw weight was measured using a weighing balance. The samples were then dried at 70 °C in a forced-air oven for three days. The oven-dried samples of grain and straw were finely ground and one gram of each sample was digested in a di-acid mixture of nitric acid (HNO_3) and perchloric acid ($HClO_4$) [17]. The digested material was analyzed spectrophotometrically for P contents following the method of Chapman and Pratt [18]. Phosphorus uptake (mg P pot^{-1}) in grain and straw was estimated by multiplying P concentration with their corresponding dry weights. Total P uptake (mg P pot^{-1}) was obtained by adding up grain and straw P uptake. The following parameters were calculated as described by Gill et al. [13]:

Phosphorus stress factor (PSF %) =

$$\frac{\text{Grain yield at high P (g pot}^{-1}) - \text{Grain yield at low P (g pot}^{-1})}{\text{Grain yield at high P (g pot}^{-1})}\times 100$$

Phosphorus harvest index (PHI %) =

$$\frac{\text{Grain P uptake (mg P pot}^{-1})}{\text{Total P uptake (grain+straw, mg P pot}^{-1})}\times 100$$

Phosphorus physiological efficiency ratio (PPER) =

$$\frac{\text{Grain yield (g pot}^{-1})}{\text{Total P uptake (grain+straw, g P pot}^{-1})}$$

Phosphorus biological yield efficiency ratio (PBER) =

$$\frac{\text{Total yield (grain+straw, g pot}^{-1})}{\text{Total P uptake (grain+straw, g P pot}^{-1})}$$

The collected data were analyzed by the analysis of variance (ANOVA) technique according to the two factorial-completely randomized factorial designs. The treatment means were differentiated by Tukey's Honestly Significant Difference (HSD) method [19] at 5% probability level. Moreover, each genotype was assigned an index score/value of 1, 2 or 3 for low (if mean is < μ - SD), medium (if mean is between μ - SD to μ + SD) and high (if mean > μ+SD) grade of performance of each character at each P level following the method of Gill et al. [13]. The μ and SD represent population mean and standard deviation, respectively. Total index score for each genotype at each P level was calculated by adding up the index values of all the characters for that particular genotype. In case of PSF, an opposite order of low and high index scores was applied because the genotypes with higher PSF values were more sensitive to low P stress.

3. RESULTS

3.1 Grain, Straw and Total Yield (g pot^{-1})

The data analysis showed that the individual effects of genotypes and P levels on grain yield were significant (P < 0.05), but their interactive effects could not produce significant effect (Table 1). Averaging across the genotypes, grain yield increased from 6.79 to 7.82 g pot^{-1} with increase in the P level from 10 to 40 mg P kg^{-1} soil. The wheat genotypes demonstrated variable yield response at each P level. At low P level, the grain yield ranged between the highest (8.42 g pot^{-1}) for EST-28/11 and the lowest (5.46 g pot^{-1}) for MSH-5. At high P level, NIA-Sunder and MSH-5 produced the highest and the lowest grain yields, respectively. Increment in grain yield by increasing P level indicates the responsiveness of the genotypes, though the genotypes varied widely in their extent of responsiveness. Genotype AA-V2 exhibited the highest response to P as it registered 43% increase in grain yield when P rate was increased from 10 to 40 mg P kg^{-1} soil. Genotypes AA-V1, MSH-3 and EST-28/11 exhibited no response to the higher level of P in soil.

Straw yield was significantly (P < 0.05) influenced by the individual as well as interactive effects of genotypes and P levels. Averaged across 10 genotypes, the straw yield increased from 14.2 to 16.3 g pot^{-1} when P application rate increased from 10 to 40 mg P kg^{-1} soil. The genotypes exhibited remarkable variations in straw yield at both P levels. The straw yield ranged from 9.66 to 17.5 g pot^{-1} at low P level and from 13.3 to 18.7 g pot^{-1} at high P level (Table 1).

Total yield (grain + straw) also increased with increase in the soil P level. About 12% increase in total yield was recorded by increasing P rate from 10 to 40 mg P kg^{-1} soil. At low P level, the highest total yield (24.3 g pot^{-1}) was produced by ESW-9525 and it was statistically at par with that of EST-28/11 and NIA-Sunder, while AA-V2, AA-V1 and MSH-5 produced the lowest and statistically identical total yield. It ranged from 19.6 to 26.5 g pot^{-1} at high P level. Like grain yield, no significant interactive effects of the genotypes and P levels could be observed on total yield (Table 1).

3.2 Phosphorus Stress Factor (PSF %)

Phosphorus stress factor (PSF) or relative tolerance to P deficiency varied significantly (P < 0.05) among wheat genotypes (Table 1). In this study, PSF ranged between 0.15 and 30.1 %, indicating an extensive genetic variability among the wheat genotypes for grain production in response to high P level. Genotypes viz., AA-V1, MSH-3 and EST-28/11 showed no response to high P level, as their PSF values were equal or lower than one. However, AA-V2, BWQ-4 and EST-29/9 with higher PSF values can be regarded as high P responsive.

3.3 Phosphorus Uptake (mg P pot^{-1})

Phosphorus uptake in both grain and straw was significantly influenced by the main as well as interactive effects of the genotypes and P levels (Table 2). Phosphorus uptake in grain increased by 45% with the application of high P rate (40 mg P kg^{-1} soil). At low P level, EST-28/11 with grain P

Table 1: Performance of wheat genotypes for grain yield, straw yield, total yield and phosphorus stress factor (PSF) at low and high P levels

	Grain yield ($g\ pot^{-1}$)		**Straw yield ($g\ pot^{-1}$)**		**Total yield ($g\ pot^{-1}$)**		**PSF (%)**
Genotypes	Low P	High P	Low P	High P	Low P	High P	
AA-V1	6.27 (2)†	6.31 (1)	12.5 (2)	13.3 (1)	18.8 (1)	19.6 (1)	0.67 (3)
AA-V2	6.17 (2)	8.82 (2)	9.66 (1)	15.1 (2)	18.5 (1)	21.3 (1)	30.1 (1)
AA-V3	6.99 (2)	8.04 (2)	13.0 (2)	14.9 (2)	20.0 (2)	22.9 (2)	12.8 (2)
MSH-3	7.95 (3)	7.98 (2)	14.6 (2)	15.1 (2)	22.6 (2)	23.1 (2)	0.38 (3)
MSH-5	5.46 (1)	6.26 (1)	13.7 (2)	15.3 (2)	19.1 (2)	21.5 (2)	12.7 (2)
BWQ-4	5.50 (1)	7.54 (2)	16.6 (3)	18.3 (3)	22.1 (2)	25.8 (2)	27.3 (1)
EST-28/11	8.42 (3)	8.43 (2)	15.5 (2)	18.1 (2)	24.0 (3)	26.5 (3)	0.15 (3)
EST-29/9	5.95 (2)	7.51 (2)	14.6 (2)	17.8 (2)	20.5 (2)	25.3 (2)	20.6 (2)
ESW-9525	6.87 (2)	7.70 (2)	17.5 (3)	18.7 (3)	24.3 (3)	26.4 (3)	10.9 (2)
NIA-Sunder	8.33 (3)	9.66 (3)	14.6 (2)	16.2 (2)	23.0 (2)	25.9 (2)	13.5 (2)
$HSD_{0.05}$, P	0.44		0.58		0.59		---
$HSD_{0.05}$, G	1.65		2.16		2.20		16.05
$HSD_{0.05}$, P×G	NS		3.45		NS		---

† Values in parentheses represent index scores.
$HSD_{0.05}$ = Honestly Significant Difference at 5% probability level; P = phosphorus levels;
G = genotypes; P×G = interaction between phosphorus levels and genotypes; NS = non-significant

Table 2: Phosphorus uptake in grain and straw of wheat genotypes grown at low and high P levels

	P uptake ($mg\ P\ pot^{-1}$)					
	Grain		**Straw**		**Total**	
Genotypes	Low P	High P	Low P	High P	Low P	High P
AA-V1	22.0 (2)†	30.6 (1)	6.10 (2)	7.40 (1)	28.1 (2)	38.0 (1)
AA-V2	19.9 (2)	40.0 (3)	3.70 (1)	7.39 (1)	23.6 (1)	47.3 (2)
AA-V3	24.6 (2)	35.8 (2)	4.05 (1)	10.8 (2)	28.7 (2)	46.6 (2)
MSH-3	30.9 (3)	39.9 (3)	8.64 (2)	10.1 (2)	39.5 (3)	50.0 (2)
MSH-5	19.9 (2)	31.3 (1)	7.12 (2)	10.6 (2)	27.0 (2)	41.9 (1)
BWQ-4	18.1 (1)	36.0 (2)	11.5 (3)	13.3 (3)	29.6 (2)	49.3 (2)
EST-28/11	38.0 (3)	41.7 (3)	5.96 (2)	10.1 (2)	43.9 (3)	51.7 (3)
EST-29/9	22.4 (2)	33.7 (2)	8.11 (2)	12.7 (3)	30.5 (2)	46.4 (2)
ESW-9525	28.5 (2)	34.3 (2)	10.4 (3)	12.0 (2)	38.9 (3)	46.3 (2)
NIA-Sunder	23.9 (2)	37.9 (2)	4.87 (2)	8.29 (2)	28.8 (2)	46.2 (2)
$HSD_{0.05}$, P	1.92		0.42		1.81	
$HSD_{0.05}$, G	7.11		1.57		6.71	
$HSD_{0.05}$, P×G	11.38		2.51		10.74	

† Values in parentheses represent index scores.
$HSD_{0.05}$ = Honestly Significant Difference at 5% probability level; P = phosphorus levels;
G = genotypes; P×G = interaction between phosphorus levels and genotypes

uptake of 38.0 mg P pot^{-1} was statistically superior to the rest of genotypes. Genotypes EST-28/11, MSH-3, AA-V2 and NIA-Sunder had the highest and statistically identical grain P uptake at high P level. Overall, P uptake in grain ranged between 18.1 and 38.0 mg P pot^{-1} at low P level and 31.3 and 41.7 mg P pot^{-1} at high P level.

Phosphorus uptake in straw ranged between 3.70 and 11.5 mg P pot^{-1} at low P level and from 7.39 to 13.3 mg P pot^{-1} at high P level depending on the genotypes. Increase in P application rate caused a 45% increase in P uptake in straw. Averaging across the genotypes, total P uptake (grain + straw) increased from 31.9 to 46.4 (45 % increase) by increasing P level in the soil. Total P uptake ranged between 23.6 to 43.9 mg P pot^{-1}at low P and 38.0 to 51.7 mg P pot^{-1} at high P. Generally, EST-28/11 was the highest accumulator of P at both P levels (Table 2).

3.4 Phosphorus Efficiency Indices

Phosphorus harvest index (PHI) represents the portion of total plant P (grain + straw) present in the

Table 3: Phosphorus efficiency indices and total index scores of wheat genotypes at low and high P levels

	PHI (%)[a]		PPER[b]		PBER[c]		Total index score[d]	
Genotypes	Low P	High P	Low P	High P	Low P	High P	Low P	High P
AA-V1	78.2 (2)†	80.5 (2)	223 (2)	167 (2)	670 (2)	517 (2)	20	12
AA-V2	84.1 (2)	84.3 (3)	261 (3)	186 (2)	789 (3)	450 (1)	17	17
AA-V3	85.8 (3)	76.8 (2)	243 (2)	172 (2)	699 (2)	496 (2)	20	18
MSH-3	78.2 (2)	79.7 (2)	201 (2)	160 (2)	571 (1)	462 (1)	23	18
MSH-5	73.3 (2)	74.3 (2)	201 (2)	149 (1)	715 (2)	528 (2)	19	14
BWQ-4	60.8 (1)	72.8 (1)	185 (2)	152 (2)	750 (2)	525 (2)	18	19
EST-28/11	86.3 (3)	80.5 (2)	192 (2)	163 (2)	548 (1)	513 (2)	25	21
EST-29/9	73.4 (2)	72.5 (1)	195 (2)	162 (2)	674 (2)	548 (2)	20	18
ESW-9525	73.2 (2)	74.0 (2)	176 (1)	166 (2)	628 (2)	573 (3)	23	21
NIA-Sunder	82.9 (2)	81.9 (2)	289 (3)	209 (3)	801 (3)	562 (3)	23	21
$HSD_{0.05}$, P	NS		5.15		28.48			
$HSD_{0.05}$, G	6.27		19.11		105.71			
$HSD_{0.05}$, P×G	10.03		30.58		169.13			

[a]PHI, phosphorus harvest index; [b]PPER, phosphorus physiological efficiency ratio; [c]PBER, phosphorus biological yield efficiency ratio; [d]Total index score is the sum of individual index scores for each parameter for each genotype at each P level.
† Values in parentheses represent index scores.
$HSD_{0.05}$ = Honestly Significant Difference at 5% probability level; P = phosphorus levels;
G = genotypes; P×G = interaction between phosphorus levels and genotypes; NS = non-significant

grain at crop harvest. The P levels could not produce significant ($P < 0.05$) effects on PHI of genotypes; however, the genotypes exhibited considerable variability for PHI at each P level. Variations among wheat genotypes for P allocation to grains were also elucidated by significant genotype × P level interactions (Table 3). The PHI ranged from 60.8 to 86.3% at low P and 72.5 to 84.3% at high P. This means that wheat genotypes remobilized most of their accumulated P towards grain.

Phosphorus physiological efficiency ratio (PPER) indicated the gram of grain produced per gram of P accumulated in grain plus straw. It varied significantly ($P < 0.05$) among the wheat genotypes at both P levels (Table 3). Genotypic variability for PPER was also elaborated by the significant ($P < 0.05$) genotype × P level interaction. The PPER of wheat genotypes ranged from 176 to 289 and 149 to 209 at low and high P levels, respectively. It can be observed from the data that the genotypes demonstrated higher PPER at low P level, where P uptake was comparatively low, than at high P supply. This implies that increasing P application rate had negative effects on PPER. Of all genotypes, NIA-Sunder attained the highest PPER at both levels.

Phosphorus biological Efficiency ratio (PBER) measures the biological/total yield (grain + straw) produced in relation to total P uptake. The genotypes and P levels as well as their interactions significantly ($P < 0.05$) affected this index of P utilization efficiency (Table 3). Like PPER, the PBER also decreased with increasing P level. It varied from 548 to 801 and 450 to 573 in low and high P treatments, respectively.

3.5 Categorization of Genotypes on the Basis of Index Scores

The wheat genotypes were grouped into low, medium or high scoring based on the index scores of 10 characters at low P level (Table 4) and 9 characters at high P level (Table 5). The classification scheme was adopted from Gill et al. [13]. A perusal of data showed that most of the genotypes were generally in the medium category for various parameters at both P levels. For instance, on the basis of grain yield, two genotypes were classified into low (< 5.67 g pot^{-1}), 5 into medium (5.67-7.91 g pot^{-1}) and three into high (> 7.91 g pot^{-1}) scoring category at low P level (Table 4). At adequate P level, two genotypes were in low (6.78 g pot^{-1}), seven in medium (6.78-8.87 g pot^{-1}) and one in high (8.87 g pot^{-1}) grain yield group (Table 5). Based on total P uptake, 1, 6 and 3 genotypes were classified as low (< 25.3 mg P pot^{-1}), medium (25.3-38.4 mg P pot^{-1}) and high (> 38.4 mg P pot^{-1}) P uptake groups, respectively, at low P level. The corresponding values for total P uptake at adequate P level were 2, 7, and 1, respectively for low, medium, and high groups.

Table 4: Classification of wheat genotypes on the basis of index scores of various parameters at low P level. Each genotype was assigned an index score of 1, 2 or 3 for low (if mean is < μ - SD), medium (if mean is between μ - SD to μ + SD) and high (if mean > μ+SD) grade of performance of each character. The μ and SD represent population mean and standard deviation, respectively.

	Low (score 1)	Medium (score 2)	High (score 3)
Grain yield (g pot^{-1})	< 5.67 MSH-5 & BWQ-4	5.67-7.91 EST-29/9, AA-V2, AA-V1, ESW-9525 & AA-V3	> 7.91 MSH-3, NIA-Sunder & EST-28/11
Straw yield (g pot^{-1})	< 12.0 AA-V2	12.0-16.4 AA-V1, AA-V3, MSH-5, EST-29/9, MSH-3, NIA-Sunder & EST-28/11	> 16.4 BWQ-4 & ESW-9525
Total yield (g pot^{-1})	< 19.1 AA-V1 & AA-V2	19.1-23.5 MSH-5, AA-V3, EST-29/9, BWQ-4, MSH-3 & NIA-Sunder	> 23.5 EST-28/11 & ESW-9525
Grain P uptake (mg P pot^{-1})	< 18.7 BWQ-4	18.7-30.9 MSH-5, AA-V2, AA-V1, EST-29/9, AA-V3, NIA-Sunder & ESW-9525	> 30.9 MSH-3 & EST-28/11
Straw P uptake (mg P pot^{-1})	< 4.43 AA-V2 & AA-V3	4.43-9.66 NIA-Sunder, EST-28/11, AA-V1, MSH-5, EST-29/9 & MSH-3	> 9.66 ESW-9525 & BWQ-4
Total P uptake (mg P pot^{-1})	< 25.3 AA-V2	25.3-38.4 MSH-5, AA-V1, AA-V3, NIA-Sunder, BWQ-4 & EST-29/9	> 38.4 ESW-9525, MSH-3 & EST-28/11
PSF (%)	> 23.6 AA-V2 & BWQ-4	2.18-23.6 ESW-9525, MSH-5, AA-V3, NIA-Sunder & EST-29/9	< 2.18 EST-28/11, MSH-3 & AA-V1
PHI (%)	< 69.8 BWQ-4	69.8-85.5 EST-29/9, ESW-9525, MSH-5, MSH-3, AA-V1, NIA-Sunder & AA-V2	> 85.5 AA-V3 & EST-28/11
PPER	< 179 ESW-9525	179-254 BWQ-4, EST-28/11, EST-29/9, MSH-3, MSH-5, AA-V1 & AA-V3	> 254 AA-V2 & NIA-Sunder
PBER	< 600 EST-28/11 & MSH-3	600-769 ESW-9525, AA-V1, EST-29/9, AA-V3, MSH-5 & BWQ-4	> 769 AA-V2 & NIA-Sunder

PSF, phosphorus stress factor; PHI, phosphorus harvest index; PPER, phosphorus physiological efficiency ratio; PBER, phosphorus biological yield efficiency ratio

Moreover, the wheat genotypes were grouped into six categories by regressing grain yield and total P uptake at low P level according to Gill et al. [13]. Two genotypes were placed in high grain yield-high P uptake (HGY-HP), three in medium grain yield-medium P uptake (MGY-MP), two in low grain yield-medium P uptake (LGY-MP) and one in each of high grain yield-medium P uptake (HGY-MP), medium grain yield-high P uptake (MGY-HP), medium grain yield-low P uptake (MGY-LP) group (Figure 1).

4. DISCUSSION

Productivity of low P input agricultural systems can be sustained by introducing crop cultivars efficient in P acquisition and/or utilization. Earlier research has shown that wheat genotypes differ in their response to P starvations [6, 13, 20, 21]. Genotypes selected on the basis of absolute grain yield in relation to P uptake, PHI, PPER, and PPBR will lead us to identify useful genetic characters which can be utilized in future breeding ventures aimed at evolving high-yielding P efficient cultivars. Such type of intervention would not only reduce the production costs, but also minimize P-associated environmental pollution hazards [22]. The present study was envisioned to identify ideal genotypes which have better adaptability to soil of varying P availability.

In this study, grain yield of AA-V1, MSH-3 and

Table 5: Classification of wheat genotypes on the basis of index scores of various parameters at high P level. Each genotype was assigned an index score of 1, 2 or 3 for low (if mean is < μ - SD), medium (if mean is between μ - SD to μ + SD) and high (if mean > μ+SD) grade of performance of each character. The μ and SD represent population mean and standard deviation, respectively.

	Low (score 1)	Medium (score 2)	High (score 3)
Grain yield	< 6.78	6.78-8.87	> 8.87
(g pot^{-1})	MSH-5 & AA-V1	EST-29/9, BWQ-4, ESW-9525, MSH-3, AA-V3, EST-28/11 & AA-V2	NIA-Sunder
Straw yield	< 14.4	14.4-18.1	> 18.1
(g pot^{-1})	AA-V1	AA-V3, AA-V2, MSH-3, MSH-5, NIA-Sunder, EST-29/9 & EST-28/11	BWQ-4 & ESW-9525
Total yield	< 21.3	21.3-26.3	> 26.3
(g pot^{-1})	AA-V1 & AA-V2	MSH-5, AA-V3, MSH-3, EST-29/9, BWQ-4 & NIA-Sunder	ESW-9525 & EST-28/11
Grain P uptake	< 32.4	32.4-39.9	> 39.9
(mg P pot^{-1})	AA-V1 & MSH-5	ESW-9525, EST-29/9, AA-V3, BWQ-4 & NIA-Sunder	MSH-3, AA-V2 & EST-28/11
Straw P uptake	< 8.18	8.18-12.3	> 12.3
(mg P pot^{-1})	AA-V2 & AA-V1	NIA-Sunder, EST-28/11, MSH-3, MSH-5, AA-V3 & ESW-9525	EST-29/9 & BWQ-4
Total P uptake	< 42.4	42.4-50.3	> 50.3
(mg P pot^{-1})	AA-V1 & MSH-5	NIA-Sunder, ESW-9525, EST-29/9, AA-V3, AA-V2, BWQ-4 & MSH-3	EST-28/11
PHI (%)	< 73.5	73.5-81.9	> 81.9
	EST-29/9 & BWQ-4	MSH-5, ESW-9525, AA-V3, AA-V1, MSH-3, EST-28/11 & NIA-Sunder	AA-V2
PPER	< 151	151-186	> 186
	MSH-5	BWQ-4, EST-28/11, EST-29/9, MSH-3, AA-V1, AA-V3, ESW-9525 & AA-V2	NIA-Sunder
PBER	< 478	478-557	> 557
	AA-V2 & MSH-3	AA-V3, EST-28/11, AA-V1, BWQ-4, MSH-5 & EST-29/9	NIA-Sunder & ESW-9525

PHI, phosphorus harvest index; PPER, phosphorus physiological efficiency ratio; PBER, phosphorus biological yield efficiency ratio

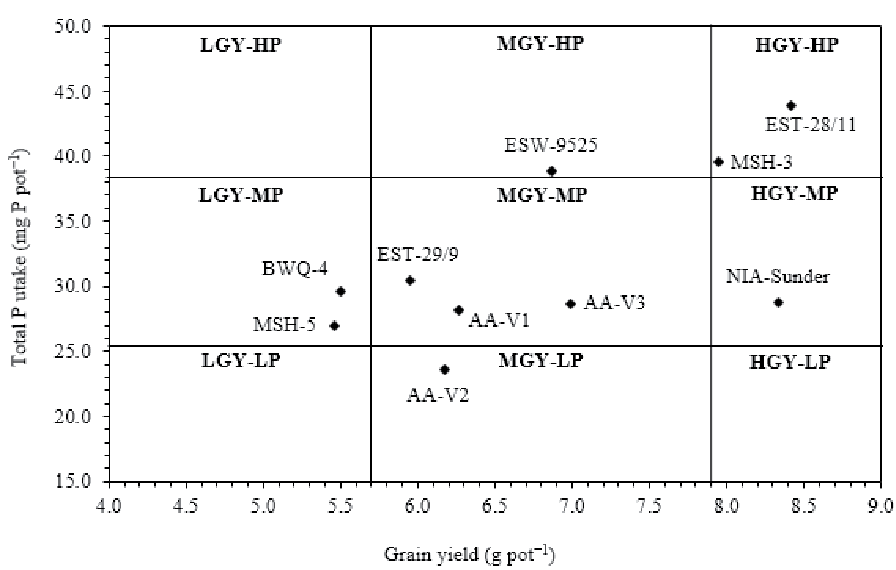

Fig. 1. Categorization of 10 wheat genotypes into different groups on the basis of grain yield and total P uptake at low P level according to Gill et al. [13]. LGY, MGY and HGY represent low, medium and high grain yield, respectively, while, LP, MP and HP represent low, medium and high P uptake, respectively.

EST-28/11 was not inhibited by P deficiency which indicated that these genotypes had a potential to sustain growth and development in P-starved environments. Yaseen and Malhi [23] have also reported that the present day wheat cultivars have ability to produce more than their older counterparts even at lower rates of P application. Genotypes viz., MSH-3 and EST-28/11, having least sensitivity to P deficiency, overcame the low P stress by allocating a major chunk of plant P in grain which is evident from their high grain as well total P uptake in low P treatment (Table 2). This information pointed out an increased translocation of absorbed P towards grain.

Grain yield of genotypes coincided much with total P uptake, though with few exceptions. For example, at deficient P supply, ESW-9525 with high P uptake characteristics was in the medium-grain-yield category and NIA-Sunder having a medium P uptake was categorized as high-grain-yielder (Table 4). Grain yield also had a strong positive relationship (r > 0.65, $P < 0.001$) with grain P uptake at both P levels, which indicates that genotypes efficient in accumulating more P in their grain also produced higher grain yield.

The PHI refers to the translocation of absorbed P towards grains. In the present study, the higher P level could not increase the pace of P translocation from straw to grain. Moreover, a strong relationship between grain yield and PHI ($r > 0.61$, $P < 0.001$) revealed that the genotypes having ability to translocate more of the accumulated P towards grains had higher grain yields at both P levels. The strong positive relationship of grain yield with grain P uptake (r > 0.82, $P < 0.001$) at both P levels also supported this argument. However, the higher PHI may result in accelerated P mining from the farmlands [24, 25] which can negatively affect the sustainability of farming systems. Breeding for low grain P concentration can be a viable option to minimize P loss; however, such intervention may have a negative effect on seed viability as well as its nutritional value. Therefore, a minimum P concentration in grain needs to be maintained for sustaining seed viability and crop establishment. High yields without reducing grain P concentration can be achieved by improved translocation of P into grains in addition to increased P uptake. In this study, 78% of total accumulated P was found in wheat grain at harvest (Table 3), showing a limited scope for increased translocation of P from straw into grain. Considering 70 to 80% of total P is present in grain, selecting for higher grain yield will further dilute grain P concentration as long as P uptake efficiency is not improved [26].

The PPER and PBER depict the efficiency by which plants utilize the accumulated P to produce grain and aboveground biomass, respectively, and they have been successfully used by Korkmaz et al. [27] and Yaseen and Malhi [23, 26] for evaluating PUE of wheat genotypes. An ideal genotype tends to absorb more P, apportions more P into grain and produces more grain per unit of absorbed P. In this study, genotypic variability for PPER at each P level indicates differential P utilization efficiency of these genotypes. It was evident from PPER results that the high-yielding genotype NIA-Sunder with high value for PPER at both P levels was efficient in P utilization and can yield well in low as well as high P environment. A positive relationship between grain yield and PPER at low ($r = 0.35$, $P > 0.05$) and high P level ($r = 0.72$, $P < 0.001$) indicated that some genotypes adopted similar physiological mechanisms to produce grain. At low P level, genotypes with high values of PBER were generally characterized with low grain yield as well as low grain P accumulation. Hence, these genotypes were inefficient in P use. This was also reflected by their relatively high values of PSF.

The results of our study highlighted that the genotypes formed six groups on the basis of grain yield and total P uptake at low P level. Such type of classification would help in identification of wheat genotypes for growing on P deficient soils and selection of parents for recombination breeding to develop P efficient cultivars [22]. Three genotypes viz., EST-29/9, AA-V3 and AA-V1 were placed in MGY-MP (medium grain yield-medium P uptake) group with a total index score of 20 for each genotype. Genotypes EST-28/11 and MSH-3, with respective index scores of 25 and 23, were placed in HGY-HP category. These genotypes were efficient in P acquisition as well as utilization for grain production under low P availability and can be selected for soils with a wide range of P contents [22, 23, 26]. Genotype NIA-Sunder was high grain yielder with a medium P accumulation (HGY-MP). The LGY-MP group comprised BWQ-4 and MSH-

5. Genotypes ESW-9525 and AA-V2 were members of MGY-HP and MGY-LP groups, respectively. Moreover, these findings suggest that some of the P-efficient genotypes viz., EST-28/11 and MSH-3 were more effective in P uptake from low P medium, and that P uptake was the primary process contributing to P efficiency for these genotypes. On the other hand, NIA-Sunder efficiently utilized the absorbed P, although the amount of absorbed P was not high. Efficient P utilization seemed to be the dominant phenomenon underlying P efficiency in this context. Wheat genotypes from various groups in this study should be used for examining shoot and root traits responsible for high P uptake, grain yield and translocation of P from different plant parts to grain sink. Earlier studies have revealed that P efficiency traits in wheat are inheritable and can be exploited in breeding programs destined for improving P efficiency [16, 28].

5. CONCLUSION

The wheat genotypes examined in this study demonstrated significant variations for grain yield and P uptake and utilization. Such genetic diversity can be useful to develop genotypes with improved genetics for P efficiency. The genotypes EST-28/11, MSH-3 and NIA-Sunder were efficient in grain production and/or P uptake; hence, they can be grown successfully on P deficient soils. Moreover, inter-mating between the wheat genotypes belonging to different groups (e.g. HGY-HP and HGY-MP) will further expand genetic variation for grain yield and P uptake.

6. REFERENCES

1. Kochian, L.V. Plant nutrition: rooting for more phosphorus. *Nature* 488(7412): 466-467 (2012.).
2. Shenoy, V.V. & G.M. Kalagudi. Enhancing plant phosphorus use efficiency for sustainable cropping. *Biotechnology Advances* 23(7): 501-513 (2005).
3. Memon, K.S. Soil & fertilizer phosphorus. In: *Soil Science*, Bashir, A. & R. Bantel (Eds.), National Book Foundation, Islamabad, pp. 291-316 (2005).
4. Vaccari, D.A. Phosphorus: a looming crisis. *Scientific American* 300: 42-47 (2009).
5. Cordell, D., J. Drangert & S. White. The story of phosphorus: global food security and food for thought. *Global Environmental Chang*e 19: 292-305 (2009).
6. Abbas, M., M. Aslam, J.A. Shah, N. Depar & M.Y. Memon. Relative growth response of hydroponically grown wheat genotypes to deficient and adequate phosphorus levels. *Pakistan Journal of Agriculture, Agricultural Engineering and Veterinary Sciences* 32(2): 169-181 (2016).
7. Rose, T.J., J. Pariasca-Tanaka, M.T. Rose, Y. Fukuta & M. Wissuwa. Genotypic variation in grain phosphorus concentration, and opportunities to improve P-use efficiency in rice. *Field Crops Research* 119: 154-160 (2010).
8. Bovill, W.D., C.Y. Huang, D.E. Mather, A. McKay, A. McNeill, K. Porker, W. Shoobridge, J.C.R. Stangoulis, R. Wheeler & G.K. McDonald. Improving phosphorus use efficiency in barley. In: *15th Australian Barley Technical Symposium*, Adelaide, Australia (2011).
9. Yang, M., G. Ding, L. Shi, F. Xu & J. Meng. Detection of QTL for phosphorus efficiency at vegetative stage in *Brassica napus*. *Plant and Soil* 339: 97-111 (2011).
10. Dorahy, C.G., I.J. Rochester, G.J. Blair & A.R. Till. Phosphorus use-efficiency by cotton grown in an alkaline soil as determined using ^{32}phosphorus and ^{33}phosphorus radio-isotopes. *Journal of Plant Nutrition* 31(11): 1877-1888 (2008).
11. Abbas, M., M. Irfan, J.A. Shah & M.Y. Memon. Intra-specific variations among wheat genotypes for phosphorus use efficiency. *Asian Journal of Agriculture and Biology* 6(1): 35-45 (2018).
12. Aziz, T., Rahmatullah, M.A. Maqsood, M. Sabir & S. Kanwal. Categorization of brassica cultivars for phosphorus acquisition from phosphate rock on basis of growth and ionic parameters. *Journal of Plant Nutrition* 34: 4: 522-533 (2011).
13. Gill, H.S., A. Singh, S.K. Sethi & R.K. Behl. Phosphorus uptake and use efficiency in different varieties of bread wheat (*Triticum aestivum* L.). *Archives of Agronomy and Soil Science* 50(6): 563-572 (2004).
14. Economic Survey of Pakistan. 2016-17. Pakistan Economic Survey, Government of Pakistan, Finance Division, Islamabad, Pakistan.
15. NFDC (National Fertilizer Development Center). *Fertilizer use survey 2004-2005*. National Fertilizer Development Center, Planning and Development Division, Islamabad, Pakistan (2005).
16. Wang, Q., J. Li, Z. Li & P. Christie. Screening Chinese wheat germplasm for phosphorus efficiency in calcareous soils. *Journal of Plant Nutrition* 28(3): 489-505 (2005).
17. Miller, R.O. Nitric-perchloric acid wet digestion in an open vessel. In: *Handbook of Reference Methods for Plant Analysis*, pp. 57-61 (1998).
18. Chapman, H.D. & F.P. Pratt. Ammonium

vandate-molybdate method for determination of phosphorus. In: *Methods of Analysis for Soils, Plants and Water*, pp. 184-203 (1961).
19. Gomez, K.A. & A.A. Gomez. *Statistical Procedures for Agricultural Research*. John Wiley & Sons, New York (1984).
20. Ozturk, L., S. Eker, B. Torun and I. Cakmak. Variation in phosphorus efficiency among 73 bread and durum wheat genotypes grown in a phosphorus-deficient calcareous soil. *Plant and Soil* 269(1-2): 69-80 (2005).
21. Yaseen, M. & S.S. Malhi. Differential growth response of wheat genotypes to ammonium phosphate and rock phosphate phosphorus sources. *Journal of Plant Nutrition* 32(3): 410-432 (2009a).
22. Irfan, M., J.A. Shah and M. Abbas. Evaluating the performance of mungbean genotypes for grain yield, phosphorus accumulation and utilization efficiency. *Journal of Plant Nutrition* 40(19): 2709-2720 (2017).
23. Yaseen, M. & S.S. Malhi. Differential growth performance of 15 wheat genotypes for grain yield and phosphorus uptake on a low phosphorus soil without and with applied phosphorus fertilizer. *Journal of Plant Nutrition* 32(6): 1015-1043 (2009b).
24. Jones, G.P.D., G.J. Blair & R.S. Jessop. Phosphorus efficiency in wheat-a useful selection criterion? *Field Crops Research* 21(3-4): 257-264 (1989).
25. Schulthess, U., B. Feil & S.C. Jutzi. Yield-independent variation in grain nitrogen and phosphorus concentration among Ethiopian wheats. *Agronomy Journal* 89: 497-506 (1997).
26. Yaseen, M. & S.S. Malhi. Variation in yield, phosphorus uptake, and physiological efficiency of wheat genotypes at adequate and stress phosphorus levels in soil. *Communications in Soil Science and Plant Analysis* 40(19-20): 3104-3120 (2009c).
27. Korkmaz, K., H. Ibrikci, E. Karnez, G. Buyuk, J. Ryan, A.C. Ulger & H. Oguz. Phosphorus use efficiency of wheat genotypes grown in calcareous soils. *Journal of Plant Nutrition* 32(12): 2094-2106 (2009).
28. Abbas, M., J.A. Shah, M. Irfan & M.Y. Memon. Remobilization and utilization of phosphorus in wheat cultivars under induced phosphorus deficiency. *Journal of Plant Nutrition* 41(12): 1522-1533 (2018).