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Original Research Article

Intra-specific variations among wheat genotypes for phosphorus use efficiency

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Abstract

Phosphorus (P) deficiency in Pakistani soils severely limits the crop production, hence, the development of P-efficient cultivars seems inevitable to uphold the productivity of P-impoverished agricultural systems. Ten wheat genotypes (AA-V1, AA-V2, AA-V3, MSH-3, MSH-5, BWQ-4, EST-28/11, EST-29/9, ESW-9525 and NIA-Sunder) were evaluated for P-efficiency and responsiveness under two phosphorus levels viz., 20 and 200 µM in hydroponic culture. Completely randomized design with two way factorial arrangement was used and the treatments were replicated five times. Seven days old seedlings were shifted to solution culture and grown for four weeks after transplanting. The plants were then harvested for recording growth and phosphorus related attributes. Low P level markedly reduced shoot and root dry weight, P concentration and accumulation in wheat genotypes. However, P utilization index of shoot and root were improved by 30 and 13% at low P supply. Shoot P utilization index was positively correlated ($r > 0.43$; $n = 50$) with shoot dry weight and shoot P accumulation at both P levels. Genotypes were grouped into four classes by regressing shoot dry weight at low P level and physiological P-use efficiency. Genotypes AA-V3 and NIA-Sunder were categorized as efficient and responsive (ER) genotypes, while AA-V1, BWQ-4 and EST-28/11 were identified as efficient but non-responsive (ENR). Genotypes AA-V2 and MSH-5 formed the non-efficient but responsive (NER) group. Non-efficient and non-responsive (NENR) category included MSH-3, EST-29/9 and ESW-9525. The results of present study indicated that AA-V3 and NIA-Sunder were the most P-efficient and responsive genotypes as they have the potential to yield more under varying levels of P availability. However, the results should be confirmed under filed conditions.

Keywords: Genotypes, Hydroponics, P-efficiency, Plant nutrition, Wheat

Introduction

World's food production is critically dependent on the continued supply of phosphorus (P) fertilizers. Phosphatic fertilizers are primarily derived from phosphate rock which is a finite and non-renewable resource and is expected to deplete in the near future. Almost 90 % of world's rock phosphate is being consumed to synthesize P fertilizers and animal feed additions (Cordell et al., 2009). Dwindling rock phosphate reserves, high costs and low recovery of P fertilizers make it imperative to increase phosphorus use efficiency at plant and farm level (Simpson et al., 2011). Agronomic management strategies like precision P fertilization, polymer coated P-fertilizers**,** and recycling of P from domestic, agricultural and industrial wastes can be helpful in improving P use at farm level (Ma et al., 2009). At plant level, development of P-efficient cultivars can greatly reduce

P fertilizer requirements in modern agriculture (Richardson et al., 2009). Improved P-efficiency can be conferred by high P uptake and/or efficient internal use of P in the plants. Strategies by which plants adapt to P-deficient soils include root structural and architectural modifications (Hammond and White, 2011), mycorrhizal associations (Smith and Read, 2008), release of organic acids and phosphatases into rhizosphere (Gahoonia and Nielsen, 2004; Wasaki et al., 2009), and efficient P use at cellular level (Rengel and Marschner, 2005).

The strategy of breeding P-efficient cultivars and their distribution to the farmers is gaining recognition as the most cost-effective and sustainable measure for improved P use and crop production. The fundamentals for evolving P-efficient cultivars include i) useable genetic diversity for P efficiency should be present, ii) characteristics underlying P efficiency should be recognized and iii) screening background should allow the manifestation of the desired characters in a reliable and repeatable way. Plant species and even genotypes within species exhibit considerable variations in their growth response to phosphorus deficiency stress (Wang et al., 2010; Irfan et al., 2017). Substantial genotypic variations in wheat for P use efficiency have been reported by many researchers (Osborne and Rengel, 2002; Ozturk et al., 2005; Mittal and Sethi, 2005; Gunes et al., 2006; Yaseen and Malhi, 2009; Korkmaz et al., 2010; Abbas et al., 2016), which can be effectively utilized in the future breeding programs. Despite the presence of extensive genetic variability for P efficiency, little progress has so far been made in developing P-efficient cultivars in wheat and other cereal crops (Rose and Wissuwa, 2013). The reason behind this slow progress is the complexity of P efficiency traits, screening of limited number of genotypes, poor understanding of screening environment and mechanisms underlying P efficiency.

Wheat is the staple food grain of Pakistani people. It accounts for 2 % of GDP of the country and 9.9 % of the value added in agriculture. The crop was cultivated on an area of 9.26 million ha during 2015-16 with production of 25.5 million tons. About 0.83 million tons of phosphorus were purchased from the market during 2015-16, half of which was consumed by the wheat crop (Pakistan economic survey, 2015-16). Improving P use efficiency in wheat crop alone can have a substantial impact on fertilizer demand in future. In this experimentation, growth response of ten wheat genotypes was studied under low and high P conditions in solution culture.

Materials and Methods

Plant culture and growth conditions

Healthy seeds of ten wheat genotypes viz., AA-V1, AA-V2, AA-V3, MSH-3, MSH-5, BWQ-4, EST-28/11, EST-29/9, ESW-9525 and NIA-Sunder were obtained from Plant Breeding and Genetics Division, Nuclear Institute of Agriculture (NIA), Tando Jam. Wheat seeds were disinfected with 2% sodium hypochlorite solution for 30 seconds and subsequently rinsed with distilled water. The seeds were germinated on plastic mesh contained in plastic cups and soaked with distilled water. After 7 days of seed germination, seedlings were shifted to polythene lined iron tubs (25-L capacity) containing modified Johnson's nutrient solution (Johnson et al., 1957). The iron tubs were placed in a rain protected net house with no control over temperature and humidity. The agro-meteorological conditions of the net house during the course of experiment are given in the Table -1. Two P levels, i.e. low (20 µM) and high (200 µM) were maintained with ammonium dihydrogen phosphate salt ($NH_4H_2PO_4$), while keeping concentration of rest of the nutrients same. The difference in nitrogen concentration between two P levels was adjusted with NH_4NO_3 salt. Completely randomized design with factorial arrangement of ten genotypes and two P levels was employed. There were five replicates of each treatment. The solution was continuously aerated and its pH was maintained at 5.5 ± 0.5 with hydrochloric acid and sodium hydroxide on daily basis. The experiment was conducted during Rabi 2015-16.

Plant harvest

After four weeks of transplanting, the plants were harvested, rinsed with distilled water and then divided into shoot and root portions. The samples were then oven-dried at 70 ^oC for 72 hours and weighed. The shoot and root biomass was expressed as mg plant^{-1}.

Phosphorus assays and P efficiency indicators

Oven-dried shoot and root samples were milled and a known quantity of the grinded material was digested in di-acid mixture of HNO_3 and $HClO_4$ (Miller, 1998). Phosphorus concentration in the digested material was then analyzed spectrophotometrically at 420 nm wavelength (Chapman and Pratt, 1961). Total P accumulation in tissue was calculated by multiplying

P concentration with dry weight of that particular tissue. The following formula was used to compute phosphorus stress factor (PSF):

$$PSF\ (\%) = \frac{\text{Shoot dry weight at high P} - \text{Shoot dry weight at low P}}{\text{Shoot dry weight at high P}} \times 100$$

Shoot/root phosphorus utilization index (PUI) was determined by the formula of Siddiqi & Glass (1981).

$$\text{Shoot/ root PUI } (g^2\ DW\ mg^{-1}\ P) = \frac{\text{Shoot/root dry weight (g plant}-1)}{\text{Shoot/root P concentration (mg P g}-1)}$$

The formula given by Fageria (1998) was employed to compute physiological phosphorus use efficiency (PPUE).

$$PPUE\ (mg\ SDW\ mg^{-1}\ P) = \frac{\text{Shoot dry weight (mg) at high P} - \text{Shoot dry weight (mg) at low P}}{\text{Shoot P accumulation (mg) at high P} - \text{Shoot P accumulation (mg) at low P}}$$

Where SDW stands for shoot dry weight.

Statistical analysis of data

The collected data were subjected to the analysis of variance according to completely randomized factorial design and the treatment means were differentiated by the Least Significant Difference (LSD) method (Gomez and Gomez, 1984). Further, the means of genotypes at each P level were separated individually using LSD at 1% probability level by employing completely randomized design. Separate statistical analysis for genotypes at each P level has been suggested by da Silva and Gabelman (1992) due to heterogeneity of error variances at two P levels.

Results

Statistical analysis of data revealed significant interactive effects of P levels and genotypes on all growth and P related parameters (Table -2, 3, 4, 5).

Biomass production

Shoot and root dry weights of 10 wheat genotypes are presented in Table -2. Significant variations ($P < 0.01$) among genotypes were observed for shoot and root dry biomass at both P levels. Under low P conditions, shoot dry weight ranged from 157 mg plant^{-1} (MSH-5) to 309 mg plant^{-1} (AA-V3) with an average value of 220 mg plant^{-1}. The difference was 97% between the lowest and the highest shoot dry weight at low P level. Shoot dry weight of MSH-5 was statistically at par with that of ESW-9525 at low P. At high P level, AA-V3 again produced the highest shoot dry weight (935 mg plant^{-1}) while ESW-9525 produced the lowest shoot dry matter (555 mg plant^{-1}) and the later was statistically at par with EST-29/9, EST-28/11 and NIA-Sunder for shoot dry weight. On an average, shoot dry weight was increased 3 folds when P concentration in culture solution was increased from low to high level. Genotypes also revealed substantial differences in root dry weight at both P levels (Table -2). Genotype AA-V3 was statistically superior to all other genotypes in root dry weight production at low P supply, while MSH-5 produced the lowest root dry weight (158 mg plant^{-1}), statistically equivalent to that of NIA-Sunder, ESW-9525 and EST-28/11. At high P level, AA-V1 produced the highest root dry matter (517 mg plant^{-1}), followed by AA-V3 (367 mg plant^{-1}) and AA-V2 (365 mg plant^{-1}). Genotype NIA-Sunder had the lowest value of root dry weight (212 mg plant^{-1}) at high P supply. Root shoot ratio (RSR) also differed significantly ($P < 0.01$) among various genotypes at both levels of P supply (Table -2). It varied between 0.74 to 1.10 at low P and 0.32 to 0.63 at adequate P supply. Overall, two fold increase was noted in root shoot ratio when P supply in growth medium was lowered from 200 to 20 µM. At low P supply, AA-V2 exhibited higher RSR which was statistically identical to those of MSH-3, MSH-5, BWQ-4, EST-29/9 and ESW-9525. Under high P conditions, AA-V1 and AA-V2 had higher RSR. Numerically, NIA-Sunder revealed the lowest RSR at both P levels.

Phosphorus stress factor (PSF) indicates the relative decrease in SDW when P supply in rooting medium was decreased from high to low level. In this study, genotypes could not produce statistically significant variations ($P > 0.05$) in PSF or comparative tolerance to phosphorus stress (Figure 1). Phosphorus stress factor ranged between 65 to 77% for different genotypes with an average value of 68%.

Phosphorus concentration and accumulation

Phosphorus concentration in root and shoot tissues varied significantly ($P < 0.01$) among wheat genotypes at both phosphorus levels (Table -3). Shoot P concentration ranged between the highest value (2544 µg P g^{-1}) for NIA-Sunder and the lowest (1775 µg P g^{-1}) for AA-V2 when the plants were grown with low P level. Genotypes viz., MSH-3, MSH-5 and EST-28/11

had statistically equivalent shoot P concentration with that of NIA-Sunder at low P supply. Under adequate P conditions, genotypes showed three times higher P concentration in shoot than when they were grown at low P supply. Genotype EST-29/9 had the highest P concentration (8333 µg P g^{-1}) in its shoot, while AA-V3 accumulated the lowest shoot P concentration of 6426 µg P g^{-1}.

Root P concentration ranged between 1849 µg P g^{-1} (AA-V2) to 2483 µg P g^{-1} (MSH-5) at low P level and from 6053 µg P g^{-1} (AA-V3) to 7625 µg P g^{-1} (EST-29/9) at high P level. On average, P concentration in shoot and root tissues decreased by 71% and 69%, respectively when P supply in growth solution was lowered from 200 to 20 µM.

Significant variations ($P < 0.01$) in shoot and root P accumulation/uptake were manifested by various genotypes at each P level (Table -4). Genotype AA-V3 had the highest shoot P accumulation (586 µg P $plant^{-1}$) followed by NIA-Sunder (568 µg P $plant^{-1}$), AA-V1 (551 µg P $plant^{-1}$) and EST-28/11 (517 µg P $plant^{-1}$), all being statistically identical in shoot P accumulation at low P. Genotypes EST-29/9, AA-V2, ESW-9525 and MSH-5 were least efficient in accumulating P in their shoot tissues. At high P level, AA-V1 had the highest shoot P accumulation (6714 µg P $plant^{-1}$) and was statistically superior to all other genotypes except AA-V3. The least P accumulation in shoot was observed in ESW-9525. The P accumulation in root tissues of various genotypes varied from 371 to 499 µg $palnt^{-1}$ at low P level and from 1509 to 3523 µg $palnt^{-1}$ at high P level. On an average, P accumulation in shoot and root tissues increased by almost 11 and 5 folds, respectively when phosphorus supply in the growing medium was increased from 20 to 200 µM.

Phosphorus efficiency indices

Shoot and root P utilization index was significantly improved under low P supply (Table -5). Averaging across the genotypes, P utilization index of shoot and root was increased by 30 and 13%, respectively when plants were grown with low P level. Shoot P utilization index (SPUI) varied from 0.06 g^2 SDW mg^{-1} P for MSH-5 to 0.16 g^2 SDW mg^{-1} P for AA-V3 with an average value of 0.13 g^2 SDW mg^{-1} P under low P condition. At high P level, SPUI varied from 0.07 g^2 SDW mg^{-1} P (EST-29/9) to 0.15 g^2 SDW mg^{-1} P (AA-V3). Genotype AA-V3 proved to be most efficient in shoot P utilization at both P levels. Root P utilization index (RPUI) ranged between 0.07 to 14 g^2 SDW mg^{-1} P at low P level and from 0.03 to 0.08 g^2 SDW mg^{-1} P at high P level. At low P level, AA-V3 was statistically superior in RPUI to the rest of genotypes and at high P level, AA-V1 appeared to be most the efficient in root P utilization. Physiological phosphorous use efficiency (PPUE) varied from 88 mg SDW mg^{-1} P for EST-29/9 to 118 mg SDW mg^{-1} P for MSH-5 with an average value of 102 mg SDW mg^{-1} P (Figure 2). There was a variation of about 34% between the highest and the lowest PPUE.

Table – 1: Agro-meteorological conditions during the course of experiment (15-12-2015 to 11-01-2016)

	Minimum temperature (ºC)	Maximum temperature (ºC)	Relative humidity (%)	Sunshine hours (hrs)	Wind speed (km hr^{-1})	Pan evaporation (mm day^{-1})
Range	4-12	22-32	50-71	6.6-9.3	0.4-2.1	2.3-4.2
Mean	8.35	25.77	58.00	8.60	1.18	3.12

Table – 2: Growth performance of ten wheat genotypes at low and high P level

Genotypes	Shoot dry weight (mg plant^{-1})		Root dry weight (mg plant^{-1})		Root shoot ratio	
	$P_{20\ \mu M}$	$P_{200\ \mu M}$	$P_{20\ \mu M}$	$P_{200\ \mu M}$	$P_{20\ \mu M}$	$P_{200\ \mu M}$
AA-V1	265 b†	835 b	207 bc	517 a	0.78 d	0.63 a
AA-V2	206 cd	698 c	225 b	365 b	1.10 a	0.53 ab
AA-V3	309 a	935 a	266 a	367 b	0.86 b-d	0.40 cd
MSH-3	212 cd	659 cd	208 bc	249 c-e	0.98 a-c	0.39 cd
MSH-5	157 e	695 c	158 d	272 cd	1.01 ab	0.39 cd
BWQ-4	229 c	662 cd	224 b	277 c	0.98 a-c	0.42 b-d
EST-28/11	226 c	649 c-e	183 cd	256 c-e	0.81 cd	0.38 cd
EST-29/9	190 d	588 de	201 bc	257 c-e	1.06 a	0.45 bc
ESW-9525	185 de	555 e	170 d	225 de	0.92 a-d	0.40 cd
NIA-Sunder	224 c	649 c-e	165 d	212 e	0.74 d	0.32 d
F values for analysis of variance						
Genotype (G)	36.40***		63.32***		7.97***	
P levels (P)	3622.89***		489.57***		771.63***	
G×P	10.91***		32.73***		6.19***	

†Means in the same column followed by the same letter(s) are statistically not different at the 1% probability level by LSD test. NS = non-significant at $P > 0.05$, * = significant at $P < 0.05$, ** = significant at $P < 0.01$, *** = significant at $P < 0.001$

Table – 3: Phosphorus concentration in shoot and root tissues of wheat genotypes at low and high P level

Genotypes	Shoot P concentration (µg P g^{-1})		Root P concentration (µg P g^{-1})	
	$P_{20\ \mu M}$	$P_{200\ \mu M}$	$P_{20\ \mu M}$	$P_{200\ \mu M}$
AA-V1	2051 b-d†	8055 ab	2318 ab	6866 a-c
AA-V2	1775 d	6988 b-d	1849 c	6286 bc
AA-V3	1903 cd	6426 d	1908 c	6053 c
MSH-3	2219 a-c	7925 a-c	1957 bc	6171 bc
MSH-5	2499 a	7031 a-d	2483 a	7160 a-c
BWQ-4	1948 b-d	7240 a-d	2174 a-c	7480 a
EST-28/11	2289 ab	7913 a-c	2013 bc	7047 a-c
EST-29/9	1912 cd	8333 a	2102 a-c	7625 a
ESW-9525	2113 b-d	7378 a-d	2196 a-c	6678 a-c
NIA-Sunder	2544 a	6665 cd	2424 a	7333 ab
F values for analysis of variance				
Genotype (G)	4.09***		5.47***	
P levels (P)	2601.96***		2401.30***	
G×P	4.79***		2.24*	

†Means in the same column followed by the same letter(s) are statistically not different at the 1% probability level by LSD test. NS = non-significant at $P > 0.05$, * = significant at $P < 0.05$, ** = significant at $P < 0.01$, *** = significant at $P < 0.001$

Table – 4: Phosphorus accumulation in shoot and root tissues of wheat genotypes at low and high P level

Genotypes	Shoot P accumulation (µg P plant^{-1})		Root P accumulation (µg P plant^{-1})	
	$P_{20\ \mu M}$	$P_{200\ \mu M}$	$P_{20\ \mu M}$	$P_{200\ \mu M}$
AA-V1	551 ab†	6714 a	469 a-c	3523 a
AA-V2	366 f	4870 b-d	419 b-d	2300 b
AA-V3	586 a	6024 ab	499 a	2216 bc
MSH-3	475 b-d	5185 bc	409 cd	1543 ef
MSH-5	397 d-f	4980 cd	391 d	2005 b-d
BWQ-4	450 c-e	4810 cd	490 ab	2075 b-d
EST-28/11	517 a-c	5099 bc	371 d	1757 d-f
EST-29/9	363 f	4916 cd	425 b-d	1883 c-e
ESW-9525	395 ef	4102 d	372 d	1509 f
NIA-Sunder	568 a	4349 cd	398 cd	1576 ef
F values for analysis of variance				
Genotype (G)	11.12***		45.82***	
P levels (P)	3666.39***		3106.91***	
G×P	8.86***		38.16***	

†Means in the same column followed by the same letter(s) are statistically not different at the 1% probability level by LSD test. NS = non-significant at $P > 0.05$, * = significant at $P < 0.05$, ** = significant at $P < 0.01$, *** = significant at $P < 0.001$

Table -5. Phosphorus utilization index of ten wheat genotypes at low and high P level

Genotypes	Shoot P utilization index (g^2 SDW mg^{-1} P)		Root P utilization index (g^2 RDW mg^{-1} P)	
	$P_{20\ \mu M}$	$P_{200\ \mu M}$	$P_{20\ \mu M}$	$P_{200\ \mu M}$
AA-V1	0.13 b†	0.10 b	0.09 de	0.08 a
AA-V2	0.12 b-d	0.10 bc	0.12 b	0.06 b
AA-V3	0.16 a	0.15 a	0.14 a	0.06 ab
MSH-3	0.10 de	0.08 c-e	0.11 c	0.04 c
MSH-5	0.06 f	0.10 bc	0.06 f	0.04 c
BWQ-4	0.12 bc	0.09 b-d	0.10 cd	0.04 c
EST-28/11	0.10 c-e	0.08 c-e	0.09 de	0.04 c
EST-29/9	0.10 c-e	0.07 e	0.10 cd	0.03 c
ESW-9525	0.09 e	0.08 de	0.08 ef	0.03 c
NIA-Sunder	0.09 e	0.10 bc	0.07 f	0.03 c
F values for analysis of variance				
Genotype (G)	36.28***		35.31***	
P levels (P)	21.98***		814.39***	
G×P	7.08***		12.74***	

†Means in the same column followed by the same letter(s) are statistically not different at the 1% probability level by LSD test. NS = non-significant at $P > 0.05$, * = significant at $P < 0.05$, ** = significant at $P < 0.01$, *** = significant at $P < 0.001$

Table – 6: Correlation matrix among various growth and P-related parameters of wheat genotypes at low and high P level

		RDW	RPC	RPAC	RPUI	RSR	SDW	SPC	SPAC
RPC	Low P	-0.49 **							
	High P	-0.24 NS							
RPAC	Low P	0.69 ***	-0.13 NS						
	High P	0.94 ***	0.01 NS						
RPUI	Low P	0.91***	-0.79***	0.53**					
	High P	0.91***	-0.52**	0.80***					
RSR	Low P	0.25 NS	-0.13 NS	-0.01 NS	0.23 NS				
	High P	0.80 ***	-0.12 NS	0.82 ***	0.75***				
SDW	Low P	0.69 ***	-0.30 NS	0.61 ***	0.62***	-0.51 **			
	High P	0.72 ***	-0.33 NS	0.62 ***	0.71***	0.27 NS			
SPC	Low P	-0.63 ***	0.58 ***	-0.42 *	-0.69***	-0.33 NS	-0.28 NS		
	High P	0.06 NS	0.35 NS	0.16 NS	-0.12NS	0.33 NS	-0.28 NS		
SPAC	Low P	0.27 NS	0.11 NS	0.31 NS	0.13NS	-0.68 ***	0.76 ***	0.28 NS	
	High P	0.77 ***	-0.13 NS	0.77 ***	0.75***	0.50 **	0.75 ***	0.18 NS	
SPUI	Low P	0.83***	-0.50**	0.67***	0.80***	-0.22NS	0.88***	-0.69***	0.43*
	High P	0.50**	-0.42*	0.37*	0.58***	0.04NS	0.89***	-0.67***	0.49**

RDW: Root dry weight, RPC: Root P concentration, RPAC: Root P accumulation, RSR: Root shoot ratio, SDW: Shoot dry weight, SPC: Shoot P concentration, SPAC: Shoot P accumulation, RPUI: Root P utilization index, SPUI: Shoot P utilization index. NS = non-significant at $P > 0.05$, * = significant at $P < 0.05$, ** = significant at $P < 0.01$, *** = significant at $P < 0.001$ (n = 50)

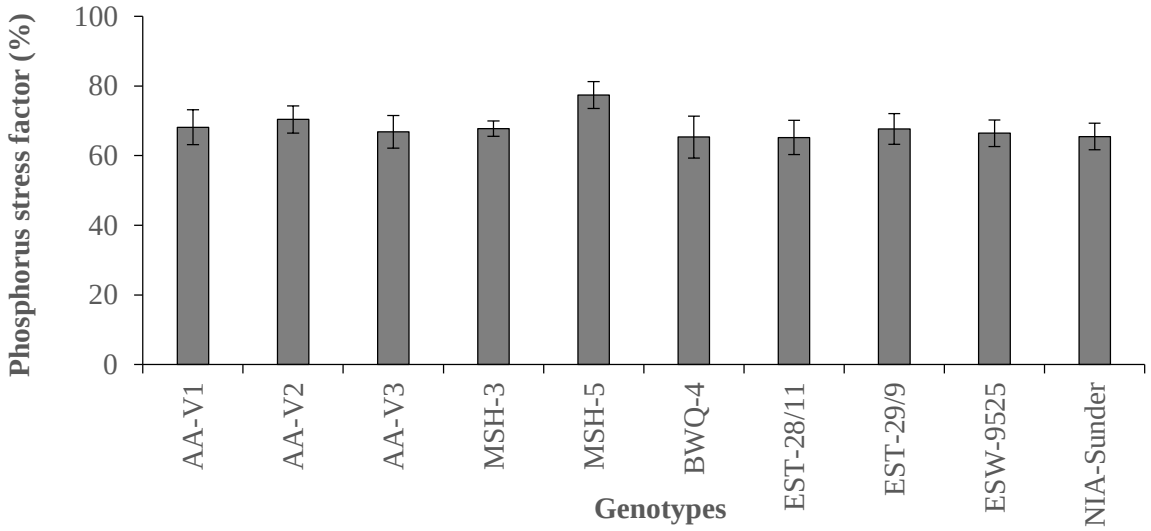

Figure – 1: Relative reduction in shoot dry weight (phosphorus stress factor) of wheat genotypes in response to low P supply

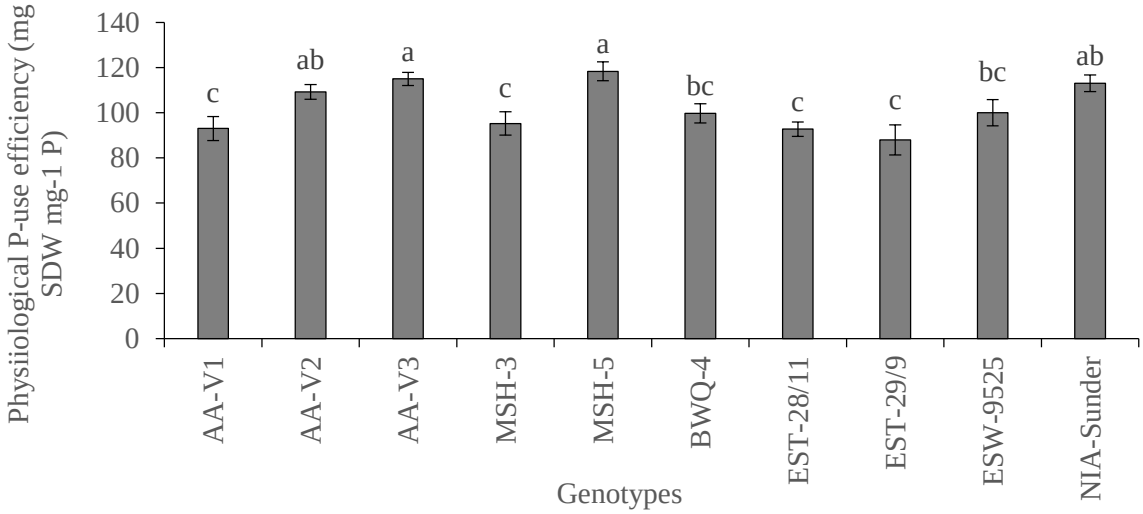

Figure – 2: Physiological P-use efficiency of wheat genotypes

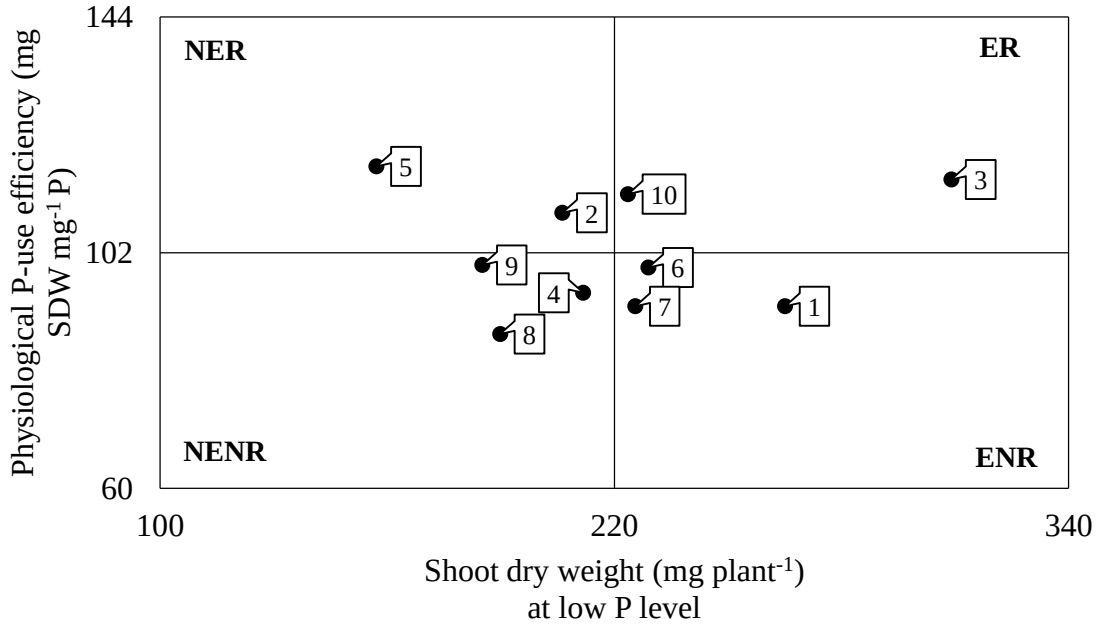

Figure – 3: Relationship between shoot dry weight at low P level and responsiveness to P, measured as physiological phosphorus use efficiency for different wheat genotypes.
The intersecting horizontal and vertical lines represent average shoot dry weight and physiological P-use efficiency of 10 wheat genotypes. ER: Efficient and responsive, NER: Non-efficient but responsive, ENR: Efficient but non-responsive, NENR: Non-efficient and non-responsive.1. AA-V1, 2. AA-V2, 3. AA-V3, 4. MSH-3, 5. MSH-5, 6. BWQ-4, 7. EST-28/11, 8. EST-29/9, 9. ESW-9525, 10. NIA-Sunder

Discussion

The main thrust of this study was to explore the extent of genotypic variations present among the genotypes for P use efficiency and to identify ideal genotypes that can have better adaptability to situations of varying P availability. Incorporation of P-efficient genotypes into future breeding programs will improve the pace of breeding efforts aimed at evolving P-efficient cultivars for the P-impoverished agricultural systems of the

Pakistan. Highly significant interactive effects of P × G on SDW production clearly indicate that useful genetic variations exist among wheat genotypes for P efficiency and responsiveness. The SDW of wheat is an important parameter and is linked to grain/economic yield of this crop in most cases. Production of higher shoot biomass under P deficient conditions is considered a reliable tool for evaluating P use efficiency at early growth stages of wheat crop (Alloush, 2003). In this study, manifestation of substantial differences among wheat genotypes for SDW at two phosphorus levels was observed and such genetic variability can successfully be exploited in breeding programs to develop new P-efficient and high yielding cultivars in future. Abbas et al. (2016) employed the similar criterion to categorize wheat genotypes for P-efficiency. Dependence of shoot dry weight on various growth and P-related parameters at both P levels was determined in terms of 'r' values (Table -6). Shoot dry weight had significant and positive relationship (r = 0.76*** and r = 0.75***) with shoot P accumulation at low and high P level, which implies that genotypes with higher shoot P accumulation produced higher shoot biomass by the efficient utilization of accumulated P. However, P concentration in both shoot and root had negative impact on the production of shoot dry biomass. A negative correlation of shoot P concentration with SDW (r = -0.28) at both P levels suggests that the genotypes with lower shoot P concentration were more efficient in P utilization than those having high shoot P concentration. Abbas et al. (2016) have disclosed similar results while evaluating P utilization efficiency of various wheat cultivars. Root dry weight had positive relationship with shoot dry weight and shoot P accumulation at both P levels, indicating the significance of root development in increased production of SDW and shoot P uptake. Root shoot ratio negatively affected SDW of genotypes, although the relationship had statistical significance at low P level only. Under low P conditions, plants tend to maintain their root development at the expense of shoot growth and more biomass is partitioned towards roots under low P availability which helped the plants to establish more extensive root system and absorb more phosphorus from P-deficient medium (Marschner, 1995; Lambers et al., 2006).

Phosphorus stress factor or relative reduction in SDW in response to P stress can also be helpful in assessing the comparative tolerance of genotypes to P deficient conditions. Genotypes with relatively low PSF are considered as more P-efficient and high yielding under low P conditions, therefore, can be selected for P deficient soils. However, PSF is not a reliable parameter for evaluating P stress tolerance, since it only shows the extent of reduction in SDW and the absolute values of SDW cannot be ignored (Abbas et al., 2016). In the present study, genotypes EST-29/9 and ESW-9525 showed PSF value (67%) similar to that of AA-V3 but their inefficiency for shoot biomass production when compared with later one make them unacceptable choice for limited P conditions. Genotypes with high PSF value (e.g. MSH-5) have low utility in P limited soils, however these genotypes are considered suitable candidates for high input agricultural systems because of their higher yield potentials.

Phosphorus utilization index denotes the amount of shoot/root biomass produced per unit of P concentration in that particular tissue. Genotypes studied in this experiment significantly differed for shoot and root P utilization index at low and high P levels. Further, a strong and positive relationship of SPUI with SDW and shoot P accumulation was revealed at both P levels which inferred that higher SDW and improved P uptake translated into high P efficiency of the genotypes. Conversely, genotypes with higher SPUI revealed lower shoot P concentration than those with lower SPUI, hence, a negative relationship (r = -0.29) was observed between SPUI and shoot P concentration. Similar outcomes were revealed by Aziz et al. (2006) and Abbas et al. (2016).

Screening of crop genotypes under low P conditions and subsequent grouping based on their growth performance forms the cornerstone of any breeding program designed for improving phosphorus efficiency in any crop. Such type of grouping/categorization will lead to the identification of genotypes appropriate for growing on soils with varying P levels. In the present study, genotypes were grouped into four classes by regressing PPUE against shoot dry weight at low P level as proposed by Fageria and Baligar (1993). Efficient and responsive (ER) group of genotypes included AA-V3 and NIA-Sunder (Figure 3). These genotypes produced SDW and PPUE higher than their respective averages computed for ten wheat genotypes. Genotypes producing more than average SDW under low P conditions, but exhibiting PPUE lower than the average were classified as efficient but non-responsive (ENR).

Genotypes AA-V1, BWQ-4 and EST-28/11 fell into this category. The third group is categorized as non-efficient but responsive (NER) and includes AA-V2 and MSH-5. Members of this group had characteristics of low SDW and high P responsiveness. Genotypes exhibiting SDW and P response less than their respective averages were identified as non-efficient and non-responsive (NENR). Genotypes MSH-3, EST-29/9 and ESW-9525 fell into this group. Among the four classes of genotypes, ER category is the most important because its members can produce more under the conditions of low as well as high P availability. Such genotypes are better adapted to growing environments with varying levels of available phosphorus. The other most important category is efficient but non-responsive and its members can be grown successfully on P-impoverished soils. The NER genotypes can be occasionally incorporated into hybridization schemes for their P-response characters, while non-efficient and non-responsive genotypes have no significance from practical point of view.

Conclusion

The results of this study indicated that considerable genetic diversity exists among wheat genotypes for P efficiency and responsiveness. Among various wheat genotypes studied in this experiment, AA-V3 and NIA-Sunder proved to be ideal ones which can be successfully grown on soils of low and high P availability. However, the results should be confirmed under filed conditions.

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