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Phosphorus Use Efficiency of Selected Wheat Genotypes Based on Morphological and Physiological Traits

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ONE of the important limiting nutrients in Wheat production is Phosphorus (P) which is depleting rapidly and may be exhausted till 2050. So, it is important to screen crop genotypes which have ability to efficiently use applied P. Therefore, P-use efficiency (PUE) in farming systems is needed to improve. Thus, morphological and physiological traits evaluation of selected wheat landraces in enhancing phosphorus use efficiency (PUE) under adequate and limited phosphorus (P) application was studied. Thirty wheat landraces were acquired from Plant Genetic Resource Institute (PGRI), National Agricultural Research Centre (NARC) Islamabad. Landraces were evaluated in a greenhouse experiment against two levels of P (20 and 100 mg kg^{-1} of soil). Plants were sampled after 50 days of sowing to evaluate agronomic and physiological parameters. Landraces 11635 and 11636 significantly improved agronomic and physiological parameters at both levels of P. Phosphorus uptake ability, dry matter, P concentration, and alkaline phosphatase activity in rhizospheric soil was enhanced. Wheat landraces 11634, 11635, 11008, 11636, 11353, 11356, 11358, 11360, 11362, 11645, 11364, 11640 and 11412 were recognized as P efficient due to improved PUE. Data analysis revealed significant variations ($p \leq 0.05$) among wheat landraces for plant fresh and dry weight, root and shoot length, P concentration, P uptake, PUE, and alkaline phosphatase activity. Evaluation of existing germplasm is a prerequisite to develop P efficient crop cultivars. There is a dire need to evaluate landraces under field conditions to develop low P input assessment criteria for development of P efficient wheat varieties.

Keywords: Low P input, Dry weight, P uptake, Wheat, Landraces.

Introduction

Phosphorus (P) availability in soil is a key limitation to pasture and crop growth. Regular application of P in soil enhanced agricultural productivity. Prices of P fertilizers increase due to high quality reserves of P which are being depleted globally. Therefore, P-use efficiency (PUE) in farming systems is essential to improve. Study of genetic variation in plants for PUE is required to efficiently use P in crops (Bovill *et al*. 2013; Van de Wiel *et al*. 2016). Optimized P application can enhance grain yield and reduce detrimental effects on environment.

Wheat is a main staple food crop for the world as well as in Pakistan. It contributes about 1.6 % to the GDP of Pakistan. Global population is increasing rapidly at an alarming scale and it is expected to reach about 9.7 billion by 2050 (Haub and Kaneda., 2013; Deng *et al*., 2018). Considering food demand of increasing global population, agroecosystems are required to intensify ecologically enhance efficiency of nutrients in plants as well as decrease fertilizer inputs. The key issue is better exploration

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of P resources in soil, and their utilization considering that ores of rock phosphate are finite, which will be exhausted in near future (Meyer *et al.* 2020). Limited P accessibility reduces development of plant and it is a widespread problem in crop production (Moller *et al*, 2018). Phosphate fertilizers are mainly manufactured from rock phosphate and used in exhaustive crop production systems to fulfill soil P deficiency impacting food sustainability. Nevertheless, rock phosphate is scarce, and non-recoverable, there is a dire need to improve P efficiency in various crop production systems (Kopp *et al.* 2023). Globally, 30 % of cultivated soils and 90 % soils in Pakistan are P deficient (Zahra *et al.* 2017). Global P reserves may diminish by 2050 (Vance *et al.* 2003; Jiang *et al*., 2019) and more than 80 % of applied P get fixed into the soil where only a small quantity of P becomes part of soil solution (Leytem and Mikkelsen, 2005; Yang at al., 2018). At the same time, crops need sufficient P at early physiological development for high yield (Müller-Stover *et al.*, 2021). Identification of crop genotypes which potentially adapt to low-input agricultural system can be achieved through exploiting genetic potential (Pedersen *et al*., 2020). Low input sustainable agriculture gained attention of researchers to hunt crop genotypes that are relatively more acclimatized in limited soil nutrients. Genetic variability, nutrients uptake ability, and their utilization are essential components to determine acclimatization potential of plant genotypes in nutrients limited condition.

Problem of P scarcity in Pakistani soils can be addressed through breeding wheat cultivars that are suitable under limited P conditions. The evolution of wheat germplasm with increased P uptake capability under P limited environment is vital objective in modern breeding programs (Garder *et al.* 2023).

Wheat landraces are essential sources for widening genetic base of cultivated wheat. The evolution of new wheat cultivars from landrace population is a vital approach to increase landrace yield, particularly under stress conditions and climate change scenario. These land races contain genes for quality attributes, and tolerance to biotic and abiotic stresses (Regueiro *et al.* 2020). There is a possibility that land races might be having traits which could increase grain yield and PUE simultaneously to sustain food security. Thus, the current research work is aimed at screening of Wheat landraces

Material and Methods

A pot experiment was conducted in green house using 30 wheat landraces. They were sown in plastic pots (12.0 cm x 18.5 cm) containing 1800 g air dried soil collected from Agriculture Research Farm (33°58'42.0"N 72°54'55.3"E) at the University of Haripur. Physio-chemical characteristics of collected soil was performed. Texture (silty loam), electrical conductivity (0.31 dS m^{-1}), pH (7.41), organic matter (1.71 %), nitrogen (0.0895 %), Olsen-P (9.54 ppm), and potassium (68 ppm) were evaluated. The experimental study had two factorial completely randomized design with three replications. Ten seeds of each wheat land race were sown in individual pot against two P levels such as adequate P1 (100 mg kg^{-1}) and deficient P2 (20 mg kg^{-1}) for 50 days crop growth. Before sowing, rest of macro and micronutrients were supplied in recommended amount and mixed thoroughly. Plants were thinned to five in each pot on basis of uniformity in height and irrigation was done to maintain soil water content at 70 % of field capacity. After 50 days of sowing, plants were manually uprooted, and data were recorded. Zn concentration was determined according to the method of Lindsay and Norvell (1978).

Soil Parameters

To find out the value of organic matter content we have multiplied organic carbon (OC) by 1.73 while Walkley and Black method was followed to determine OC titrimetrically. To find out the value of phosphorus, soil was shaken with 0.03 M NH_4F—0.025 M HCl solution at pH < 7.0. Nitrogen was determined by Kjeldahl method. To evaluate the value of K, we have used the ammonium bicarbonate-DTPA technique (AB-DTPA).

Plant shoot-root fresh and dry weight (mg kg^{-1})

Plant shoot-root fresh weights were calculated by taking 10 randomly selected plants from each replication of every treatment and then weighted these plant shoots and roots individually with the aid of analytical balance which has given the values of shoot and root fresh weights. On the other hand, dry weights of shoot and root were determined after drying these samples in oven for 24 hours at 120

Celsius, which were then placed on weighing balance to determine their weight.

Plant P concentration (%)

Harvested plant samples were ground and digested for P analysis in plant tissues. To determine P concentration, fresh plant samples were dried in oven at 70 ^{o}C, ground using a grinding mill (PX-MFC 90D) having 20-40 mm mesh screen. Ashing was done by placing 0.5 g plant sample in a muffle furnace (NEYCRAFT JFF 2000) at 500±50 ^{o}C for 4-5 h and samples were acid digested in 1 N HCl solution. Samples were further filtered using Whatman No. 2 filter paper. Absorbance of filtered samples was measured against standards at 410 nm wavelength using a spectrophotometer (T80+) (Kitson and Mellon, 1944). Total P uptake (mg) was measured by multiplying plant dry weight with P concentration in plant sample (Garder *et al.* 2023) and PUE was also calculated using formula:

$$PUE\ (\%) = \left(\frac{shoot\ dry\ weight\ at\ low\ P\ level}{shoot\ dry\ weight\ at\ recommended\ P\ level}\right) x\ 100$$

Acid and alkaline phosphatase (µmol g^{-1} min^{-1}) in soil

The 1g air dry sieved soil was taken in 50 ml Erlenmeyer flask. Toluene (0.2 ml), Modified Universal Buffer (4 ml) and p-nitrophenyl phosphate solution (1 ml) were added in soil sample. It was incubated at 37 ^{o}C for 1 h. A 0.5 M (1 ml) $CaCl_2$ and 0.5 M (4 ml) NaOH were added in flask and filtered through Whatman No. 2 filter paper. The absorbance was recorded at 400-420 nm wavelength using spectrophotometer (T80+) (Tabatbai and Bremner,1969).

Root and shoot length (cm)

Root and shoot length were estimated through measuring rod when 10 randomly selected plants were taken from field to estimate the plant fresh and dry weight.

Plant P concentration (%) and P uptake (mg kg^{-1})

To determine plant phosphorus (P) concentration (%) and P uptake (mg kg^{-1}), first, harvest the plant and separate it into different parts (e.g., roots, stems, leaves). Dry the plant material in an oven at 60-70°C until it reaches a constant weight, then grind it into a fine powder. For P concentration, digest a known amount of the dried and ground plant material using a strong acid, typically a mixture of nitric and perchloric acids. Analyze the digested sample for P content using an appropriate method such as colorimetry or inductively coupled plasma optical emission spectrometry (ICP-OES). Calculate the P concentration as a percentage of the plant's dry weight. For P uptake, multiply the P concentration by the total dry weight of the plant to obtain the total P uptake per plant in milligrams.

Zn Concentration (%)

The Lindsay and Norwell (1978) method for determining zinc concentration in soils involves shaking soil samples with a DTPA extractant solution buffered to pH 7.3, then filtering the mixture, and measuring the Zn concentration in the filtered extract using an atomic absorption spectrophotometer (AAS) or inductively coupled plasma optical emission spectrometer (ICP-OES).

Statistical analysis

Collected data was statistically analyzed using Statistix 8.1, analysis of variance technique and LSD at 5 % probability to compare differences among treatment means (Keskinen *et al*., 2023).

Results

Plant fresh and dry weight (mg kg^{-1})

The statistical analysis of data showed significant variation among wheat land races at both P levels for fresh weight ($p \leq 0.05$) (Table 1). Highest fresh weight of plant was recorded in wheat land race 11635 (1969.3 mg kg^{-1}) followed by 11636 (1903 mg kg^{-1}) while minimum fresh weight was recorded in 11348 (815.5 mg plant^{-1}). Interaction of wheat land races at different P levels for fresh weight was also significant ($p \leq 0.05$). At adequate P level (100 mg kg^{-1}), fresh weight ranged from 948 mg plant^{-1} (E.11348) to 1974 mg plant^{-1} (E.11635). At deficient P level (20 mg plant^{-1} of soil), fresh weight ranged from 673.5 mg plant^{-1} (E.11349) to 1964.5 mg kg^{-1} (E.11635). Results showed ability of E.11635 to produce more fresh weight under P stress. All wheat landraces responded positively to P supply regarding plant fresh weight.

Plant dry weight was significantly affected by different P levels (100 mg kg^{-1} and 20 mg kg^{-1}) and wheat landraces as well as interaction between wheat landraces and P levels ($p \leq 0.05$) (Table 1). Highest dry matter production was recorded in wheat genotype 11635 (393.8 mg plant^{-1}) followed by wheat landrace 11636 (381.2 mg kg^{-1}) while minimum dry weight was recorded in wheat landrace 11348 (163.1 mg kg^{-1}). At adequate P level, plant dry weight varied between 189.6 to 394.8 mg kg^{-1}. Dry matter production ranged at deficient level was 134.7 to 392.9 mg kg^{-1}.

TABLE 1. Response of wheat landraces (E) regarding plant fresh and dry weight (mg kg^{-1}) at adequate (P1) and deficient (P2) supply of phosphorus (P).

	Plant fresh weight (mg kg^{-1})		**Plant dry weight (mg kg^{-1})**	
E	**P1**	**P2**	**P1**	**P2**
11634	1327.5±27.5^{K-M}	1292.5±12.5^{M-O}	265.5±5.5^{K-M}	258.5±2.5^{M-O}
11635	**1974.00**±06.0$^{\mathbf{A}}$	**1964.5**±14.5$^{\mathbf{A}}$	**394.8**±1.2$^{\mathbf{A}}$	**392.9**±2.9$^{\mathbf{A}}$
11004	1183.00±17.0^{PQ}	741.0±41^{Za}	236.6±3.4^{PQ}	148.2±8.2^{Za}
11005	972.5±27.5^{T-V}	770±29^{YZ}	194.5±5.5^{T-V}	154±5.8^{YZ}
11006	1235.5±14.5^{N-P}	1002±36^{TU}	247.1±2.9^{N-P}	200.4±7.2^{TU}
11007	1491.51±9^{FG}	855.5±55.5^{WX}	298.2±1.8^{FG}	171.1±11.1^{WX}
11008	1547.00±12^{EF}	1482.5±7.5^{F-H}	309.4±2.4^{EF}	296.5±1.5^{F-H}
11009	1145±15^{Q-S}	730.5±19.5^{Za}	229±3^{Q-S}	146.1±3.9^{Za}
11347	1227.5±17.5^{OP}	998.5±12.5^{TU}	245.5±3.5^{OP}	199.7±2.5^{TU}
11348	**948±22**$^{\mathbf{UV}}$	**683±17**$^{\mathbf{a}}$	**189.6±4.4**$^{\mathbf{UV}}$	**136.6**±3.4$^{\mathbf{a}}$
11349	1415.5±89.5^{H-J}	**673.5±23.5**$^{\mathbf{a}}$	283.1±17.9^{H-J}	**134.7**±4.7$^{\mathbf{a}}$
11350	1330.5±19.5^{K-M}	1028±22^{T}	266.1±3.9^{K-M}	205.6±4.4^{T}
11351	1561.5±38.5^{DE}	1282.5±17.5^{M-O}	312.3±7.7^{DE}	256.5±3.5^{M-O}
11636	**1924.5**±21.5$^{\mathbf{AB}}$	**1888**±9$^{\mathbf{B}}$	**384.9**±4.3$^{\mathbf{AB}}$	**377.6**±1.8$^{\mathbf{B}}$
11353	1420±80^{H-J}	1368.0±68^{J-L}	284±16^{H-J}	273.6±13.6^{J-L}
11354	1234.5±34.5^{N-P}	877±23^{WX}	246.9±6.9^{N-P}	175.4±4.6^{WX}
11355	1300.0±10^{MN}	1104±5^{S}	260±2^{MN}	220.8±1^{S}
11356	1479.5±26.5^{F-H}	1394.5±3.5^{I-K}	295.9±5.3^{F-H}	278.9±0.7^{I-K}
11357	1339±27^{K-M}	910±10^{VW}	267.8±5.4^{K-M}	182±2^{VW}
11358	1327.5±18.5^{K-M}	1291.5±6.5^{M-O}	265.5±3.7^{K-M}	258.3±1.3^{M-O}
11359	1341.5±16.5^{K-M}	1107.5±9.5^{S}	268.3±3.3^{K-M}	221.5±1.9^{S}
11360	1675±26^{C}	1632.5±32.5^{C}	335±5.2^{C}	326.5±6.5^{C}
11361	960.5±39.5^{T-V}	736±15^{Za}	192.1±7.9 $^{T-V}$	147.2±3 ^{Za}
11362	1325.5±19.5^{LM}	1292.0±7^{M-O}	265.1±3.9 ^{LM}	258.4±1.4 $^{M-O}$
11645	1438±28^{G-I}	1379±13^{I-L}	287.6±5.6 $^{G-I}$	275.8±2.4 $^{I-L}$
11364	1230±20^{OP}	1176.5±10.5^{P-R}	246±4 ^{OP}	235.3±2.1 $^{P-R}$
11640	1672.5±27.5^{C}	1615.5±10.5^{CD}	334.5±5.5 ^{C}	323.1±2.1 ^{CD}
11641	1114.5±14.5^{RS}	811±10^{XY}	222.9±2.9 ^{RS}	162.2±2 ^{XY}
11412	1505±5^{E-G}	1471.5±6.5^{GH}	301±1 $^{E-G}$	294.3±1.3 ^{GH}
11638	1313.5±12.5^{LM}	1012±13^{TU}	262.7± 2.5 ^{LM}	202.4±2.6 ^{TU}
Mean	**1365.3**$^{\mathbf{A}}$	1152.4^{B}	**273**$^{\mathbf{A}}$	230.4^{B}
LSD for P at P ≤ 0.05 = 12.339			LSD for P at P ≤ 0.05 = 2.4679	
LSD for E at P ≤ 0.05 = 47.790			LSD for E at P ≤ 0.05 = 9.5580	
LSD for P x E at P ≤ 0.05 = 67.585			LSD for P x E at P ≤ 0.05 = 13.517	

*Mean values of the same group having similar letters are non-significant using LSD test at 5% level of probability.

Alkaline phosphatase activity (µmol g^{-1} min^{-1}) and PUE (%)

The statistical analysis of data revealed significant differences among wheat landraces for alkaline phosphatase activity at different level of P (p≤0.05) (Table 2). Maximum alkaline phosphatase activity was observed in wheat landrace 11635 (20.8 µmol g^{-1} min^{-1}) followed by 11361 (17.4 µmol g^{-1} min^{-1}), 11640 (18.6 µmol g^{-1} min^{-1}) and 11636 (17.8 µmol g^{-1} min^{-1}) respectively while minimum activity was noticed in wheat landrace 11348 (11.5 µmol g^{-1} min^{-1}) respectively. Interaction between wheat landraces and different P levels was also significant (p≤0.05). At adequate P level (100 mg kg^{-1}), phosphatase activity ranged from 8.9 µmol g^{-1} min^{-1} (E.11348) to 16.4 µmol g^{-1} min^{-1} (E.11635) with a mean of 12.3 µmol g^{-1} min^{-1}. At deficient P level (20 mg kg^{-1}), phosphatase activity varied between 10.8 µmol g^{-1} min^{-1} (E.11349) to 25.3 µmol g^{-1} min^{-1} (E.11635). Overall, wheat landraces provided with deficient level of P (20 mg kg^{-1}) produced more organic acids by their roots in soil than at adequate levels of P (100 mg kg^{-1}) which showed ability of wheat landraces to reuse and remobilize soil P.

The PUE of different wheat landraces varied significantly (Table 2). The PUE ratio with respect to plant dry matter yield ranged from 48 % (E.11349) to 100 % (E.11635). Wheat landraces having PUE greater than mean (83 %) were considered as P efficient (Garder *et al.* (2023). A high relative growth rate was shown by wheat landraces 11634, 11635, 11636, 11008, 11353, 11356, 11358, 11360, 11362, 11645, 11364, 11640, 11412 which ultimately resulted in high dry matter yield in these landraces than mean yield at deficient P levels.

TABLE 2. Response of wheat landraces (E) regarding alkaline phosphatase activity (mg $plant^{-1}$) and phosphorus use efficiency (%) at adequate (P1) and deficient (P2) supply of phosphorus (P)

E	Alkaline phosphatases activity (µmol g^{-1} min^{-1})		Phosphorus use efficiency (%)
	P1	P2	
11634	15±0.097^{I-O}	**20.4±0.481^{B}**	**97**
11635	**16.4±0.414^{E-K}**	**25.3±0.923^{A}**	**100**
11004	11.9±2.698^{S-X}	13.4±0.810^{O-T}	63
11005	12.1±0.775^{R-W}	15.8±1.048^{F-M}	79
11006	10.2±0.555^{X-Z}	15.6±0.454^{G-M}	81
11007	10.5±0.438^{W-Z}	15.6±0.639^{G-M}	57
11008	9.9±0.765^{YZ}	16.5±0.147^{E-K}	**96**
11009	11.4±0.481^{U-Y}	15.7±0.445^{F-M}	64
11347	11±0.172^{V-Y}	14.1±0.186^{L-Q}	81
11348	**8.9±0.693^{Z}**	14.1±0.168^{L-Q}	72
11349	12.5±0.145^{Q-V}	**10.8±0.555^{V-Z}**	**48**
11350	10.9±0.236^{V-Y}	15.6±0.360^{G-M}	77
11351	12.1±0.501^{R-X}	16.6±0.383^{E-J}	82
11636	15.2±0.670^{H-O}	**20.4±0.394^{B}**	**98**
11353	13±0.212^{P-U}	17.6±0.494^{C-F}	**96**
11354	12.6±0.506^{Q-V}	15.3±0.392^{H-N}	71
11355	11.2±0.293^{U-Y}	16±0.210^{F-L}	85
11356	13.5±1.603^{N-S}	17.1±2.039^{D-H}	**94**
11357	10.8±0.162^{V-Z}	14.6±0.487^{K-P}	68
11358	12.5±1.429^{Q-V}	17.3±1.265^{C-G}	**97**
11359	11±0.067^{V-Y}	15.6±0.366^{G-M}	83
11360	14.7±0.425^{J-P}	**20.2±0.230^{B}**	**97**
11361	11.3±0.220^{U-Y}	12.2±0.069^{Q-W}	77
11362	13.9±0.030^{M-R}	16.7±0.341^{E-I}	**97**
11645	13.4±0.337^{O-T}	18.1±0.427^{C-E}	**96**
11364	12.6±0.551^{Q-V}	19.2±0.502^{BC}	**96**
11640	16.6±1.214^{E-I}	**20.6**±0.502^{B}	**97**
11641	10.9±0.018^{V-Y}	13.5±0.437^{N-S}	73
11412	12.5±0.435^{Q-V}	19±0.500^{B-D}	**98**
11638	11.4±0.382^{T-Y}	15±0.018^{I-O}	77
Mean	12.3^{B}	**16.6^{A}**	**83**
LSD for P at $P \leq 0.05$ = 0.3526			
LSD for E at $P \leq 0.05$ = 1.3658			
LSD for P x E at $P \leq 0.05$ = 1.9315			

*Mean values of the same group having similar letters are non-significant using LSD test at 5% level of probability

Root and shoot length (cm)

Significant differences were observed among various landraces for root and shoot length at different levels of P (p≤0.05) (Table 3). Maximum root length was observed in wheat landrace 11635 (18.2 cm) followed by wheat landrace 11360 (14 cm) while minimum root length was produced by wheat landraces 11647 (7.3 cm) and 11348 (7.7 cm) respectively. Interaction of wheat landraces with different P levels was also significant for root and shoot length (p≤0.05). Regarding different P level, root length ranged from 6.4cm (E.11348) to 14cm (E.11635) at adequate P level while at low P supply, root length ranged from 7.4cm (E.11347) to 22.4 cm (E.11635). Maximum shoot length was observed in wheat landrace 11635 (17 cm) followed by 11006 and 11007 (15 cm) respectively while minimum shoot length was found in 11353 (8.60 cm), 11348 (8.80 cm) and 11361 (10.5 cm) respectively. The interaction of wheat landraces with different P levels for shoot length was also significant (p≤0.05). Shoot length ranged from 9.7 cm (E.11348) to 20.2 cm (E.11635) at adequate P supply. At deficient P application, shoot length ranged from 8cm (E.11634) to 16.1 (E.11005).

Table 3. Response of wheat landraces (E) regarding root and shoot length (cm) at adequate (P1) and deficient (P2) supply of phosphorus (P)

	Root length (cm)		**Shoot length (cm)**	
E	**P1**	**P2**	**P1**	**P2**
11634	9.2±0.15^{R-W}	11.7±0.2^{IJ}	14.4±0.2^{K-O}	**8±0.15^{f}**
11635	**14**±0.15^{FG}	**22.4**±0.25^{A}	**20.2**±0.15^{A}	15±0.15^{F-L}
11004	8.1±0.15^{Z-d}	7.8±0.35^{a-e}	16±0.85^{D-G}	13.5±0.45^{N-S}
11005	8.6±0.65^{V-Z}	10.0±0.55^{M-P}	14.1±0.35^{K-P}	**16.1±1.9^{D-F}**
11006	8.3±0.15^{Y-c}	8.4±0.45^{X-b}	16.1±0.8^{D-F}	14.5±0.5^{J-O}
11007	8.7±0.25^{U-Z}	9.6±0.55^{M-S}	17.8±1.65^{BC}	12.7±0.3^{R-V}
11008	9.6±0.05^{M-S}	15.4±0.25^{B-D}	14.8±0.25^{G-M}	12.4±0.15^{S-V}
11009	9±0.15^{S-Y}	7.7±0.2^{c-e}	13.8±0.2^{M-R}	11.5±0.35^{V-Z}
11347	7.3±0.25^{e}	**7.4±0.2^{e}**	14.2±0.1^{K-O}	12.9±0.55^{P-U}
11348	**6.4**±0.2^{f}	7.8±0.2^{b-e}	**9.7±0.2^{b-d}**	11.7±0.25^{U-Y}
11349	8.6±0.15^{V-Z}	7.6±0.1^{de}	15.3±0.2^{F-K}	12.3±0.15^{S-W}
11350	9.3±0.15^{P-V}	10±0.1^{M-Q}	14.9±0.1^{F-M}	13.7±0.3^{M-R}
11351	9±0.2^{S-Y}	9.9±0.3^{M-R}	15±0.05^{E-J}	14±0.45^{J-O}
11636	10.1±0.1^{M-O}	14.3±0.2^{E-G}	**18.2**±0.1^{B}	10.4±0.25^{Z-c}
11353	**9.4**±0.8^{O-U}	**13.9**±1.2^{G}	14±0.8^{L-Q}	9.1±0.3^{d-f}
11354	8.3±0.15^{Y-c}	9.3±0.2^{Q-V}	13.9±0.1^{L-R}	8.4±0.45^{ef}
11355	9.1±0.15^{S-X}	9.5±0.35^{N-T}	13.9±0.15^{L-Q}	11.1±0.25^{W-a}
11356	9.6±0.15^{M-S}	14.7±0.65^{D-F}	13.8±0.35^{L-R}	10.1±0.2^{a-d}
11357	9.0±0.1^{S-Y}	8.7±0.1^{U-Z}	14.7±0.2^{H-N}	12.1±0.15^{T-W}
11358	8.7±0.2^{U-Z}	15.5±0.35^{BC}	14.5±0.4^{J-O}	10.1±0.4^{a-d}
11359	8.9±0.1^{T-Y}	10.9±0.1^{KL}	14.6±0.4^{I-N}	12.9±0.15^{P-U}
11360	12.4±0.45^{H}	15.5±0.35^{BC}	15.8±0.2^{E-I}	12.8±0.2^{Q-U}
11361	10.2±0.25^{L-N}	11.0±0.15^{JK}	11.8±0.2^{U-X}	9.3±0.3^{c-e}
11362	9.2±0.25^{R-W}	15.3±0.25^{B-D}	16.7±0.2^{C-E}	10.5±0.2^{Z-c}
11645	10.3±0.2^{LM}	**15.8**±0.35^{B}	15.8±0.25^{E-H}	10.7±0.3^{X-b}
11364	10.3±0.2^{LM}	13.8±0.15^{G}	15.9±0.25^{D-G}	9.9±0.3^{b-d}
11640	11.3±25^{JK}	15.1±0.25^{B-D}	17.1±0.15^{B-D}	10.5±0.25^{Y-b}
11641	8.6±0.15^{V-Z}	9±0.15^{S-Y}	13.3±0.25^{O-T}	10.1±0.15^{a-d}
11412	12.3±0.2^{HI}	14.8±0.15^{C-E}	16.8±0.3^{C-E}	9.9±0.3^{b-d}
11638	8.5±0.15^{W-a}	9.5±0.1^{O-T}	13.5±0.3^{N-S}	12±0.1^{U-W}
Mean	9.4^{B}	**11.7^{A}**	**15^{A}**	11.6^{B}
LSD for P at P ≤ 0.05 = 0.1293			LSD for P at P ≤ 0.05 = 0.2210	
LSD for E at P ≤ 0.05 = 0.5009			LSD for E at P ≤ 0.05 = 0.8561	
LSD for P x E at P ≤ 0.05 = 0.7084			LSD for P x E at P ≤ 0.05 = 1.2107	

*Mean values of the same group having similar letters are non-significant using LSD test at 5% level of probability.

Root and shoot fresh weight (mg plant^{-1})

Statistical analysis of data showed significant differences among various landraces of wheat for root and shoot fresh weight at different levels of P (p≤0.05) (Table 4). Maximum root fresh weight was produced by wheat landraces 11635 (798.9 mg plant^{-1}) and 11636 (771.7 mg plant^{-1}) followed by 11360, 11640 and 11412 respectively while minimum root fresh weight was produced by wheat landrace 11348 (313.6 mg plant^{-1}). Maximum shoot fresh weight was produced by wheat landrace 11635 (1166 mg plant^{-1}) followed by wheat landraces 11636 (1130.2 mg plant^{-1}) while minimum shoot fresh weight was produced by wheat land races 11005 (526 mg plant^{-1}), 11348 (479.9 mg plant^{-1}) and 11361 (494.1 mg plant^{-1}) respectively. The interactive effect of different wheat landraces at different P levels for root and shoot fresh weight was also significant (p≤0.05). At adequate P supply, root fresh weight varied between 364.6 mg plant^{-1} (E.11348) to 600.6 mg plant^{-1} (E.11351) while shoot fresh weight ranged from 579.5 mg plant^{-1} (E.11348) to 1405.7 mg plant^{-1} (E.11635). Conversely, at low P supply root fresh weight ranged between 259.1 mg plant^{-1} (E.11349) to 1033.9 mg plant^{-1} (E.11635) while shoot fresh weight varied between 399.3 mg plant^{-1} (E.11361) to 980.7 mg plant^{-1} (E.11645). Overall root fresh weight showed an upward trend at deficient level of P while shoot fresh weight showed an upward trend at adequate P level.

Table 4. Response of wheat landraces (E) regarding root and shoot fresh weight (cm) at adequate (P1) and deficient (P2) supply of phosphorus (P).

	Root fresh weight (mg)		Shoot fresh weight (mg)	
E	**P1**	**P2**	**P1**	**P2**
11634	442.5±9.17^{QR}	680.3±6.58^{FG}	880.7±18.33^{GH}	608±5.92^{T-X}
11635	564±1.71^{H-K}	**1033.9**±7.63^{A}	**1405.7±4.29^{A}**	926.3±6.87^{FG}
11004	**326.1±76.03^{Z-b}**	336.2±36.19^{X-a}	829.8±70.18^{I-L}	**402.6±2.66^{b}**
11005	335.4±9.48^{X-a}	350±13.18^{W-a}	634.5±18.02^{Q-V}	417.4±15.82^{ab}
11006	426±5.00^{RS}	345.5±12.41^{W-a}	806.9±9.50^{K-M}	653.9±23.59^{O-T}
11007	514.1±3.10^{L-N}	295±19.14^{bc}	974.3±5.90^{DE}	557.9±36.36^{Y}
11008	528.9±0.42^{K-M}	780.3±3.95^{D}	1014.9±11.82^{CD}	698.3±3.55^{OP}
11009	440.4±5.77^{QR}	**281**±7.50 ^{c}	700.7±9.23^{O}	445.6±12.00^{Z-b}
11347	472.1±6.73^{O-Q}	384±4.81^{T-W}	751.5±10.77^{N}	610.6±7.69^{S-X}
11348	364.6±8.46^{V-Z}	**262.7**±6.54^{c}	**579.5**±13.54^{XY}	416.4±10.46^{ab}
11349	544.4±34.42^{J-L}	**259.1**±9.04^{c}	867.2±55.08^{HI}	**410.6±14.46^{b}**
11350	511.7±7.50^{L-O}	395.4±8.46^{S-V}	814.9±12.00^{J-M}	628.8±13.54^{R-W}
11351	600.6±14.81^{H}	493.3±6.73^{M-O}	957±23.69^{EF}	785.4±10.77^{L-N}
11636	549.9±6.14^{J-L}	**993.6**±4.74^{B}	**1370.3±15.36^{A}**	890±4.26^{GH}
11353	473.3±26.67^{O-Q}	720±35.79 ^{EF}	943.7±53.33^{EF}	644.8±32.21^{Q-U}
11354	425.7±11.90^{RS}	417.6±10.95^{R-T}	808.3±22.60^{K-M}	458.9±12.05^{Za}
11355	448.3±3.45^{P-R}	480±2.17^{N-Q}	851.3±6.55 $_{H-K}$	623.5±2.83^{R-X}
11356	493.1±8.83^{M-O}	734±1.84^{E}	983.5±17.67$_{C-E}$	657.8±1.66^{O-S}
11357	478.3±9.64^{N-Q}	325±3.57^{Z-b}	857.9±17.36^{H-J}	582.1±6.43^{W-Y}
11358	474.1±6.61^{O-Q}	679.8±3.42^{G}	850.6±11.89^{H-K}	609±3.08^{T-X}
11359	516±6.35^{L-N}	426±3.65^{RS}	823.5±10.15^{I-M}	679.5±5.85^{O-Q}
11360	567.8±8.81^{H-K}	850.3±16.93^{C}	1105.3±17.19^{B}	780.3±15.57^{MN}
11361	369.4±15.19^{V-Y}	334.5±6.82^{Y-b}	588.9±24.31^{V-Y}	**399.3±8.18^{b}**
11362	441.8±6.50^{QR}	687.3±3.72^{FG}	880.6±13.00^{GH}	601.6±3.28^{U-Y}
11645	410.9±8.00^{R-U}	394±3.71^{S-V}	1022.8±20.00^{C}	**980.7**±9.29^{C-E}
11364	410±6.67^{R-U}	560.2±5.00^{I-K}	818±13.33^{J-M}	614.3±5.50^{S-X}
11640	**597.3±9.82^{HI}**	824.3±5.36^{C}	1070.9±17.68^{B}	787±5.14^{L-N}
11641	445.8±5.80^{QR}	324.4±4.00^{ab}	666±8.70 $^{O-R}$	483.9±6.00^{Z}
11412	578.8±1.92^{H-J}	817.5±3.61^{CD}	924.0±3.08^{FG}	651.8±2.89^{P-T}
11638	486.5±4.63^{N-P}	374.8±4.81^{U-X}	824.7±7.87^{I-M}	634.9±8.19^{Q-V}
Mean	474.5^{B}	**527.9^{A}**	**886.9^{A}**	621.3^{B}
LSD for P at P ≤ 0.05 = 7.2918			LSD for P at P ≤ 0.05 = 8.7558	
LSD for E at P ≤ 0.05 = 28.241			LSD for E at P ≤ 0.05 = 33.911	
LSD for P x E at P ≤ 0.05 = 39.939			LSD for P x E at P ≤ 0.05 = 47.958	

*Mean values of the same group having similar letters are non-significant using LSD test at 5% level of probability.

Plant P concentration (%) and P uptake (mg plant^{-1})

Significant differences were observed among various landraces of wheat for P concentration and P uptake at different levels of P (p≤0.05) (Table 5). Highest P concentration was observed in wheat landrace 11635 (0.17 %) followed by 11636 (0.15 %) while minimum P concentration was observed in wheat landrace 11349 (0.09 %). Maximum P uptake was observed in wheat landrace 11635 (67.2 mg plant^{-1}) followed by wheat landrace 11636 (60.1 mg plant^{-1}) while minimum P uptake was observed in wheat landrace 11348 (16.3 mg plant^{-1}). The interaction between different wheat landraces and P levels was also significant for P concentration and P uptake (p≤0.05). Regarding different P levels, P concentration was in optimum range at adequate P level and ranged from 0.10 % (E.11348) to 0.16 % (E.11635) with an average of 0.12 % while at deficient P level it was ranged between 0.08% (E.11348) to 0.18 % (E.11635). At adequate P supply, P uptake ranged from 20.1 mg plant^{-1} (E.11348) to 63.6 mg plant^{-1} (E.11636). At low P level, P uptake varied between 10.7 mg plant^{-1} (E.11349) to 71.1 mg plant^{-1} (E.11635). Overall, there was an upward trend in wheat landraces for P uptake and P concentration that were applied with recommended dose of P than applied with deficient dose of P.

Table 5. Response of wheat landraces (E) regarding P concentration and P uptake at adequate (P1) and deficient (P2) supply of phosphorus.

	P concentration (mg)		P uptake (mg)	
E	P1	P2	P1	P2
11634	0.13±0.003^{E-G}	0.12±0.003^{G-I}	35.9±1.41^{H-J}	32±1.09 $^{K-N}$
11635	**0.16**±0.005$^{\mathbf{B}}$	**0.18**±0.003$^{\mathbf{A}}$	**63.1**±1.78$^{\mathbf{B}}$	**71.3**±0.46$^{\mathbf{A}}$
11004	0.11±0.003^{I-K}	0.08±0.005^{OP}	27.6±0.31^{PQ}	12.5±1.37^{Za}
11005	0.11±0.001^{J-L}	0.09±0.005^{M-O}	21.3±0.41^{S-U}	14.6±1.32^{X-Z}
11006	0.12±0.002^{H-J}	0.10±0.004^{L-N}	28.9±0.83^{N-P}	19.7±1.41^{T-V}
11007	0.11±0.005^{I-K}	0.09±0.010^{N-P}	32.9±1.80^{J-L}	15.3±0.72^{X-Z}
11008	0.12±0.003^{G-I}	0.11±0.008^{J-L}	39.1±1.08^{F-H}	32.3±2.54^{K-M}
11009	0.11±0.003^{J-L}	0.09±0.006^{M-O}	25.5±0.91^{QR}	13.4±1.24^{Y-a}
11347	0.11±0.002^{J-L}	0.10±0.002^{L-N}	27.4±0.10^{PQ}	19.9±0.65^{T-V}
11348	**0.10**±0.003^{K-M}	0.09±0.003^{M-O}	**20.1**±0.01^{T-V}	12.5±0.72^{Za}
11349	0.11±0.003^{I-K}	**0.08**±0.005$^{\mathbf{P}}$	32.2±2.79^{K-M}	**10.7**±0.38$_{\mathbf{a}}$
11350	0.12±0.002^{H-J}	0.10±0.002^{K-M}	31.6±0.99^{K-O}	21.2±0.07^{S-U}
11351	0.12±0.004^{H-J}	0.11±0.002^{J-L}	37.2±0.17^{G-I}	28.2±0.10^{PQ}
11636	**0.16**±0.004$^{\mathbf{B}}$	0.15±0.002^{CD}	**63.6**±0.64$^{\mathbf{B}}$	56.6±1.03^{C}
11353	0.12±0.010^{H-J}	0.11±0.005^{J-L}	33.8±4.74^{JK}	29.2±2.82^{M-P}
11354	0.11±0.003^{I-K}	0.10±0.002^{L-N}	28.6±1.54^{O-Q}	17.6±0.06^{V-X}
11355	0.11±0.003^{I-K}	0.10±0.003^{K-M}	30.2±0.96^{L-P}	23.6±0.77^{RS}
11356	0.13±0.006^{F-H}	0.13±0.004^{F-H}	38.2±2.42^{GH}	35.9±1.04^{H-J}
11357	0.12±0.002 $^{H-J}$	0.10±0.003^{K-M}	32.1±1.18^{K-M}	18.6±0.25^{U-W}
11358	0.14±0.002^{D-F}	0.12±0.003^{G-I}	37.5±1.19^{GH}	32.6±0.81^{KL}
11359	0.12±0.003^{G-I}	0.11±0.002^{I-K}	34.2±1.09^{I-K}	25.6±0.22^{QR}
11360	0.14±0.002^{D-F}	0.12±0.002^{H-J}	45.7±1.21^{E}	39.5±1.44^{FG}
11361	0.11±0.004^{J-L}	0.09±0.005^{M-O}	21.1±1.64^{S-U}	13.9±0.95^{Y-a}
11362	0.12±0.001^{H-J}	0.11±0.002^{I-K}	31.4±0.80^{K-O}	30.1±0.81^{L-P}
11645	0.14±0.002^{C-E}	0.14±0.002^{C-E}	42±1.39^{F}	39.5±0.79^{FG}
11364	0.12±0.005^{G-I}	0.12±0.001^{H-J}	30.5±1.73^{L-P}	27.8±0.58^{PQ}
11640	0.15±0.003^{CD}	0.14±0.002^{D-F}	50±1.66^{D}	45.4±1.10^{E}
11641	0.11±0.002^{I-K}	0.10±0.001^{L-N}	25.5±0.67^{QR}	16.3±0.44^{W-Y}
11412	0.15±0.003^{BC}	0.14±0.004^{C-E}	46.3±1.06^{E}	41.6±1.14^{F}
11638	0.12±0.004^{G-I}	0.10±0.004^{K-M}	32.7±0.61^{KL}	21.8±1.09ST
Mean	**0.12**$^{\mathbf{A}}$	0.11^{B}	**34.9**$^{\mathbf{A}}$	27.3^{B}
LSD for P at P ≤ 0.05 = 2.202E-03			LSD for P at P ≤ 0.05 0.5823	
LSD for E at P ≤ 0.05 = 8.526E-03			LSD for E at P ≤ 0.05 = 2.2551	
LSD for P x E at P ≤ 0.05 = 0.0121			LSD for P x E at P ≤ 0.05 = 3.1892	

*Mean values of the same group having similar letters are non-significant using LSD test at 5% level of probability

Zn Concentration (%)

Significant differences were observed among various landraces of wheat for Zn concentration at different levels of P while their interaction was also significant (p≤0.05) (Table 6). Regarding different P levels, Zn concentration was in optimum range at deficient P level and ranged from 0.10% (E.11348) to 0.16% (E.11635) with an average of 0.12% while at deficient P level it was ranged between 0.08% (E.11348) to 0.18% (E.11635). Wheat landrace 11635 produced greater Zn concentration (14.1 %) at deficient level of P which is statistically at par with landrace 11634 (13.9 %) while minimum Zn concentration was observed at adequate P level in wheat landrace 11004 (5.4 %). Overall, there was an upward trend in wheat landraces for Zn concentration that were applied deficient dose of P than supplied with adequate dose of P.

Table 6. Response of wheat landraces (E) regarding Zn concentration at adequate (P1) and deficient (P2) supply of phosphorus (P).

	Phosphorus levels(P)	
E	**P1**	**P2**
11634	7.2±5.09^{T-V}	**13.9±9.76^{AB}**
11635	7.8±5.59^{S}	**14.1±9.97^{A}**
11004	**5.4±3.96^{f}**	10.4±7.42^{Q}
11005	5.9± 4.24^{e}	12.1±8.49^{JK}
11006	6.0± 4.31^{de}	12.2±8.70^{JK}
11007	5.1±3.68^{g}	10.0±7.14^{R}
11008	5.9±3.89^{e}	12.7±9.05^{GH}
11009	5.8±4.10^{e}	10.9±7.78^{P}
11347	6.6±8.98^{Z-b}	12.8±4.74^{GH}
11348	6.8±8.34^{Y-a}	11.7±3.61^{M}
11349	5.0±4.74^{g}	9.8±6.93^{R}
11350	6.7±4.74^{Y-a}	11.5±8.20^{MN}
11351	6.1±4.38^{de}	12.1±8.63^{JK}
11636	7.4±5.23^{T}	13.8±9.83^{B}
11353	7.1±5.02^{U-W}	13.5±9.62^{CD}
11354	6.2±4.31^{cd}	11.3±8.06^{NO}
11355	6.7±4.67^{Y-a}	12.5±8.84^{HI}
11356	6.8±4.74^{Y-a}	12.8±8.98^{FG}
11357	6.0±4.31^{de}	11.0±7.85^{OP}
11358	7.1±5.09^{U-W}	13.7±9.76^{BC}
11359	6.4±4.60^{bc}	12.3±8.77^{IJ}
11360	7.1±5.09^{U-X}	13.5±9.48^{CD}
11361	6.5±4.60^{ab}	11.8±8.41L^{M}
11362	7.0±5.02^{V-Y}	13.4±9.55^{D}
11645	6.8±4.95^{X-Z}	13.1±9.19^{EF}
11364	6.5±4.67^{ab}	12.9±9.05^{FG}
11640	6.8±4.88^{Y-a}	13.3±9.55^{DE}
11641	6.6±4.74^{Z-b}	11.3±8.13^{N}
11412	7.3±5.23^{TU}	13.5±9.55^{CD}
11638	6.9±4.81^{W-Y}	12.0±8.41^{KL}
Mean	6.5^{B}	12.3^{A}
LSD for P at P ≤ 0.05 = 0.0545		
LSD for E at P ≤ 0.05 = 0.2109		
LSD for P x E at P ≤ 0.05 = 0.2983		

*Mean values of the same group having similar letters are non-significant using LSD test at 5% level of probability.

Discussion

Phosphorus is one of the important nutrients required for successful wheat crop production in Pakistan (Ahmed *et al.* 2018). The availability of P in soil is crucial for plant growth improvement (Khan *et al.* 2013; Amin, 2023). Most of chemical

P fertilizer get precipitated in soil and make it unavailable to plants. It is important to screen crop genotypes which have ability to efficiently use applied P. Development of P efficient genotypes in modern breeding requires enough genotypic variation for acclimatization to P deficient soils. As wheat landraces contain genes to tolerate biotic and abiotic stresses and they are capable to survive a wide range of low input farming schemes (Chuda, 2021). This study was designed to assess various landraces in a greenhouse for PUE and related morphological traits. Adequate supply of P at early growth stages is essential to get maximum plant biomass (Mumtaz *et al.* 2014; Damaceno *et al*., 2019). Deficient P level resulted in low fresh biomass in most of wheat landraces. Plants reduce their biomass in P deficiency by causing reduction in plant fresh weight and distracting resources in a disproportional manner to growth of roots. Recommended application of P can increase plant biomass up to 80 % (Shabnam *et al.* 2018). However, De Souza *et al.* 2019 noted that plant biomass enhanced in a commercial wheat genotype under P deficient environment. Wheat land races 11636, 11640 and 11635 utilized P efficiently and enhanced plant biomass. To select P efficient wheat genotypes, phosphatase activity can be used as an early indicator. More release of organic acids by plant roots in rhizosphere is a reliable trait in assessing PUE (Sun and Zhang., 2002). Wheat landraces 11005, 11635 and 11640 produced more alkaline phosphatase to remobilize fixed P from soil at P deficient level due to which these landraces accumulated more P in their roots and shoots. These results are in proximity with Lemming *et al.* (2019) who observed increase in phosphatase activity in wheat genotypes under P deficient soil. More phosphatase activity was noted by Nuruzzaman *et al.* (2006) near roots and showed that phosphatases activity decreases by increasing distance from roots. Phosphorus use and mobilization traits of wheat plant roots show different behavior by increasing P deficiency in soil (Shen *et al.* 2018).

In this study, PUE ranged from 48-100 % for different wheat landraces. Li *et al*. (2019) classified wheat genotypes as P efficient or non-efficient on basis of their PUE. Results showed that genotypes which produces more dry matter at P-deficient level than P-adequate level are P responsive because these genotypes have ability to produce more yield in a P stress environment. Similar results regarding PUE were reported by Pedersen *et al.* (2020) and Gomez-Mu *et al.* (2018). Zou *et al.* (2022) also proposed that PUE is controlled genotypically when plants are exposed to different P doses. The genotypes having P greater than mean were recognized as P efficient (Garder *et al.* 2023). Wheat landraces 11634, 11635, 11636, 11008, 11353, 11356, 11358, 11360, 11362, 11345, 11664, 11612 and 11636 are P efficient based on their PUE. Although adequate P level enhanced plant dry weight in most wheat land races but 11635 produced more dry weight at P-deficient level. Garder *et al.* (2023) also found significant variation in different wheat genotypes against two levels of P for plant dry weight.

More root length was recorded under P deficiency and shoot length increased with increasing P supply. Ahmed *et al.* (2018) also noticed significant differences in wheat genotypes for shoot length against different levels of P. They noticed significant increase in shoot length by increasing available P. These results are in proximity with results of Nisar *et al.* (2016) where significant differences among various genotypes of wheat for shoot and root length were noticed. Root length in wheat is closely linked with PUE. Root length in wheat is not affected by P deficiency rather an increase in root length was observed in P deficient environment (De Souza *et al.* (2019. Stangoulis, J. (2019) proposed that more total root length, root surface area, and root tip can increase productivity of wheat on P deficient soils.

Root and shoot fresh weight were also significantly affected by different levels of P for various wheat landraces. Adequate level of P increased shoot fresh weight of most wheat land races linearly. These results are in accordance with those of Mihoub *et al*., (2023) who noted linear increase in shoot biomass because of enhanced P supply. Pedersen *et al.* (2020) also noted that increase in P supply can enhance shoot biomass by 119 % than deficient supply of P. Effect of low P supply was more severe in less efficient wheat landraces such as 11004 that produced 50 % less shoot fresh weight at P-deficient level than at P-adequate level. These results agree with those of De Souza *et al.* (2019). Cadot *et al.* (2018) also noted significant effects of P fertilization on shoot biomass.

Phosphorus concentration increased with increasing P supply in most wheat landraces except 11636 which accumulated more P in root and shoot in P-deficient condition. Results are in proximity with those of Bilal *et al.* (2018) that showed significant variation among various wheat landraces. Phosphorus uptake is among most reliable parameters used to assess PUE of wheat genotypes (Wang *et al.* 2005). Low P availability is a limiting factor in wheat crop yield so breeding of wheat genotypes for more P uptake ability and related traits is necessary (Manske *et al.* 2001). Significantly high P uptake was observed in wheat landraces 11635 and 11360 at P-deficient level. Total P uptake in wheat crop is not significantly affected if adequate moisture is available in soil (He *et al.* 2021). Adequate amount of P fertilizer promotes P uptake in wheat crop, but excessive P fertilizers do not further increase P uptake of wheat crop (Teng *et al.* 2013). Liu *et al.* (2019) also observed different response of wheat genotypes to P deficiency in terms of P uptake. Similar results regarding P uptake against different P level in wheat crop were reported by Yeseen *et al.* (2009). Results regarding P uptake were in proximity with those of Shabnam *et al.* (2016) that found significant variation among wheat genotype for P uptake. The P uptake was high when wheat plants were supplied with adequate supply of P than at zero level of P. Abbas *et al.* (2018) and Epie and Maral (2018) also reported similar results for P uptake in their experiments on wheat genotypes.

The increased supply of phosphorus significantly reduced shoot Zn concentration but deficient supply of P could not affect the uptake of Zn towards shoot. The increased Zn shoot concentration was noted in plants that were supplied with deficient supply of P. Our results are in close proximity with those of Ilhan and Sakin., (2010) who also noted reduced shoot Zn concentration in wheat as a result of increased P supply. They noted P induced Zn deficiency in wheat crop as a result of excessive P supply. Zang *et al*., (2012) tested the effect of increased P supply on four micronutrients and discovered that shoot Zn concentration was significantly. They proposed that increased P application affects mycorrhizal colonization in the rhizosphere which ultimately reduce Zn uptake. Similar results regarding negative effect of P supply on Zn concentration in wheat was also noted by Ova *et al*., (2015) and Zhang *et al*., (2016).

Zinc (Zn) plays a crucial role in enhancing phosphorus use efficiency (PUE) in rice cropping systems, addressing the challenge of limited phosphorus (P) availability in flooded conditions (Ahmad *et al*., 2021). Zn is vital for root growth, enzyme activation, membrane function, and hormone production, all of which improve P uptake and utilization (Akhtar *et al*., 2019). While high P levels can reduce Zn availability, adequate Zn levels enhance root morphology and activate enzymes that solubilize P (Degryse *et al*., 2024). Practical applications include soil and foliar Zn fertilization, integrated nutrient management, breeding for improved nutrient uptake, and water-saving techniques (Ceasar *et al*., 2016; Brownrigg *et al*., 2022). Optimizing Zn and P nutrition in rice can lead to more sustainable and productive agriculture. Further research is needed to fully elucidate Zn-P interactions and develop effective management strategies (Cai *et al*., 2020).

Conclusion

Wheat being an important global crop gained key importance with increasing population. Availability of nutrients and their uptake determines the plant growth. One of the important limiting nutrients is phosphorus which is depleting rapidly. Considering it, a study was planned to evaluate P-uptake in various wheat landraces. Based on results it is concluded that wheat landraces11634, 11635, 11008, 11636, 11353, 11356, 11358, 11360, 11362, 11645, 11364, 11640 and 11412 are recognized as P efficient because these wheat landraces produced more dry weight in P deficient environment than at adequate P level. These wheat landraces should be further evaluated under field conditions and efficient genotypes can be used by plant breeders to develop wheat cultivars which are best adopted under P stress environment to reduce cost of production.

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Conflicts of Interest

The authors declare no conflicts of interest.

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