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Full Length Article

Enhancing Phosphorus use Efficiency by Supplementing through Soil Applications and Seed Phosphorus Reserves in Maize (*Zea mays*)

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Abstract

Phosphorus (P) nutrition is considered essential for increasing yield in cereals, particularly under limited soil P conditions. Higher plants fulfill their P requirements both through soil and seed reserves. Maize seeds can use 86% of endogenous P, localized in their scutellum for early plant growth until get depleted and plants are solely dependent on soil P supply. Better P acquisition by plants during early season ensures higher uptake for boosting vegetative growth and then mediates allocation of accumulated P in grains at maturity. To evaluate the additive influence of P enriched seeds along with soil P supply, seeds having two ranges of P reserves were sown in separate plots under four soil applied P levels including no P (control). Seeds with different P reserves (1.5 mg kg^{-1} and 3.2 mg kg^{-1}) did not appear with significant effects however, soil applied P at 150 kg ha^{-1} provided maximum grain yield (4.28±0.07 t ha^{-1}), biomass yield (10.2±0.25 t ha^{-1}), agronomic P use efficiency (17.4±0.57 kg kg^{-1} P), total P uptake (16.1±0.52 kg ha^{-1}) and seed P contents (3.34±0.12 mg kg^{-1}) at maturity. In addition soil applied P improved the phosphorus harvest index (88.8±1.9%), phosphorus biological yield efficiency ratio (728±49) and phosphorus physiological efficiency index (286±12) irrespective of seed P contents. Use of 150 kg ha^{-1} P is recommended for better agronomic performance in terms of higher grain yield and better P harvest index of maize.

Keywords: Nutrient availability; Grain yield; Productivity; Phosphorus remobilization.

Introduction

Ever growing population coupled with insufficient and poor quality will lead to food insecurity in Pakistan. This situation calls for viable and strategical response in order to revamp the existing crops' production practices. Field crops critically stand in need for advancement in Pakistan in order to grapple with over more hike in future food demands. Although the major field crops are showing fair progress but prevailing plight stand in need for some extraordinary improvement in quality and quantity of their produce. Maize holds the key position amongst cereal crops not only in Pakistan but also at global level due to its higher production potential consequently requiring more nutrients than other cereal crops (Chen *et al*., 1994).

Calcareous nature of Pakistani soils renders an acute deficiency of P because of its poor availability from soil and applied fertilizer (Rashid and Memon, 2001). Early season P deficiency may result in severe alterations in plant growth and development and situation persists even if soil P supply is optimal at later growth stages (Colomb *et al*., 2000; Grant *et al*., 2001). Much of the damage occurs during early growth stages of the plants (Pellerin *et al*., 2000) so, every effort made for supply of P as early as possible, will improve its use efficiency notably. Phosphorus availability has been considered a most growth limiting factor in crops under most of the agricultural soils (Hinsinger, 2001) because P facilitates cellular energy transfer (Pellerin *et al*., 2000) and controls overall plant growth behavior of crops (Kaya and Higgs, 2001). Since, P occupies different pools in the soil as fixed (80%) and labile in soil solution which either precipitates or up taken by the plants (Leytem and Mikkelsen, 2005). Plants mostly absorb labile P during germination and initial growth stages (Grant *et al*., 2001). Maize seedlings are also able to fulfill their P needs through seed P reserves due to scarcity in soil P supply (Nadeem *et al*., 2011).

In tissues of higher plants, P reserves are in its inorganic form (Park *et al*., 2006) while in seeds most of the P (50–80% of total P) is in the organic form on dry weight basis. The stored P reserves also perform a direct role for predicting its sufficiency or deficiency level in plants (Colomb *et al*., 2000). Although during adequate soil P supply to plant roots, seed P is not metabolized but when plant suffers P deficiency during its early growth then stored inorganic reserves are depleted. This suggests that endogenous seed P plays role in early season P nutrition and also preserves the metabolic forms of P in plants which are utilized during P stress time at later stages of a crop (Grant *et al*., 2001).

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Phosphorus use efficiency (PUE) is often defined as yield or biomass produced per unit of fertilizer P up taken by the crop (Hammond *et al*., 2009) while harvest index of P provides a quantitative estimate of ability of plants to uptake and accumulate P in different plant parts and grains (Yaseen and Malhi, 2009). Improved PUE needs to be acquired, (i) to minimize P fertilizer costs per unit of grain yield produced (Sarwar *et al*., 2016), (ii) to enhance P uptake by plants from the soil to attain greater biomass of the crop at harvest (Veneklaas *et al*., 2012) (iii) and to reduce environmental impacts associated with P exports from the field (Tiessen, 2008; Childers *et al*., 2011). A contemporary understanding of the individual PUE components may be helpful to quantify the physiological attributes and mechanisms (such as P uptake, assimilation, translocation and accumulation) involve within the plant parts that finally affect final crop PUE and grain yield (Yaseen and Malhi, 2009).

In Pakistan, farmers in the maize growing areas are still practicing heavy doses of fertilizer P by targeting maximum grain yield without considering total soil P availability, plant P acquisition, P requirements for biomass allocation and accumulation in maize grains. Such nutrient management practices which mainly entail for excessive N and P fertilization only mostly increase the cost of production per unit of fertilizer applied and disturb the nutrients balance in such soils. Conversely, very less attention has been paid to study the physiological PUE in maize and to find the variations in P acquisition efficiency by plants through soil application along with seed P reserves. Therefore, this study was conducted to explore the benefits of increased P supply to maize plants in improving its agronomic performance and to evaluate physiological PUE attributes for promoting P allocation in grains.

Materials and Methods

Experimental Details and Treatments

Preliminary-experiment seed production: A preliminary experiment was conducted with the objective of obtaining maize seeds with a wide range of seed P contents. A synthetic maize variety MMRI-Yellow (Maize and Millet Research Institute, Yusafwala, Sahiwal) was sown with the help of single hand drill during autumn season, 2013 by using seed rate of 25 kg ha^{-1} in 45 cm apart rows and 5 rows per plot. Thinning was done to maintain 16 plants per row.

Fertilizer Treatments

Diammonium phosphate (DAP) was applied with six P rates; viz. 0, 30, 60, 90, 120 and 150 kg ha^{-1}. Seeds harvested during this experiment were sorted (i.e., low seed P=1.5 mg kg^{-1} and high seed P=3.2 mg kg^{-1}) based on final P contents on dry weight basis and were used in further field experiments during spring season, 2014 and 2015. All experiments were established at the Agronomic Research Area of University of Agriculture, Faisalabad, Pakistan. Seed production study was laid out in Randomized Complete Block Design with a net plot size of 2.7 m × 5 m (gross total area was 243 m^2 for all plots) by using three replications.

Soil Physico-chemical Properties

Soil sampling was done (i.e., 3 cores from each replication area at 20 cm depth) before sowing and the composite samples (n=3) were transported to the Soil Fertility laboratory, Ayub Agricultural Research Institute, Faisalabad for further analyses. These composite samples were subjected to hot air for drying and sieved through 2 mm screen and hydrometer method was used to determine soil texture (Gee and Bauder, 1982) which was sandy clay loam. While chemical analyses details included 7.8 pH, 1.79 dS m^{-1} EC, 0.94% OM, 4.9% $CaCO_3$, 0.23% nitrogen, 5.51 mg kg^{-1} phosphorus, 171 mg kg^{-1} potassium, 0.62 mg kg^{-1} DTPA-extractable Zn and 0.47 mg kg^{-1} hot water extractable boron. Total nitrogen in the soil was determined by Kjeldahl method (Bremner and Mulvaney, 1982; Buresh *et al*., 1982). The available P (Olsen P) was determined by sodium bicarbonate method (Olsen and Sommer, 1982). Available K in soil was determined with ammonium acetate solution (Richards, 1954). Organic matter content was determined by Walkley-Black method (Nelson and Sommers, 1982). Calcium carbonate was measured by acid dissolution (Allison and Moodie, 1965). Available Zn in soil was extracted with 0.005 M DTPA (Lindsay and Norvell, 1978) and determined with atomic absorption spectrophotometer (Chapman and Pratt, 1961). The hot-water extraction procedure (Berger and Truog, 1939) was used to extract available B in the soil and was measured colorimetrically using azomethine-H (Bingham, 1982).

Field Experimental Details

The other two experiments were laid out in a randomized complete block design with factorial arrangement of treatments and were replicated thrice. The net plot size was 3 m × 5 m with gross total area of 810 m^2 for all plots. Soil samples were collected (i.e., 6 cores from each replication area at 20 cm depth) before sowing of crop, during February, 2014 and 2015 and composite samples (n=9) were sent to the laboratory. Similar analytical protocols were followed as for the preliminary experiment of seed production, to determine the soil physico-chemical properties (Table 1).

Fertilizer Treatments

Seeds with different P reserves were dibbled on 45 cm apart ridges separately with planting distance of 30 cm by using a seed rate of 25 kg ha^{-1} on 15th February, 2014 and 20th March, 2015. Urea was applied to provide N (130 kg ha^{-1})

Table 1: Soil physico-chemical analysis

Year	Depth of soil (cm)	Soil texture	pH	$CaCO_3$(%)	EC (dS m^{-1})	Organic matter (%)	N (%)	P	K	Zn	B
2014	20	Sandy clay loam	7.8	4.9	1.79	0.94	0.23	5.51	171	0.62	0.47
2015	20	Sandy clay loam	7.9	5.1	1.63	0.63	0.2	4.8	177	0.56	0.44

and SOP used to apply K (62 kg ha^{-1}). All P was applied with DAP using five P treatments; viz. 0, 50, 100, 150 and 200 kg ha^{-1} that both bulks of seed P reserves were treated equally. All nutrients were applied at planting except N and was applied in three splits i.e., 44.5 kg ha^{-1} at the time of planting, 28 kg ha^{-1} at V8 and 57 kg ha^{-1} at V15 (Ijaz-ul-Hassan *et al*., 2012). In total, 10 canal water irrigations exclusive of presoaking irrigation were applied till the maturity of crop. All necessary cultural and chemical methods were adopted to control weeds, insects and pests' infestation during the whole season of maize crop (Ijaz-ul-Hassan *et al*., 2012).

Plant Tissue and Grain Samples Analysis

Plant tissue and grain samples analyses were performed to determine P concentration (Chapman and Pratt, 1961) and P uptake was calculated by using method of Yaseen and Malhi (2009). At maturity, the second and third leaf from top of the plant including stem (15 cm long) and cobs were harvested. After threshing the cobs, the grains and collected vegetative samples were dried in oven at 70°C for 48 h before recording their dry weights. Dried straw and grain samples were ground in Wiley mill and about one-gram portion was digested using a mixture of nitric acid and perchloric acid (2:1) and P was measured by the vanadate-molybdate yellow color method (Chapman and Pratt, 1961). Phosphorus concentration was determined by measuring the intensity of the vanadomolybdate yellow color using spectrophotometer (Shimadzu, UV-1201, Kyoto, Japan). Agronomic use efficiency of P was calculated by employing the method of Memon *et al*. (2011).

$$\text{P uptake (kg P/ha)} = \frac{\text{P concentration in grain}}{\text{P concentration in straw}} \times 1000$$

$$\text{Agronomic efficiency} = \frac{\text{Yield (fertilized treatment)-Yield (control)}}{\text{Fertilizer P applied (kg ha}^{-1}\text{)}}$$

Physiological P use efficiency parameters were calculated with the help of following formulas (Yaseen and Malhi, 2009):

$$\text{Phosphorus harvest index (PHI,\%)} = \frac{\text{P uptake in grain}}{\text{Total P uptake}} \times 100$$

$$\text{Phosphorus biological yield efficiency ratio (PBER)} = \frac{\text{Biological yield}}{\text{Total P uptake}}$$

$$\text{Phosphorus physiological efficiency index (PPEI)} = \frac{\text{Grain yield}}{\text{Total P uptake}}$$

Statistical Analysis

Data were analyzed using Statistix 8.1 (Analytical Software, Tallahassee FL 32317. USA) and treatments' comparison was done employing Tukey's HSD all-pairwise comparisons test at 5% probability.

Results

Effect of Seed P Contents on Agronomic, P uptake and Physiological PUE Attributes

Seed P contents depicted non-significant impacts on biological yield, grain yield, harvest index, grain P content, total P uptake and agronomic P efficiency (Tables 2 and 3). However, significantly higher PHI (90.6%) and PPEI (310) was recorded with seeds containing higher P over lower P, during 2014 only (Table 4).

Effect of Soil Applied P Levels on Agronomic, P uptake and Physiological PUE Attributes

All calculated attributes of maize crop; biomass and grain yield, AEP, grain P contents and total P uptake performed better during 2014 than 2015 but harvest index values remained unaffected by the effect of years (Tables 2 and 3). Highest biological yield (BY) (10.02 and 8.54 kg ha^{-1}) and grain yield (GY) (4.35 and 3.63 kg ha^{-1}) were obtained at 150 and 200 kg P ha^{-1}. While, 150 and 200 kg P ha^{-1} were followed by 100 kg ha^{-1} (3.08 and 2.60 kg ha^{-1} GY) and (7.41 and 6.22 kg ha^{-1} BY). Moreover, lowest BY (3.76 and 3.45 kg ha^{-1}) and GY (1.68 and 1.40 kg ha^{-1}) were recorded in control during 2014 and 2015, respectively. However, harvest indices remained non-significant during both years of study. With increasing levels of P, a continuous enhancement in AEP was witnessed during both years of study. Whereas, lowest AEP (14.3 and 7.48 kg kg^{-1} P) was observed at 50 kg P ha^{-1} during both years of study.

In 2014, more grain P contents (3.41 mg kg^{-1}) were recorded with 200 kg P ha^{-1} which declined with the declining P application rates. While, statistically similar and higher P contents were observed at 200, 150 and 100 kg P ha^{-1}, during 2015. Furthermore, control manifested lower P contents (2.23 and 1.91 mg kg^{-1}) than other treatments over temporal variability. Higher P uptake (16.7 and 12.3 kg ha^{-1}) was observed with 150 and 200 kg ha^{-1} P than other P levels, during 2014 and 2015 respectively. While, lesser P uptake (2.21 and 1.51 kg ha^{-1}) was obvious in control than other treatments during both years of study.

Table 2: Influence of soil applied P levels and seed P reserves on different agronomic parameters of maize

P Treatments	Grain yield (t ha^{-1})		Biological yield (t ha^{-1})		Harvest index (%)	
Seed P content	2014	2015	2014	2015	2014	2015
SDP_L (1.5 mg P kg^{-1})	3.11±0.27	2.64±0.26	7.35±0.66	6.25±0.59	42.7±0.96	42.4±1.23
SDP_H (3.2 mg P kg^{-1})	3.24±0.31	2.58±0.25	7.48±0.67	6.06±0.60	43.4±0.98	42.6±1.09
Tukey's HSD ($p \geq 0.05$)	NS	NS	NS	NS	NS	NS
Soil P rates						
0 kg P ha^{-1} (Control)	1.68±0.11 d	1.40±0.1 c	3.76±0.22 d	3.45±0.19 c	44.5±0.68	40.7±1.63
50 kg P ha^{-1}	2.43±0.09 c	1.78±0.08 c	5.85±0.31 c	4.03±0.18 c	41.8±2.03	44.2±0.66
100 kg P ha^{-1}	3.08±0.08 b	2.60±0.16 b	7.41±0.24 b	6.22±0.41 b	41.7±1.19	42.2±2.43
150 kg P ha^{-1}	4.28±0.07 a	3.64±0.17 a	10.2±0.25 a	8.28±0.25 a	42.1±1.65	44.3±2.68
200 kg P ha^{-1}	4.42±0.16 a	3.62±0.08 a	9.84±0.24 a	8.80±0.14 a	45.1±1.59	41.3±0.82
Tukey's HSD ($p \leq 0.01$)	0.465	0.391	1.179	0.951	NS	NS
Year means	3.18±0.2 a	2.61±0.18 b	7.42±0.46 a	6.16±0.41 b	43.0±0.68	42.5±0.81
Tukey's HSD ($p \leq 0.05$)	0.54		1.245		1.54	

SDP_L=Seeds containing low P content, SDP_H=Seeds containing high P content
Means ± standard error not sharing a common letter within a column differ significantly at $p \leq 0.01$ for soil P levels and at $p \leq 0.05$ for year means
NS=Non-significant

Table 3: Influence of soil applied P levels and seed P reserves on different P uptake parameters of maize

P Treatments	Agronomic efficiency of P (kg kg^{-1} P)		Grain P content (mg kg^{-1})		Total P uptake (kg ha^{-1})	
Seed P content	2014	2015	2014	2015	2014	2015
SDP_L (1.5 mg P kg^{-1})	14.5±0.63	12.1±0.94	2.83±0.16	2.60±0.13	10.15±1.6	7.08±1.19
SDP_H (3.2 mg P kg^{-1})	15.2±0.62	11.5±0.86	2.97±0.11	2.44±0.15	10.02±1.61	7.38±1.26
Tukey's HSD ($p \geq 0.05$)	NS	NS	NS	NS	NS	NS
Soil P rates						
0 kg P ha^{-1} (Control)	-	-	2.23±0.14 d	1.91±0.2 c	2.21±0.06 d	1.51±0.12 c
50 kg P ha^{-1}	14.3±0.62 b	7.48±0.48 c	2.64±0.13 cd	2.36±0.22 b	5.03±0.42 c	3.35±0.26 c
100 kg P ha^{-1}	14.0±0.72 b	13.6±0.64 a	2.89±0.11 bc	2.78±0.16 a	9.75±0.29 b	6.69±0.29 b
150 kg P ha^{-1}	17.4±0.57 a	14.9±0.3 a	3.34±0.12 ab	2.80±0.17 a	16.1±0.52 a	11.6±0.78 a
200 kg P ha^{-1}	13.8±0.78 b	11.1±0.28 b	3.41±0.1 a	2.76±0.14 ab	17.4±0.44 a	13.0±0.34 a
Tukey's HSD ($p \leq 0.01$)	2.32	1.68	0.451	0.409	1.866	1.862
Year means	14.8±0.44 a	11.8±0.63 b	2.90±0.1 a	2.52±0.1 b	10.08±1.11 a	7.24±0.85 b
Tukey's HSD ($p \leq 0.05$)	1.54		0.277		2.809	

SDP_L=Seeds containing low P content, SDP_H=Seeds containing high P content
Means ± standard error not sharing a common letter within a column differ significantly at $p \leq 0.01$ for soil P levels and at $p \leq 0.05$ for year means
NS=Non-significant

Table 4: Influence of soil applied P levels and seed P reserves on P use efficiency parameters of maize

P Treatments	Phosphorus harvest index (%)		Phosphorus biological yield efficiency ratio		Phosphorus physiological efficiency index	
Seed P content	2014	2015	2014	2015	2014	2015
SDP_L (1.5 mg P kg^{-1})	80.8±2.51 b	79.7±3.3	754±47	938±66	293±10 b	311±9
SDP_H (3.2 mg P kg^{-1})	90.6±1.40 a	74.8±3.1	770±46	881±76	310±10 a	315±11
Tukey's HSD ($p \leq 0.05$)	5.03	NS	NS	NS	13.4	NS
Soil P rates						
0 kg P ha^{-1} (Control)	77.5±5.4 b	67.5±5.8 b	1017±52 a	1183±130 a	347±6 a	358±12 a
50 kg P ha^{-1}	84.3±4.3 ab	78.0±5.9 ab	826±42 b	1021±104 ab	320±5 ab	333±10 ab
100 kg P ha^{-1}	91.6±1.9 a	86.3±3.6 a	760±19 bc	941±81 ab	317±12 b	313±9 bc
150 kg P ha^{-1}	88.8±1.9 ab	79.3±3.3 ab	641±33 cd	728±49 b	268±10 c	286±12 cd
200 kg P ha^{-1}	86.8±1.9 ab	75.1±4.2 ab	567±16 d	676±16 b	254±6 c	272±7 d
Tukey's HSD ($p \leq 0.05$)	11.45	16.97	172	395	30	27
Year means	85.7±1.7 a	77.2±2.3 b	762±34 b	910±50 a	301±7	313±7
Tukey's HSD ($p \leq 0.05$)	5.65		119		NS	

SDP_L=Seeds containing low P content, SDP_H=Seeds containing high P content
Means ± standard error not sharing a common letter within a column differ significantly at $p \leq 0.01$ for soil P levels and at $p \leq 0.05$ for year means
NS=Non-significant

Data regarding PUE parameters in table (4) exhibited that soil applied P levels depict maximum values of PHI (91.6 and 86.3%) at 100 kg P ha^{-1} whereas this rate was statistically similar to 50, 150 and 200 kg P ha^{-1} except control, during both years of study. Highest PBER (1017 and 1183) were observed in control than other treatments. While less PBER was at 150 kg P ha^{-1} (641 and 728) and 200 kg P ha^{-1} (567 and 673) during 2014 and 2015, respectively. Similarly, lesser PBER (826) was recorded at 50 kg P ha^{-1} in 2014 but was at par with control (1021) in 2015. Similarly, for PPEI, maximum values (347 and 358) were attained at control and statistically similar responses

(320 and 333) were at 50 kg P ha^{-1} during 2014 and 2015, respectively. While minimum values (261 and 279) were observed at increased P supply (150 and 200 kg ha^{-1}), during both years of study.

Discussion

Maize production requires rational management of P under its limited soil conditions that becomes even more challenging in calcareous soils. To increase P acquisition and internal use efficiency of applied P in field crops particularly in maize, incremental soil P application is the only way to achieve desired yield targets. Based upon their responses, all the described parameters necessitated for higher P supply to ensure better uptake and P application improved all studied parameters over control. Additionally, the significant effect of seed P contents and soil P levels during 2014 might be attributed to overall better crop performance due to favorable environmental conditions as compared to 2015.

Plants are able to acquire P from soil during growing season and increased synergistic effects obtained as a result of sufficient P supply. Higher P uptake might have augmented biomass and grain yield over control. Moreover, use of phosphate fertilizers has been studied regularly and aimed at increasing target yield benefits, sustain soil fertility levels and to increase productivity of crops (Aulakh and Garg, 2007; Zhang *et al*., 2008). Thus, the significant results strengthened our insights about the relationship among grain yield and soil applied P levels. Finally, at the end of the growing season triggered the maturity of the crop with significant dry matter accumulation as well as higher grain yield. Similarly, increased grain yield (2.68 t ha^{-1}) was attained where 120 kg P_2O_5 ha^{-1} was applied without adding crop residues to supplement P needs of maize (Mahmood and Ali, 2015). Contrarily, Mazengia (2011) did not find any significant increase in maize grain yield under higher P levels (69 and 92 kg P ha^{-1}) instead he observed higher yield in the control. He justified that decreased maize yield might be due to enhanced P fixation at higher P application rates. But in the present study, increased P applications enhanced its solubility in the soil and roots might have attained better growth. Thus, increased P solubility in the soil positively increased its uptake by roots that improved P accumulation in grains, higher weight and grain yield of crop plants (Shaharoona *et al*., 2006; Ditta *et al*., 2015). However, non-significant harvest indices might be attributed to increased biomass yield while less proportional increase in grain yield was observed under all soil applied P levels. Apparently, no toxicity symptoms were observed at any level of P. These findings described that optimum P supply in maize ensured higher P uptake through better roots development, better assimilation of acquired P into vegetative/reproductive tissues and ultimately more biomass and grain yield at maturity.

Within the plants, higher P might have remobilized and partitioned towards grains and thus improved grain P contents. The P concentration in seeds is the remobilized form of P from senescing leaf tissues which varies according to P availability in the soil. In the present study, 33.8 and 31.3% higher grain P accumulation was observed on an average at 150 and 200 kg P ha^{-1} as compared to control during 2014 and 2015, respectively. These findings justified that increase in grain P contents was linearly related to total P uptake under elevated P levels. However, high P concentration in cereal grains is not mostly desirable (Raboy, 2009) due to its binding ability with iron and zinc. Moreover, higher P contents in plants under elevated P applications can be elucidated in terms of higher AEP. Thus, P application enhanced AEP over control and increased P contents in grains.

The translocation of P towards grains which was absorbed during whole growing season of crop can be defined in terms of PHI which varied according to soil applied P. Most of the absorbed P was accumulated in vegetative tissues (source) first and then allocated towards grains (sink) at maturity or when leaf senescence started (Veneklaas *et al*., 2012). More P uptake under higher applied P over control might be due to improved root growth and stimulated roots to absorb more P. However, PHI values at lower P levels and in control were also overlapping with the higher applied P which also confirmed the root activity to acquire P under deficient conditions. Moreover, PBER and PPEI was more under P application. Significant lower values for PBER and PPEI justified that when plants become able to acquire P sufficiently to fulfill their needs, relative yield benefits in terms of maximum biomass and grains are achieved. Higher PHI, PBER and PPEI values for different wheat genotypes under stressed P conditions were observed by Yaseen and Malhi (2009) and variability in efficiency of genotypes for total P uptake was considered vital under adequate and stressed P conditions. This can be inferred that MMRI-Yellow responded well to elevated soil applied P levels in terms of higher PHI which might be attributed to higher P uptake as described previously. Similarly, high average PHI was observed in rice by Rose *et al*. (2010) but correlations between pattern of P accumulation in vegetative and grain tissues were found weak. This necessitated the P availability to plants for higher biomass accumulation through additive effects on higher P uptake and virtually higher grain yield as deficiency of P affected all these processes negatively (Colomb *et al*., 2000). However, in the present study, very meaningful relationship between PPEI and AEP can be deduced for improved PUE in terms of its higher acquisition with indirect effects of higher yield benefits. Lessening of PPEI ultimately caused higher P uptake over years.

Conclusion

Finally, outcomes regarding grain and biomass yield of this study helped us to conclude that irrespective of seed P contents higher soil P supply ensured better crop performance and agronomic efficiency of P compared to sufficient soil P management. Results of two years' studies clearly demonstrated improved P supply through variable soil applied levels and 150 kg P ha^{-1} was found best for improving grain yield through better agronomic performance of maize. Moreover, this P rate was found optimum for enhancing the PUE under calcareous soil conditions of Faisalabad. However, various nutrient ratios [N:P] can be explored further both in vegetative and reproductive tissues to optimize soil applied N and P levels through their better accumulation, distribution and remobilization in maize.

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