 Doi: 10.33158/ASB.2015v1i1p33

Phosphorus acquisition and use efficiency in bean cultivars of the "Carioca" and "Preto" commercial groups

Harold Eduardo Rubiano Perilla[1,*], Vania Moda Cirino[2], Paulo Mauricio Ruas[1], Marcos Antonio Pavan[2] and Leandro Simões Azeredo Gonçalves[1]

[1]Agronomy Department, Universidade Estadual de Londrina (UEL), Rodovia Celso Garcia Cid Km 380, CEP 86051-900, Londrina, PR Brazil. [2]Plant Breeding, Instituto Agronômico do Paraná (IAPAR), Rodovia Celso Garcia Cid Km 375, 86047-902, Londrina, PR Brazil. *Corresponding author, E-mail: eduardorubianop@gmail.com

ABSTRACT

This study aimed to evaluate phosphorus (P) acquisition and use efficiency in bean cultivars of the "Carioca" and "Preto" commercial groups in nutrient solution. Six cultivars of the "Carioca" group ("Pérola," "IPR Siriri," "IPR Eldorado," "BAT 477," "Campeão 2," and "Aporé") and 7 cultivars of the "Preto" group ("IPR," "Uirapuru," "IPR Graúna," "IPR Tiziu," "IPR Tuiuiú," "FT Soberano," "BRS Esplendor," and "BRS Supremo") were evaluated at 2 levels of phosphorus (6.25 and 25.02 μM L^{-1}). The experiment was conducted in a greenhouse and arranged in a completely randomized factorial design with 6 replicates, and the dry weights of the shoots (fractioned into the dry weights of the stems, leaves, pods, and beans) and roots were evaluated at physiological maturity. Phosphorous content was determined in these vegetative structures using an atomic emission spectrophotometer, and indices of P absorption, translocation and use efficiency were then quantified. Statistically significant differences were observed in all P absorption and use efficiency indices for the "Preto" group cultivars whereas in the "Carioca" group, only the P absorption and translocation indices showed significant differences. The "IPR Eldorado" and "IPR Graúna" cultivars stood out for P absorption and translocation efficiency while the "IPR Uirapuru" and "IPR Tiziu" cultivars stood out for P use efficiency. These cultivars have the potential for use in future bean genetic improvement programs aimed at reducing phosphate fertilizer use and production costs.

Key words: *Phaseolus vulgaris* L., mineral nutrition, plant genetic improvement, abiotic stress.

INTRODUCTION

Bean (*Phaseolus vulgaris* L.) is an important basic but high quality food that provides large quantities of proteins, vitamins, and minerals to the human diet in many countries (Broughton et al., 2003; Miklas et al., 2006; Blair et al., 2012). Brazil is considered the third largest bean producer in the world and is responsible for 12.69% (2.94 million tons) of production with a mean yield of 1,037 Kg ha^{-1} (FAO, 2014).

This yield is considered low compared to the potential production that can be achieved with new cultivars (Paula Júnior et al., 2008; Martins et al., 2009). The reasons for this low yield include pests and diseases, poor quality seeds, adverse climatic conditions, the use of unadapted cultivars, and the inappropriate use of agricultural input, such as correctives and fertilizers (Farinelli et al., 2006; Zucareli et al., 2011; Mingotte et al., 2013).

Bean plants have high nutritional demands and short lifecycles, so they require readily available nutrients to avoid limits to their yield (Araújo and Teixeira 2008). In this context, the low levels of available P in Brazilian soils are considered one of the main obstacles to increased crop yield as these soils are mostly characterized by an advanced degree of weathering, high acidity, and consequently, low nutrient availability, especially of P (Arf 1994).

The strategy employed to minimize this problem is the use of correctives and phosphate fertilizers, i.e., adjusting the soil to suit the plant. Phosphate fertilizer, which is predominantly derived from phosphate rock, is extensively used in agriculture and has significantly contributed to increased food production and food security (Richardson et al., 2011; Veneklaas et al., 2012). However, recent estimates indicate that the prices of phosphate fertilizers will likely increase over the coming decades, as readily minable P reserves could be exhausted within this century (Cordell, Drangert and White 2009; Scholz et al., 2013).

Therefore, increasing P use efficiency in agricultural systems is essential for sustainable food production (Elser 2012; Rose, Liu and Wissuwa 2013). Accordingly, studies aimed at developing plants with higher soil phosphate absorption capacity (P acquisition efficiency - PAE) and increased productivity, or biomass per unit of absorbed P (P use efficiency - PUE), have become paramount to the maintenance of sustainable agricultural systems (Veneklaas et al., 2012).

Phosphorous acquisition efficiency can be determined by morphological, physiological, and biochemical differences in the root systems of plants, such as the development of lateral roots and root hairs, root architecture, symbiotic associations with mycorrhizae, and the production of root exudates, including organic anions and phosphatase enzymes (Wang, Shen and Liao 2010). Phosphorous use efficiency is especially attributed to the translocation and use efficiency of P stored in plants, in which P is transported from metabolically inactive sites to active sites under conditions of low P availability (Kouas et al., 2009; Veneklaas et al., 2012).

The selection of bean cultivars that have higher P absorption and use efficiency is a feasible alternative for reducing phosphate fertilizer use and production costs. Therefore, this study aimed to determine the P acquisition and use efficiency in cultivars of the "Carioca" and "Preto" commercial groups grown in nutrient solution.

MATERIALS AND METHODS

From September to December, 2012, two experiments using nutrient solution were conducted in a greenhouse at the Agronomic Institute of Paraná (Instituto Agronômico do Paraná - IAPAR) experimental station in Londrina - PR, Brazil (latitude 23° 30'S, longitude 51° 32'W, and an altitude of 585 meters) (Figure 1). The first experiment included six cultivars of the "Carioca" commercial group ("Pérola," "IPR Siriri," "IPR Eldorado," "BAT 477," "Campeão 2," and "Aporé") while the second experiment included seven cultivars of the "Preto" commercial group ("IPR Uirapuru," "IPR Graúna," "IPR Tiziu," "IPR Tuiuiú," "FT Soberano," "BRS Esplendor," and "BRS Supremo"). These cultivars are extensively used by farmers in Brazil.

Figure 1. Common bean experiment with different phosphorus sources.

Experiments I and II were arranged in a completely randomized factorial design with treatments comprised of 6 and 7 cultivars, respectively, and 2 P concentrations (6.25 and 25.02 μM L^{-1}), with six repetitions. The cultivars were sowed in 128-cell Styrofoam trays containing commercial horticulture substrate and placed in a greenhouse for germination and seedling growth. Five days after emergence, seedlings with uniform shoot and root development were selected and then transplanted into 5-L polyethylene pots containing Hoagland and Arnon (1950) nutrient solution as modified by Pavan and Bingham (1982). The seedlings were fixed using foam in holes made in polyethylene plates that were placed on the surface of the pots. The pH and electrical conductivity (EC) of the nutrient solution were monitored daily with the pH maintained at 5.5 ± 0.2 through the addition of 1N HCl or NaOH. The pots were placed on tables inside the greenhouse under controlled conditions, and the solutions were permanently aerated. The nutrient solutions were replaced every 20 days to ensure water and nutrient availability until the end of the cycle.

The following evaluations were performed during the stage of development leading to physiological maturity: shoot dry weight (SDW) fractioned into the dry weights of the stems, leaves, pods and beans, and root dry weight (RDW). SDW and RDW were obtained after drying in a forced-circulation oven at 60°C to constant weight. The tissues were then ground and homogenized in a Wiley mill with a number 20 sieve, and 0.4 g samples were removed and subjected to nitropercloric digestion with a 3:1 ratio HNO_3:$HClO_4$ solution (Miyazawa et al., 1999). The P harvest index (PHI, g kg^{-1}) was determined with an atomic emission spectrophotometer (Thermo Jarrell Ash ICAP 61E). The P contents (mg) of the stems (SPCONT), leaves (LPCONT), pods (PPCONT), and beans (BPCONT) were obtained as the product of the dry matter weight of the section of the plant analyzed and the P content of the collected sample (0.4 g). The sum of the above P contents (SPCONT, LPCONT, PPCONT, and BPCONT) resulted in the aerial parts P content (APPCONT) variable. The total P content of the plants (TPCONT) was obtained by adding APPCONT and root P content (RPCONT) together.

The efficiency indices were estimated using the method proposed by Siddiqi and Glass (1981) and adapted by Moura et al. (1999) according to the following equations:

- P absorption efficiency (PAE): TPCONT (mg)/RDW (mg)
- P translocation efficiency (PTE): APPCONT (mg)/TPCONT (g)x100
- Aerial part P use efficiency (APPUE): SDW (g)/APPCONT (mg)
- Total P use efficiency (TPUE): RDW (g)/TPCONT (mg)
- Aerial part P use efficiency for bean dry matter production (APPUEB): BDW (g)/APPCONT (mg)
- P harvest index PHI: BPCONT (mg)/APPCONT (mg)x100

The data were subjected to individual analysis of variance (ANOVA) and then joint ANOVA by applying the F test under conditions of homogeneity of residual variances. Tukey's test at 5% was used to compare the means of the treatments. The 'Agricolae' package of the R statistical software (www.r-project.org) was used for these analyses.

RESULTS AND DISCUSSION

The ANOVA revealed significant differences in RDW and SDW between the different P concentrations (6.25 and 25.02 μM L^{-1}) in the two bean groups, indicating that the treatments were sufficient to cause P deficiency to the point of altering plant morphology (Table 1). Only RDW was a significant source of variation in the cultivars and the cultivar x P concentrations for the "Carioca" group whereas all of the sources of variation were significant for the "Preto" group, indicating different cultivar behavior in relation to P concentrations. The mean RDW values were 1.39 and 1.27 g for the "Carioca" and "Preto" groups, respectively, and the mean SDW values were 5.32 and 7.20 g.

There was no difference between the cultivars of the "Carioca" group at 6.25 μM L^{-1} P in RDW whereas the highest value was obtained by "BAT 477" (2.37 g) at 25.02 μM L^{-1} with no difference in the "Campeão 2" and "IPR Siri" cultivars (2.12 and 1.87 g, respectively) (Figure 2). In the "Preto" group, the "IPR Uirapuru" cultivar obtained the highest RDW values with no difference in the "BRS Esplendor" and "IPR Tuiuiú" cultivars at all concentrations, which points to the potential of these cultivars to generate root mass at low P concentrations. For SDW, there was no difference between the cultivars of the "Preto" group at 6.25 μM L^{-1}, but the highest values were obtained by the "IPR Tuiuiú," "IPR Uirapuru," and "BRS Esplendor," cultivars at 25.02 μM L^{-1} (13.07, 12.07, and 11.94 g, respectively).

Increased P concentration led to increased RDW and SDW for most of the cultivars, indicating that physiological alteration was promoted in the cultivars with an increase in dry matter due to the P concentration in the medium. Fageria (1998) evaluated the effect of P doses (natural soil, 50 and 200 mg P Kg^{-1} – triple super phosphate) on the morphological attributes of bean cultivars in a greenhouse and found that all of the growth and P absorption parameters were significantly affected by P treatment.

Araújo, Teixeira and Almeida (1998) evaluated P use efficiency in wild accessions grown under 2 levels of soil P (20 and 80 mg P Kg^{-1}) and observed broad variability between them. The authors also noted that improved genotypes generated higher root mass and root/shoot ratios, suggesting that long-term selection resulted in plants that preferably invest in root production, which is a valuable characteristic in low P soils. These results were also confirmed by Beebe et al. (1997), who evaluated 364 bean plant accessions (commercial and wild) from different geographic regions and found low P use efficiency in the wild accessions, suggesting that the characteristics related to P use efficiency were acquired during or after domestication.

For the "Carioca" group, the values of PAE, PTE, APPUE, TPUE, and PHI significantly differed with P concentration whereas only PAE and PTE differed significantly by cultivar (Table 2). In the "Preto" group, the PAE, APPUE, TPUE, and APPUEB characteristics differed significantly with both P concentration and cultivar, and PTE and PHI only differed by cultivar.

Table 1. Mean squares, means, and coefficients of experimental variation for root dry weight (RDW) and shoot dry weight (SDW) at two P concentrations (6.25 and 25.02 μM L^{-1}) in six bean cultivars of the "Carioca" commercial group and seven bean cultivars of the "Preto" group grown in nutrient solution.

Source of variation	DF	"Carioca" group		DF	"Preto" group	
		Mean squares			Mean squares	
		RDW	SDW		RDW	SDW
Concentration (Co) ((C(Co) Levels (L)	1	19.70**	353.82**	1	9.25**	576.71**
Cultivar (C)	5	0.38**	0.46^{ns}	6	2.01**	26.72**
Co x C	5	0.34*	5.22^{ns}	6	0.35*	15.82**
Error	60	0.11	2.37	83	0.12	4.33
Mean		1.39	5.32		1.27	7.20
CVe (%)		24.19	28.92		27.05	28.93
QMr $^{+}$/QMr $^{-}$		3.01	4.76		5.40	6.93

^{NS}Non-significant (P>0.05);
**Significant at P≤0.01; and
*Significant at P≤0.05.

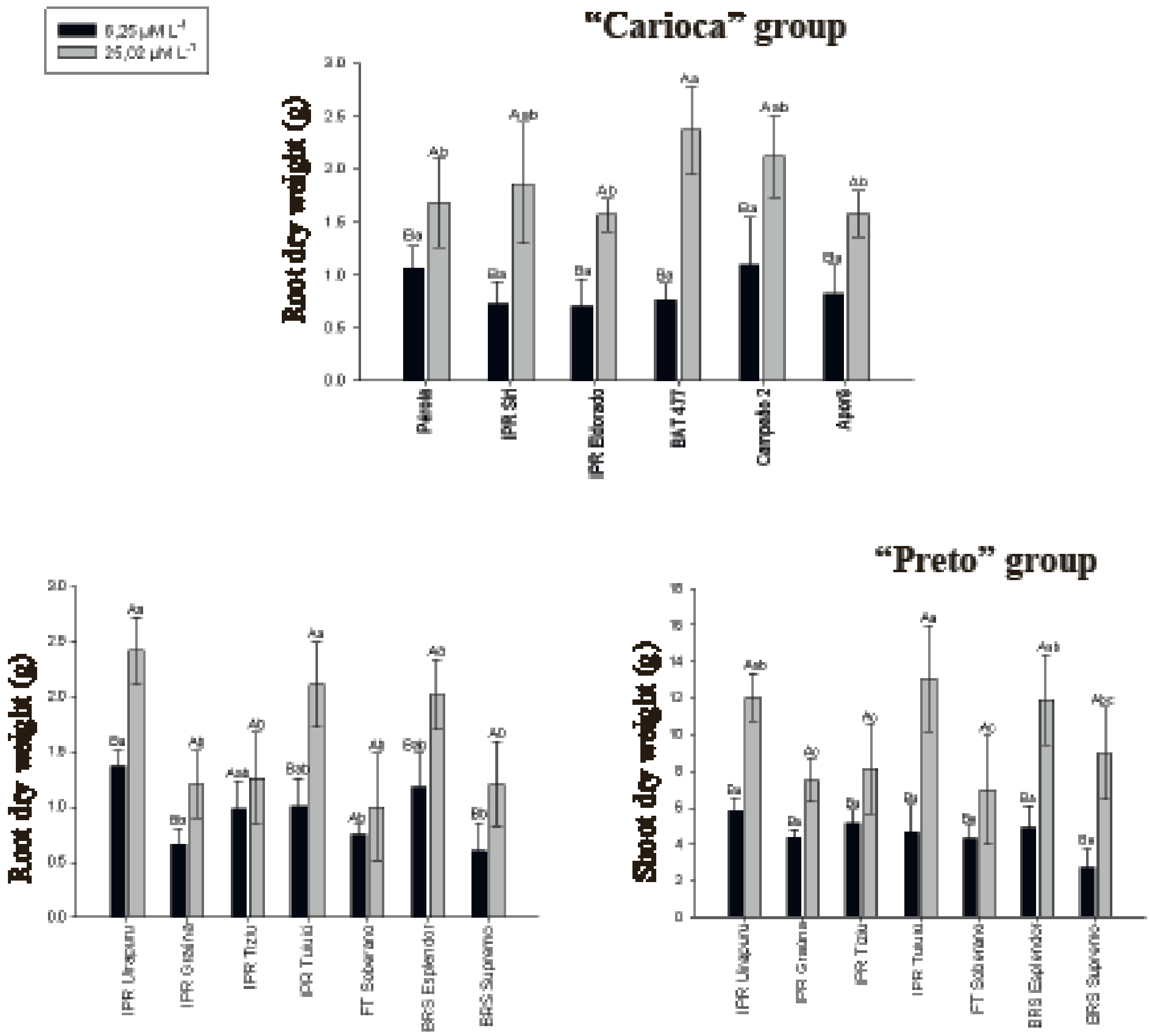

Figure 2. Means compared by Tukey's test (P≤0.05) for root dry weight (RDW) and shoot dry weight (SDW) at two P concentrations (6.25 and 25.02 μM L^{-1}) in six bean cultivars of the "Carioca" commercial group and seven bean cultivars of the "Preto" group grown in nutrient solution. Means followed by the same uppercase and lowercase letters are not significantly different from each other.

MECENAS PUBLISHING

Table 2. Mean squares, means, and coefficients of experimental variation for P absorption and use efficiency at two P concentrations (6.25 and 25.02 µM L^{-1}) in six bean cultivars of the "Carioca" commercial group and seven bean cultivars of the "Preto" group grown in nutrient solution.

Source of Variation	DF	Mean squares					
		PAE[1]	PTE	APPUE	TPUE	APPUEB	PHI
Experiment I – "Carioca" group							
Concentration (Co)	1	74.23^{**}	1886.50^{**}	1.95^{**}	0.80^{**}	0.0009^{ns}	0.96^{**}
Cultivar (C)	5	17.48^{*}	337.57^{**}	0.04^{ns}	0.03^{ns}	0.005^{ns}	0.05^{ns}
Co x C	5	1.76^{ns}	143.85^{ns}	0.04^{ns}	0.06^{**}	0.004ns	0.01^{ns}
Error	60	6.22	73.09	0.03	0.01	0.0037	0.03
Mean		6.81	73.12	0.85	0.78	0.13	0.30
CVe (%)		36.63	11.69	19.71	15.46	48.27	46.72
QMr^{+}/QMr^{-}		1.04	1.57	1.72	1.52	1.44	3.03
Experiment II – "Preto" group							
Concentration (Co)	1	133.86^{**}	0.10^{ns}	0.59^{**}	0.66^{**}	0.11^{**}	0.018ns
Cultivar (C)	6	62.77^{**}	100.81^{**}	0.33^{**}	0.35^{**}	0.06^{**}	0.11^{**}
Co x C	6	13.73^{*}	9.09^{ns}	0.12^{ns}	0.11^{*}	0.01^{ns}	0.02^{ns}
Error	83	5.33	17.97	0.06	0.05	0.009	0.02
Mean		7.37	84.73	0.77	0.80	0.17	0.25
CVe (%)		31.34	5.00	30.79	27.18	57.96	46.44
QMr^{+}/QMr^{-}		5.96	1.06	1.33	1.38	3.56	3.40

[1]PAE: P absorption efficiency (mg); PTE: P translocation efficiency (%); APPUE: aerial parts P use efficiency (g); TPUE: total P use efficiency (g); APPUEB: aerial parts P use efficiency for bean dry matter production (g), and PHI: P harvest index (%).
^{NS}Non-significant (P>0.05);
**Significant at P≤0.01; and
*Significant at P≤0.05.

Table 3. Means compared by Tukey's test (P≤0.05) for P absorption and use efficiency at two P levels (6.25 and 25.02 µM L^{-1}) in seven bean cultivars of the "Preto" commercial group grown in nutrient solution.

Cultivar	PAE[1]		PTE		APPUE	
	6.25	25.02	6.25	25.02	6.25	25.02
"IPR Uirapuru"	4.11**Ad**[2]	4.29**Af**	82.87**Ad**	80.73**Ad**	1.07**Aa**	1.02**Aa**
"IPR Graúna"	9.11**Aa**	9.78**Ac**	89.45**Aa**	86.81**Ab**	0.71**Ac**	0.61**Ac**
"IPR Tiziu"	5.13**Bc**	9.05**Ad**	83.61**Ad**	84.92**Ac**	1.12**Aa**	0.55**Bc**
"IPR Tuiuiú"	4.69**Acd**	6.68**Ae**	83.53**Ad**	85.61**Abc**	0.83**Ab**	0.77**Ab**
"FT Soberano"	7.04**Bb**	13.35**Aa**	85.96**Ac**	85.87**Abc**	0.86**Ab**	0.53**Bd**
"BRS Esplendor"	5.06**Ac**	6.39**Ae**	80.37**Ac**	80.56**Ad**	0.87**Ab**	0.82**Ab**
"BRS Supremo"	7.58**Bb**	10.85**Ab**	87.56**Ab**	88.35**Aa**	0.52**Ad**	0.51**Ad**

Cultivar	TPUE		APPUEB		PHI	
	6.25	25.02	6.25	25.02	6.25	25.02
"IPR Uirapuru"	1.13**Aa**	1.06**Aa**	0.16**Bb**	0.31**Aab**	0.32**Aab**	0.31**Ab**
"IPR Graúna"	0.75**Ac**	0.63**Ac**	0.09**Ac**	0.12**Ad**	0.10**Ae**	0.14**Ae**
"IPR Tiziu"	1.13**Aa**	0.58**Bcd**	0.16**Ab**	0.16**Ac**	0.26**Ac**	0.18**Ad**
"IPR Tuiuiú"	0.86**Ab**	0.83**Ab**	0.20**Ba**	0.32**Aa**	0.29**Abc**	0.28**Ab**
"FT Soberano"	0.88**Ab**	0.54**d**	0.08**Ac**	0.11**Ad**	0.16**Ad**	0.21**Ad**
"BRS Esplendor"	0.90**Ab**	0.82**Ab**	0.16**Bb**	0.28**Ab**	0.35**Aa**	0.49**Aa**
"BRS Supremo"	0.57**Ad**	0.54**Ad**	0.07**Ac**	0.12**Ad**	0.19**Ad**	0.27**Ac**

[1]PAE: P absorption efficiency (mg); PTE: P translocation efficiency (%); APPUE: aerial parts P use efficiency (g); TPUE: total P use efficiency (g); APPUEB: aerial parts P use efficiency for bean dry matter production (g), and PHI: P harvest index (%). [2]Means followed by the same uppercase and lowercase letters in the same rows and columns, respectively, do not differ statistically between each other.

These results reflect broad variation among the cultivars of different groups with regard to P absorption and translocation and thus provide more useful information for developing genetic improvement programs with the aim of obtaining efficient and responsive cultivars. In contrast, PUE only varied in the cultivars of the "Preto" group. Lana et al. (2006) evaluated 8 bean cultivars subject to 2 P doses (24 and 120 mg dm^3) in a greenhouse and observed broad variability among the cultivars in P absorption and use efficiency. For the concentration x cultivar interaction, only TPUE was significant for the "Carioca" group, but there were differences in PAE and TPUE in the "Preto" group, demonstrating different behaviors among the cultivars in response to P concentration.

For PAE, the "IPR Eldorado" cultivar of the "Carioca" group was most efficient at 6.25 μM L^{-1} with 9.61 mg whereas there were no differences among the cultivars at 25.02 μM L^{-1} (Figure 3). The "IPR Eldorado" cultivar also exhibited high PAE values and did not differ between P concentrations, which demonstrates that increasing the P level did not increase P acquisition. For the "Preto" group, the "PR Graúna" cultivar obtained the highest PAE value at 6.25 μM L^{-1} (9.11 mg) while at 25.02 μM L^{-1}, the highest value was obtained by the "FT Soberano" cultivar with 13.35 mg (Table 3).

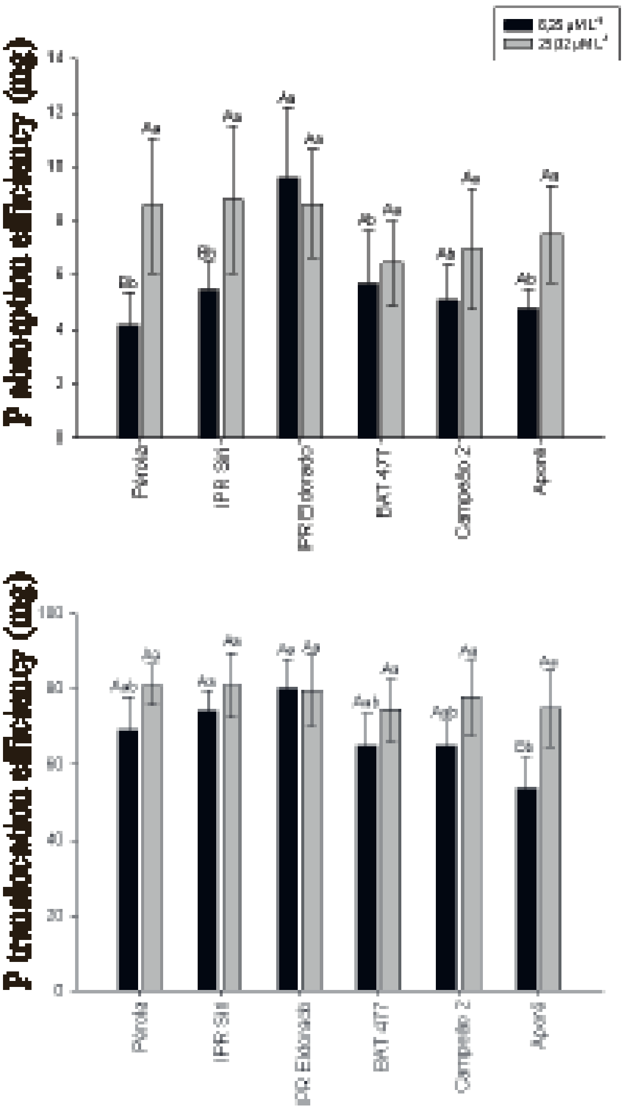

Figure 3. Means compared by Tukey's test (P≤0.05) for P absorption and translocation efficiency at two P concentrations (6.25 and 25.02 μM L^{-1}) in six bean cultivars of the "Carioca" commercial group grown in nutrient solution. Means followed by the same uppercase and lowercase letters are not significantly different from each other.

PTE from the roots to the aerial parts is related to the high P affinity of the transporters present in the plant, especially under conditions of low P availability (Shenoy and Kalagudi 2005; Wang, Shen and Liao 2010). The "IPR Eldorado" cultivar also exhibited high PTE values, 80.35 and 79.78%, at both concentrations (6.25 and 25.02 μM L^{-1}), respectively, but these values were not significantly different from each other. For the "Preto" group, the highest values were obtained by the "IPR Graúna" and "BRS Supremo" cultivars at 6.25 and 25.02 μM L^{-1}, respectively.

The "IPR Uirapuru" and "IPR Tiziu" cultivars obtained the highest APPUE (1.07 and 1.12, respectively) and TPUE (1.13) values at 6.25 μM L^{-1} whereas the "IPR Uirapuru" cultivar obtained the highest APPUE and TPUE values of 1.02 and 1.06, respectively, at 25.02 μM L^{-1} (Table 3). The "IPR Tuiuiú" cultivar also obtained the highest APPUEB values at both 6.25 and 25.02 μM L^{-1} (0.20 and 0.32 g, respectively). The differences in nutrient absorption and use observed in the "Preto" group can be explained by different regulatory mechanisms, so future studies must consider the plant as a whole system and evaluate several characteristics simultaneously (Araújo and Teixeira 2000).

Regarding PHI, which is the fraction of the P content in the grains compared to the P content in the aerial parts, the highest values were observed in the "Preto" group cultivars ("IPR Uirapuru" and "BRS Esplendor") in both 6.25 μM L^{-1} (0.32 and 0.35%, respectively) and 25.02 μM L^{-1} (0.31 and 0.49%, respectively). However, Araújo and Teixeira (2012), while evaluating the variability in nutrient harvest indices and their relationship with grain production in bean plant genotypes, observed highly negative phenotypic and genotypic correlations (-0.55 and -0.83, respectively) between grain P content and grain production, i.e., selection for high yield may be accompanied by lower grain P removal. Therefore, the "IPR Graúna" cultivar obtained the lowest PHI at all concentrations.

CONCLUSIONS

There was variability among the "Preto" bean cultivars in P acquisition and use efficiency, but there was only variability in P acquisition in the "Carioca" group. The cultivars of the "Carioca" ("Pérola" and "IPR Eldorado") and "Preto" groups ("IPR Graúna," "IPR Tiziu," and "IPR Uirapuru") have the potential for use in genetic improvement programs to enhance P use efficiency.

LITERATURE CITED

Araújo AP, Teixeira MG and Almeida DL (1998) Variability of traits associated with phosphorus efficiency in wild and cultivated genotypes of common bean. Plant and Soil 203: 173-182.

Araújo AP and Teixeira MG (2000) Ontogenetic variations on absorption and utilization of phosphorus in common bean cultivars under biological nitrogen fixation. Plant and Soil 225: 1-10.

Araújo AP and Teixeira MG (2008) Relationships between grain yield and accumulation of biomass, nitrogen and phosphorus in common bean cultivars. Revista Brasileira de Ciência do Solo 32: 1977-1986.

Araújo AP and Teixeira MG (2012) Variabilidade dos índices de colheita de nutrientes em genótipos de feijoeiro e sua relação com a produção de grãos. Revista Brasileira de Ciência de Solo 36: 137-146.

Arf O. (1994). Importância da adubação na qualidade do feijão e caupi. In: Sá ME and Buzzeti S. Importância da adubação na qualidade dos produtos agrícolas. Ícone, São Paulo, p.233-248.

Beebe S, Lynch J, Galwey N, Tohme J and Ochoa I (1997) A geographical approach to identify phosphorus-efficient genotypes among landraces and wild ancestors of common bean. Euphytica 95: 325-338.

Blair MW, Herrera AL, Sandoval TA, Caldas GV, Filleppi M and Sparvoli F (2012) Inheritance of seed phytate and phosphorus levels in common bean (*Phaseolus vulgaris* L.) and association with newly-mapped candidate genes. Molecular Breeding 30: 1265-1277.

Broughton WJ, Hernández G, Blair M, Beebe S, Gepts P and Vanderleyden J (2003) Beans (*Phaseolus* spp.) – model food legumes. Plant Soil 252: 55-128.

Cordell D, Drangert J and White S (2009) The story of phosphorus: Global food security and food for thought. Global Environmental Change 19: 292-305.

Elser JJ (2012) Phosphorus: a limiting nutrient for humanity? Current Opinion in Biotechnology 23: 833-838.

Fageria NK (1998) Eficiência de uso de fósforo pelos genótipos de feijão. Revista Brasileira de Engenharia Agrícola e Ambiental 2: 128-131.

FAO (2014) Food and Agriculture Organization of the United Nations. Cereal supplies rise, international prices fall. Available at http://www.fao.org/docrep/011/ai474e/ai474e02.htm. Accessed on Jan 18, 2015.

Farinelli R, Lemos LB, Cavariani C and Nakagawa J (2006) Produtividade e qualidade fisiológica de sementes de feijão em função de sistemas de manejo de solo e adubação nitrogenada. Revista Brasileira de Sementes 28: 102-109.

Hoagland DR and Arnon DI (1950) The water-cultured method for growing plants without soil. California Agricultural Experiment Station, California, 32p.

Kouas S, Debez A, Slatni T, Labidi N, Drevon JJ and Abdelly C (2009) Root proliferation, proton efflux, and acid phosphatase activity in common bean (*Phaseolus vulgaris* L.) under phosphorus shortage. Journal of Plant Biology 52: 395-402.

Lana RMQ, Zanão Júnior LA, Correia NM and Lana AMQ (2006) Variabilidade entre genótipos de feijoeiro na eficiência no uso do fósforo. Ciência Rural 36: 778-784.

Martins M, Fonseca LF, Melo LC, Oliveira DRF, Alvim KRT and Santana DG (2009) Avaliação de genótipos de feijoeiro comum do grupo comercial carioca cultivados nas épocas das águas e do inverno em Uberlândia, Estado de Minas Gerais. Acta Scientiarum Agronomy 31: 23-28.

Miklas PN, Kelly JD, Beebe SE and Blair MW (2006) Common bean breeding for resistance against biotic and abiotic stresses: from classical to MAS breeding. Euphytica 147: 105-131.

Mingotte FLC, Guarnieri CCO, Farinelli R and Lemos LB (2013). Desempenho produtivo e qualidade pós-colheita de genótipos de feijão do grupo comercial carioca cultivados na época de inverno-primavera. Bioscience Journal 29: 2013.

Miyazawa M, Pavan M, Muraoka T, Carmo CAFS and Mello WJ (1999) Análise química de tecido vegetal. In: Silva, F.C. (Org) Manual de análises químicas de solos, plantas e fertilizantes. Embrapa, Brasília, p. 171-223.

Moura WM, Casali VWD, Cruz CD and Lima PC (1999) Divergência genética em linhagens de pimentão em relação à eficiência nutricional de fósforo. Pesquisa Agropecuária Brasileira 34: 217-224.

Paula Júnior TJ, Vieira RF, Teixeira H, Coelho RR, Carneiro JES, Andrade MJB and Rezende AM (2008) Informações técnicas para o cultivo do feijoeiro-comum na região central brasileira: 2007-2009. Epamig, Viçosa.

Pavan MA and Bingham FT (1982) Toxicity of aluminum to coffee seedlings grown in nutrient solution. Journal of Soil Science Society of America 46: 993-997.

Richardson AE, Lynch JP, Ryan PR, Delhaize E, Smith FA, Smith SE, Harvery PR, Ryan MH, Veneklaas EJ, Lambers H, Oberson A, Culvenor RA and Simpson RJ (2011) Plant and microbial strategies to improve the phosphorus efficiency of agriculture. Plant and Soil 349: 121-156.

Rose TJ, Liu L and Wissuwa M (2013) Improving phosphorus efficiency in cereal crops: Is breeding for reduced grain phosphorus concentration part of the solution? Frontiers in Plant Science 4: 1-6.

Scholz RW, Ulrich AE, Eilitta M and Roy A (2013) Sustainable use of phosphorus: A finite resource. Science of the Total Environment 461: 799-803.

Shenoy VV and Kalagudi GM (2005) Enhancing plant phosphorus use efficiency for sustainable cropping. Biotechnology Advances 23: 7-8.

Siddiqi MY and Glass DM (1981) Use index: a modified approach to the estimation and comparison of nutrient use efficiency in plants. Journal of Plant Nutrition 4: 289-302.

Veneklaas EJ, Lambers H, Bragg J, Finnegan PM, Lovelock CE, Plaxton WC, Price CA, Scheible WR, Shane MW, White PJ and Raven JA (2012) Opportunities for improving phosphorus-use efficiency in crop plants. New Phytologist 195: 306-320.

Zucareli C, Prando AM, Ramos Júnior EU and Nakagawa J (2011) Fósforo na produtividade e qualidade de sementes de feijão Carioca Precoce cultivado no período das águas. Revista Ciência Agronômica 42: 32-38.

Wang X, Shen J and Liao H (2010) Acquisition or utilization, which is more critical for enhancing phosphorus efficiency in modern crops? Plant Science 179: 302-306.

Received: January 28, 2015.

Accepted: February 27, 2015.

Published: April 02, 2015.