Phosphorus use efficiency of improved faba bean (*Vicia faba*) varieties in low-input agro-ecosystems

Amsalu Nebiyu[1]*, Jan Diels[2], and **Pascal Boeckx[3]**

[1] College of Agriculture and Veterinary Medicine, Jimma University, POB 1316, Jimma, Ethiopia
[2] Department of Earth and Environmental Sciences, KU Leuven, Celestijnenlaan 200E box 2411, 3001 Leuven, Belgium
[3] Isotope Bioscience Laboratory – ISOFYS, Faculty of Biosciences Engineering, Ghent University, Coupure links 653, 9000 Gent, Belgium

Abstract

The use of phosphorus (P)-efficient legumes is a prerequisite for sustainable intensification of low-input agro-ecosystems. A study was undertaken in a farmer's field in the tropical highlands of Ethiopia to assess the agronomic performance, P acquisition efficiency (PAE), and P utilization efficiency (PUE) of six improved faba bean varieties (*Vicia faba* L. var. CS-20DK, Degaga, Gebelcho, Moti, Obse, Walki) without and with P application. Varieties showed significant variations in PUE, but P application had no significant effect on PUE. Variety Moti demonstrated highest PUE of 272 kg grain kg^{-1} P, which was 1.6-fold higher than the lowest PUE (164 kg grain kg^{-1} P) of Gebelcho. PUE was significantly and positively correlated with grain yield ($r = 0.542$) and negatively correlated with shoot PAE ($r = -0.541$), indicating that PUE is important for grain yield. The results demonstrate that variations in grain and biomass yield of faba beans were largely due to differences in PUE and not due to PAE. Therefore, we argue that genetic resources of faba bean varieties showing optimal agronomic performance and high PUE in low-input agro-ecosystems should be better explored. Introduction of such varieties in low-input cereal-based cropping systems could improve and enhance P use efficiency at the system level.

Key words: agro-ecosystems / biomass / P acquisition / P utilization

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1 Introduction

Growing population pressure and declining soil fertility are among the critical problems limiting the satisfaction of increased food demands in Sub-Saharan Africa (SSA; *Chianu* et al., 2011). The call for sustainable intensification of agriculture in SSA has gained support in recent years, especially in densely populated areas where natural fallows are no longer an option (*Vanlauwe* et al., 2012). Owing to these problems and the need to produce diverse products from the ever decreasing per capita landholdings, there is an urgent need to sustainably develop the small-land holder cropping systems of SSA (*Chianu* et al., 2011; *Vanlauwe* et al., 2012). However, most soils in SSA have deficiencies of available phosphorus (P), which is the main constraint for cereal and legume production (*Naab* et al., 2009; *Belane* and *Dakora*, 2010). The use of chemical fertilizers could be a means to alleviate low nutrient levels and improve crop yields. However, at recommended application rates, chemical fertilizers are generally inaccessible to resource-poor farmers in SSA. A complementary strategy to increase soil fertility is the inclusion of P-efficient grain legumes in traditional cropping systems (*Belane* and *Dakora*, 2010). Such grain legumes are a necessary component that complements fertilizer application in SSA and should be introduced into crop rotation, *e.g.*, legume-cereal rotations. Hence, fertilizer use efficiency in the cropping systems could be improved.

Soil P deficiency is a major constraint to increase (legume) crop yields in tropical and subtropical regions (*Kirkby* and *Johnston*, 2008). No or too little P fertilizer is actually used in those parts of the world and P inputs could have a major effect on food production (*Syers* et al., 2008). Low levels of plant-available P and large crop responses to P-fertilizer applications are common for both cereals and legumes (*Gizaw* et al., 1999; *Sanginga* et al., 2000; *Ahmad* et al., 2001; *Agegnehu* et al., 2006; *Agegnehu* and *Chilot*, 2009). Phosphorus fertilizers are often expensive for the smallholder farmers due to the lack of locally available resources. However, if properly used at the recommended dose, time and mode of application P fertilizers can be a major step forward toward the intensification of smallholder cropping systems in SSA.

Selection of crops that yield well in soils with low available P may be a cost-effective way of improving crop yields in low-input farming systems (*Rose* et al., 2011; *Rose* and *Wissuwa*, 2012). Such P-efficient crops would ideally have high P acquisition efficiency (PAE) and efficient P utilization efficiency (PUE; *Rose* et al., 2011). PAE is defined as the plant ability to extract and take up the nutrient from the soil, and PUE as grain yield per unit of P taken up in above ground plant material (*Rose* and *Wissuwa*, 2012). Thus, plant species producing equal grain yield at lower P uptake (compared to other plants) or higher grain yield at equal P concentrations would be considered to have better PUE.

* Correspondence: A. Nebiyu; e-mail: amsalu.nebiyu@ju.edu.et

Intra-species differences for PAE and PUE are well known for different grain legumes and cereals. Large genotypic differences in respect of PAE and PUE were reported for soybean (*Glycine max* L.; *Furlani* et al., 2002; *Jemo* et al., 2006), cowpea (*Vigna unguiculata* L.; *Sanginga* et al., 2000; *Nwoke* et al., 2007), common bean (*Phaseolus vulgaris* L.; *Vadez* et al., 1999), faba bean (*Vicia faba* L.; *Stelling* et al., 1996; *Daoui* et al., 2012), and wheat (*Triticum aestivum* L.; *Sepehr* et al., 1999; *Manske* et al., 2001, 2002; *Korkmaz* et al., 2009). Therefore, an important agronomic strategy to improve P nutrition of crops is through selection of P-efficient varieties. Moreover, there is evidence that legume genotypes may have developed specific strategies to acquire P from sparingly available sources (*Marschener*, 1998; *Bagayoko* et al., 2000; *Nuruzzaman* et al., 2005; *Rose* et al., 2010).

Among legumes, faba bean (*Vicia faba* L.) is of great importance in legume–cereal production systems, in which it is used as break crop for cereals (*Amanuel* et al., 2000) and has the potential to enhance N and P nutrition of cereals (*Nuruzzaman* et al., 2005; *Habtemichial* et al., 2007; *Rose* et al., 2010). In Ethiopia, faba bean is grown from 1300 to 3800 m altitude, but mostly at 2000 to 2500 m (*Agegnehu* and *Chilot*, 2009). The crop is well adapted to diverse soil types of Ethiopia where legumes are prominently used as traditional soil-fertility maintenance crops in mixed cropping systems. However, little effort has been made to select faba bean varieties for high PUE at low levels of available P in low-input cropping systems. The general aim of this research was therefore to assess faba bean varieties that are productive under low soil-P conditions or possess better capacities to take up and use P sources more efficiently. Identification and use of such varieties in the prevailing cropping systems could improve P nutrition of the legume and possibly also the non-legume components in a rotation. The specific objectives were to determine the agronomic performance, PAE, and PUE of elite faba bean varieties in low-input agro-ecosystems of SW Ethiopia.

2 Material and methods

2.1 Field sites

This study was conducted in a farmer's field in Dedo, in SW Ethiopia at 7°28′48′′ N, 36°52′19′′E, and at an elevation of 2160 m asl. Geologically, the soils are derived from debris of eruptions of the *Jimma Volcanics* with abundant rhyolites and trachybasalt (*Regassa*, 2009). The mean annual temperature is 20 ± 0.2°C and average yearly rainfall is 1880 ± 78.5 mm (data from 1975–2010, obtained from the National Meteorology Agency of Ethiopia). Total rainfall during the experimental year was 1562 mm and the minimum and maximum daily temperatures were 12°C and 23°C, respectively. Soils are classified as *Nitisols* in the FAO/WRB system. Participatory rural appraisal (PRA) research indicated that the cropping system is characterized by cereal (wheat, teff, barley) and legume (faba bean, field pea) production. Cereal-legume-based cropping systems can be found on hill slopes and valley bottoms with good vegetation cover with trees, shrubs, and enset (*Ensete ventricosum* L.). However, most agricultural lands located on the hill slopes are affected by soil erosion and landslides, which has developed into one of the major crop production constraints particularly in the "outfields" (fields distant from homesteads). Low productivity, poor response of crops to chemical fertilizers and the very high cost of chemical fertilizers have also been reported as constraints for enhanced production (*Bekele* et al., 2010). Given that the soils are of volcanic origin, they are known to be P-fixing.

In the 2010/11 growth season, six faba bean genotypes (Table 1) were tested for agronomic performance and P use efficiency. The six varieties were selected because they had good adaptation potential to the study area, effective nodulation with local rhizobia, and good agronomic performance among 15 accessions screened in the 2008/09 cropping season at two sites (low and high altitude in the Gilgelgibe catchment; *Nebiyu* et al., 2010). The six faba bean genotypes were grown with two levels of P fertilizer application (0 and 30 kg P ha^{-1}) given as triple super phosphate (TSP) during the main cropping season (July–November) arranged factorial in a randomized complete block design with three replications. The TSP fertilizer was applied in rows and incorporated

Table 1: Source of varieties and agronomic characteristics of six selected faba bean varieties (data from *MoARD*, 2009).

Variety Name	Pedigree name	Source	Days to flowering	Days to maturity	Grain yield potential / t ha^{-1}	Adaptation zone[b] / m asl
CS-20DK	CS20DK	Ethiopia	57–67	145–160	1.5–3.0	2300–3000
Degaga	R878-3	ICARDA[a]	45–62	116–135	2.0–4.5	1800–3000
Moti	ILB4432 x Kuse 2-27-33	ICARDA	43–65	108–165	2.3–3.5	1800–3000
Gebelcho	Tesfa x ILB4726	ICARDA	51–69	103–167	2.0–3.0	1800–3000
Obse	CS20DK x ILB4427	ICARDA	43–65	87–166	2.1–3.5	1800–3000
Walki	Bulga-70 x ILB4615	Ethiopia/ICARDA	49–61	133–146	2.0–4.2	1800–2800

[a]International Center for Agricultural Research in the Dry Areas, Aleppo, Syria.
[b]meters above sea level.

into the soil just before sowing. Seeds were obtained from the breeding center for faba beans at Holeta Agricultural Research Center of the Ethiopian Institute of Agricultural Research. The plot size used was 4.0 m × 1.6 m. There were four rows in each plot and a planting density of 40 cm between rows and 10 cm within rows was maintained.

2.2 Soil sampling and analysis

Soil samples (0–30 cm) were collected from three different places within each replication and mixed to a representative composite sample (a total of nine sub-samples were composited). After air-drying, soil was ground and sieved (2 mm) and analyzed for pH, texture (*Day*, 1965), CEC, and exchangeable bases (*Van Reeuwijk*, 2002), available P with modified Bray II (*Bray* and *Kurtz*, 1945), and total P (*Bowman*, 1988). Total carbon (TC) and nitrogen (TN) were analyzed with an elemental analyzer-isotope ratio mass spectrometry (EA-IRMS) (20-20, SerCon, Crewe, UK) to characterize the site (Table 2).

2.3 Plant sampling

During late flowering, five faba bean plants were randomly selected from the central two rows and plant parts were separated into root and shoot components. Soil adhering to the roots was removed by washing with tap water. The plots were additionally sampled for yield measurement at physiological maturity and, hence, the central two rows in each plot were harvested and subsequently separated into grains and crop residues (shoots and empty pods). Samples were dried at 70°C for 48 h and milled. Grain dry yield (GDY t ha^{-1}), total biomass yield [TBY t ha^{-1} = GDY + shoot (SDY t ha^{-1}), empty pod (PDY t ha^{-1}) dry yield] and harvest index (HI% = GDY/TBY × 100) were calculated on a dry-weight basis.

2.4 Phosphorus analysis

Phosphorus concentration (%) in shoot (PCs), grain (PCg), and pod (PCp) samples was determined according to *Chapman* and *Pratt* (1961) using slight modifications according to *Ryan* et al. (2001). Plant samples (0.5–1.0 g) were ashed in porcelain crucibles at 550°C for 5 h. The ash was dissolved in 5 mL 2 N HCl and milli-Q water was added up to a volume of 25 mL. The solution was filtered through Whatman No. 5 filters and P in filtrates was analyzed with an auto-analyzer (Autoanalyzer 3, Bran+Luebbe, Norderstedt, Germany).

Subsequently, the following variables were calculated: total P acquisition efficiency (PAE, kg P ha^{-1}) in shoots (shoot PAE = %PCs × SDY t $ha^{-1}/10^3$), grains (grain PAE = %PCg × GDY t $ha^{-1}/10^3$), pods (pod PAE = %PCp × PDY t $ha^{-1}/10^3$), total above-ground biomass (total PAE = shoot PAE + grain PAE + pod PAE), and P harvest index in % (PHI = grain PAE/total PAE × 100). Phosphorus utilization efficiency (PUE, kg grain kg^{-1} P) was defined as the grain yield (GDY) per unit of P accumulated in the total above-ground biomass (*Rose* and *Wissuwa*, 2012) and is given as: GDY kg ha^{-1}/total PAE kg ha^{-1}. Apparent P-fertilizer recovery (APFR) was calculated as follows: APFR (%) = (total PAE_{+P} – total PAE_{-P})/P applied × 100, where total PAE_{+P} and total PAE_{-P} are total plant above-ground biomass P acquisition efficiency with and without P fertilization, respectively (*Johnston* and *Syers*, 2009).

2.5 Statistical analysis

A two-way analysis of variance (ANOVA) for the factors variety and P level was performed using the general linear model (GLM) procedure of Statistical Analysis System (SAS) software version 9.2 (*SAS*, 2008) for all parameters except for APFR for which one-way ANOVA was performed. All data were first checked for normality of residuals using the Proc univariate, option Normal procedure of SAS. Quantile-Quantile plot (Q-Q plot) on the residuals from ANOVA was taken into consideration for assessing the normality of the data. Due to lack of significant variety by P interaction (P > 5%) for most of the response variables studied, except for PHI, only the main effect of the factors are studied and discussed. For PHI, the variety by P interaction effect is presented in this paper. Whenever the F test denotes a significant effect due to the main effect or interactions, the least significant difference (LSD) was used to compare treatment means at P < 5%. In a balanced design where the same number of observations contributed to each mean, the LSD is more appropriate for mean comparison (*Webster*, 2007).

3 Results

3.1 Grain and total biomass yield, P response, and P recovery of faba beans

ANOVA revealed highly significant effects of the variety and P application factors for GDY and TBY, and non-significant effects for harvest index (HI%) of faba beans (Table 3). There was no significant interaction effect between variety and P levels for GDY and TBY. Varieties CS-20DK and Gebelcho produced the lowest grain and total biomass yield compared to other varieties (Table 4). Application of 30 kg P ha^{-1} resulted in a highly significant response to grain and total bio-

Table 2: Means ± standard deviations of physicochemical soil characteristics of the farmer's field in Dedo.[a]

pH_{KCl}	pH_{H_2O}	TC	TN	TP	Available P	Clay	Silt	Sand	CEC	Ca	Mg	Na	K
		/ %	/ %	/ mg P kg^{-1}		/ %			/ $cmol_c$ kg^{-1}				
5.1 ± 0.16	5.6 ± 0.15	2.8 ± 0.33	0.2 ± 0.03	1190 ± 96	9.9 ± 3.80	54.1 ± 2.09	43.7 ± 2.11	2.1 ± 0.33	37.3 ± 1.79	13.8 ± 1.31	2.6 ± 0.29	0.07 ± 0.01	1.2 ± 0.28

[a]TC = Total C, TN = total N, TP = total P.

Table 3: P values for the analysis of variance of grain dry yield (GDY), total dry biomass yield (TBY), harvest index (HI), apparent fertilizer P recovery (AFPR), P concentration in shoot (PCs), grain (PCg), pod (PCp), P acquisition efficiency in shoot (shoot PAE), pod (pod PAE), grain (grain PAE), total plant (total PAE), P utilization efficiency (PUE), and P harvest index (PHI) of six faba bean varieties and two P application levels used in the Ethiopian highlands.

Factor	GDY	TBY	HI	AFPR	PCs	PCp	PCg	Shoot PAE	Pod PAE	Grain PAE	Total PAE	PUE	PHI
Variety (V)	0.007	0.0005	0.098	0.351	0.0001	0.0001	0.017	0.031	0.602	0.042	0.620	0.019	< 0.0001
P application (P)	0.0004	0.0001	0.103	–	0.0003	0.009	0.277	< 0.0001	0.002	< 0.0001	< 0.0001	0.191	0.241
V × P	0.238	0.362	0.195	–	0.446	0.359	0.342	0.629	0.597	0.390	0.611	0.133	0.042
CV[a] / %	21.9	13.7	10.2	49	17.5	21.7	13.7	24.3	43.7	22.1	19.2	22.4	7.2

[a]CV = coefficient of variation.

mass yield as compared to no P fertilizer application, but not to harvest index, irrespective of the varieties (Table 4), indicating that most of the faba bean varieties are responsive to P application.

There was no significant effect of variety for apparent fertilizer P recovery (AFPR) of faba beans. AFPR ranged between 20% (CS-20DK) and 43% (Obse) with no significant difference between varieties (Fig. 1).

3.2 P concentration, P acquisition, and P utilization efficiency

ANOVA showed highly significant effects of the variety and P application on shoot and pod P concentrations. Phosphorus grain concentration was affected only by variety (Table 5). P shoot concentration was highest for CS-20DK, Gebelcho, and Walki, and lowest for varieties Obse, Degaga, and Moti (Table 5). CS-20DK had a significantly higher P concentration of pods compared to others and Walki had the lowest P pod concentration (Table 5). Grain P concentration was significantly higher for Gebelcho, Obse, and Degaga compared to others. P addition (30 kg ha^{-1}) significantly enhanced P concentration in shoots and pods but had no significant effect on grain P concentration irrespective of the varieties (Table 5).

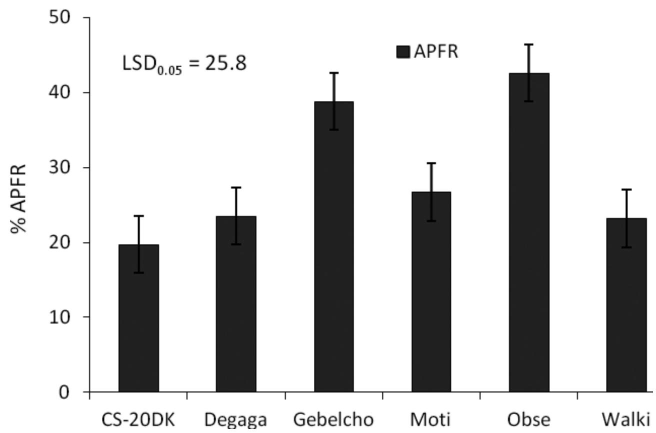

Figure 1: Apparent P fertilizer recovery (APFR) of six faba bean varieties grown on farmers' fields at Dedo, Southwest Ethiopia. Varieties did not differ significantly for APFR. Vertical bars denote standard errors.

Table 4: Main effects of variety and P application on dry grain yield (DGY t ha^{-1}), total above-ground biomass yield (TBY t ha^{-1}) and harvest index (HI%) of six faba bean varieties used in a field experiment in the Ethiopian highlands. The values are mean ± SE. Means followed with different letters in a column are significantly different at $P < 5\%$.

	GDY / t ha^{-1}	TBY / t ha^{-1}	HI / %
Variety			
CS-20DK	3.7 ± 0.3bc	7.6 ± 0.5b	49.0 ± 2.0
Degaga	4.8 ± 0.4ab	9.9 ± 0.6a	48.4 ± 1.9
Gebelcho	3.2 ± 0.5c	7.5 ± 0.8b	42.3 ± 1.7
Moti	5.5 ± 0.6a	10.8 ± 0.6a	50.5 ± 2.9
Obse	4.7 ± 0.7ab	10.0 ± 1.1a	45.9 ± 2.6
Walki	4.5 ± 0.4ab	9.6 ± 0.7a	47.0 ± 1.3
$LSD_{0.05}$	1.2	1.5	Ns
P application / kg ha^{-1}			
0	3.7 ± 0.3B	8.0 ± 0.5B	45.8 ± 1.4A
30	5.1± 0.3A	10.4 ± 0.4A	45.5 ± 1.1A
$LSD_{0.05}$	0.7	0.9	3.3

Significant variations were observed in shoot and grain PAE for variety and P application. No variety effect was observed for pod and total PAE, but P application did show significant effects on pod and total PAE (Table 3). Gebelcho and Walki had the highest shoot PAE of 6.5 kg P ha^{-1}, followed by CS-20DK (Table 5). Obse did show the lowest shoot PAE (4.3 kg P ha^{-1}) but had the highest (17.0 kg P ha^{-1}) grain PAE which, however, was not statistically different from Degaga, Moti and Walki. Grain PAE was lowest (11.3 kg P ha^{-1}) for CS-20DK. Total plant PAE ranged from 19.1 kg P ha^{-1} for CS-20DK to 22.8 kg P ha^{-1} for Obse with no statistical difference between varieties. Phosphorus addition (30 kg ha^{-1}) significantly improved shoot (60%), pod (60%), grain (47%), and total plant

Table 5: Main effects of variety and P application on P concentration (mg P kg^{-1} DM), P acquisition efficiency (PAE kg P ha^{-1}) of shoot, pod, grain, and total plant, and P utilization efficiency (PUE kg grain kg^{-1} P) of six faba bean varieties used in a field experiment in the Ethiopian highlands. The values are means ± SE. Means followed by different letters in a column are significantly different at $P < 5\%$.

	P concentration / mg P kg^{-1} DM			PAE / kg P ha^{-1}				PUE / kg grain kg^{-1} P
Variety	Shoot	Pod	Grain	Shoot	Pod	Grain	Total	
CS-20DK	0.23a	0.13a	0.31b	6.3ab	1.5a	11.3c	19.1a	196.3bc
Degaga	0.14b	0.07cd	0.32ab	4.7cb	1.2a	15.4ab	21.3a	230.7ab
Gebelcho	0.22a	0.09b	0.36a	6.5a	1.2a	11.9bc	19.7a	164.7c
Moti	0.15b	0.08bc	0.28b	5.2abc	1.5a	14.9abc	21.6a	272.3a
Obse	0.12b	0.07bcd	0.36a	4.3c	1.5a	17.0a	22.8a	205.0bc
Walki	0.20a	0.06d	0.31b	6.5a	1.0a	14.0abc	21.6a	213.2bc
$LSD_{0.05}$	0.04	0.02	0.05	1.6	0.7	3.7	4.8	57.3
P application / kg ha^{-1}								
0	0.15B	0.07B	0.32A	4.3B	1.0B	11.4B	16.4B	224.4A
30	0.20A	0.09A	0.33A	6.9A	1.6A	16.8A	25.4A	202.9A
$LSD_{0.05}$	0.02	0.01	0.03	0.9	0.4	2.1	2.8	33.1

PAE (55%) of faba beans, irrespective of the variety. The PAE of pod, grain, and total plant were significantly positively correlated with GDY and TBY (Table 6).

PUE was significantly affected by variety, but P application had no significant effect (Table 3). Varieties Moti and Degaga demonstrated highest PUE with 272.3 and 230.7 kg grain kg^{-1} P, respectively, with no statistical difference between these varieties (Table 5). Gebelcho had lowest PUE of 164.7 kg grain kg^{-1} P. Although not significant, application of 30 kg P ha^{-1} reduced average PUE of faba bean plants from 224.4 kg grain kg^{-1} P (0 P) to 202.9 kg grain kg^{-1} P (30 P; Table 5). PUE was significantly positively correlated with GDY and significantly negatively correlated with P concentrations in shoot, grain, and shoot PAE (Table 6).

The PHI (proportion of P exported *via* grains) varied due to the interaction of varieties with P application levels (Table 7).

Table 6: Correlation coefficients between grain yield (GDY), total biomass yield (TBY), P utilization efficiency (PUE) versus the P acquisition efficiency (shoot PAE, grain PAE) of faba bean in a field experiment in the Ethiopian highlands.[a]

	Shoot PAE	Grain PAE	PUE
GDY	0.163^{ns}	0.818**	0.542*
TBY	0.228^{ns}	0.918**	0.125^{ns}
PUE	–0.541*	0.086^{ns}	1.000

[a]* = correlation is significant at $P < 5\%$; ** = correlation is significant at $P <= 1\%$; ns = correlation is not significant.

Table 7: Interaction effect of variety and P application on P-harvest index (PHI%) of six faba bean varieties at two P application levels in a field experiment in the Ethiopian highlands. The values are mean ± SE. Means followed by different letters in a column and row are significantly different at $P < 5\%$.

Variety	PHI (%) 0P	30P
CS-20DK	58.7 ± 1.5ed	59.9 ± 2.6ed
Degaga	75.2 ± 1.6a	69.8 ± 0.9abc
Gebelcho	55.9 ± 3.5e	62.9 ± 1.8cde
Moti	76.4 ± 2.6a	64.2 ± 0.7cd
Obse	73.4 ± 8.4ab	74.4 ± 2.7a
Walki	66.2 ± 1.6bcd	63.1 ± 2.9cde
$LSD_{0.05}$	8.2	

Without P application, PHI ranged from 55.9 to 76.4%. This range was 59.9% to 74.4% for the 30 P. CS-20DK and Gebelcho had significantly lower PHI at both 0 P and 30 P. Varieties Moti and Degaga had the highest PHI (%) with 76.4 and 75.2% at 0 P and Obse 74.4% at 30 P applications, though these values did not differ significantly from each other.

4 Discussion

Our results show that there was a varietal difference in grain and total biomass yield of the improved Ethiopian faba bean varieties. The varieties CS-20DK and Gebelcho produced the lowest grain and total biomass yield, but harvest index did not significantly differ for varieties or P application (Table 4). Thus, the differences in yield could be related to changes in dry matter production with no change in partitioning indicating that harvest index in faba bean is conservative across the present varieties and P levels. P application also resulted in a significant response to grain and biomass yield of faba beans indicating how much grain and biomass yield was lost when no P was applied. Significant grain yield increase by P application in faba beans growing in P-limited soils was previously reported in Ethiopia (*Amanuel* et al., 2000; *Agegnehu* and *Fessehaie*, 2006) and Morocco (*Daoui* et al., 2012). Our results further support the findings of previous studies (*Bolland* et al., 2000; *Daoui* et al., 2012) indicating that P fertilizer is required for grain production of faba beans. Further, the differences in grain yield might have arisen from the significant differences in the PUE of genotypes such that PUE was significantly correlated with GDY (Table 6). In view of this, the superior grain yield performance of variety Moti may further suggest that Moti may have mechanisms that efficiently translocate P in the internal plant system and avoid too much P storage in the tissue (had lower tissue P concentrations) such that growth is not limited by P shortage. *Daoui* et al. (2012) also reported a genotypic effect on grain and biomass production potential of faba beans that some genotypes do respond under various levels of P application and this corroborates our findings.

The shoot PAE and shoot P concentrations of varieties CS-20DK and Gebelcho were the highest, however, did not result in a corresponding high PUE and high grain and biomass yield. This also suggests that the difference in grain and biomass production among the varieties primarily stems from the PUE and not from the PAE or P concentration because varieties with the highest P concentration and PAE resulted in a lower grain and biomass yield, *e.g*., CS-20DK and Gebelcho. Analysis also revealed negative correlations of PUE with P concentrations of shoot, grain, and shoot PAE. Likewise, grain and biomass yields were also negatively correlated with P concentrations in shoots, pods, and grains. *Baon* et al. (1993) showed that PUE of plants usually decreases with increased shoot P concentration. Our results are consistent with the findings of *Stelling* et al. (1996) and *Daoui* et al. (2012) who found that PUE was more important than PAE to explain genotypic variations in P use (in terms of grain and biomass production) by faba bean. However, *Nuruzzaman* et al. (2005) showed that high PUE of faba bean was related to PAE from low available P sources *via* the plant's extensive root system that can explore a larger volume of soil to access relatively immobile nutrients such as P.

Optimal performance in low-P soils is one of the major selection criteria for faba bean in low-input agro-ecosystems. Most legume breeding programs in Africa look for genotypes that give high yield under low soil-P situations (*Sanginga* et al., 2000). All the varieties, except for Moti, require P application for enhanced biomass production. Moti, therefore, meets this requirement and could fit well in cropping systems where little or no fertilizer is used and where crop yields are associated with subsistence farming.

The grain P level was generally higher than the shoot and pod P levels in the present study (Table 5). *Rose* et al. (2007) suggested that crop P requirement after flowering is largely dominated by two competing processes (P sinks): the P requirements of vegetative tissues to continue normal growth and development until senescence and the P demand of the developing grain. Further, *Raboy* (2009) showed that P levels in grains are well above the P levels required for normal cellular function. The lower levels of P in faba bean pods in the present study may imply that pods are not strong P sinks in the plant system. Therefore, it may be suggested that lower levels of P in pods would be due to reduced sink strength of pods as P storage organs rather than a lower physiological P requirement by pods. *Rose* and *Wissuwa* (2012) expressed a similar view on low sink strength of grains. Reduced P sink strength of pods and certainly of grains may therefore be an additional PUE parameter in further PUE studies involving grain legumes. Thus, under low P conditions grain yield is higher. *Rose* and *Wissuwa* (2012) also argue that targeting genotypes for low grain P can improve PUE of the system. However, the potential impact of low grain P characteristics on the nutritional value and seedling growth and vigor in P-limited soils needs further investigation.

Several studies have investigated the possibility of reducing grain P levels using criteria such as PHI at maturity (*Batten*, 1992; *Jones* et al., 1992; *Manske* et al., 2002; *Rose* et al., 2010). Our data also show that there was significant interaction effect between variety and P on PHI (Table 7). The total P exported to the grains of varieties CS-20DK and Gebelcho was lower compared to others at both P levels. The lower PHI and grain PAE of CS-20DK and Gebelcho may indicate that P was not always efficiently translocated from shoots into grains, though these varieties demonstrated a relatively higher shoot PAE. This suggests that, due to their low P export to grains, CS-20DK, Gebelcho, and Walki may also be suitable varieties when aiming at faba bean genotypes with the potential of improving the P nutrition in crop rotations *via* its residues.

5 Conclusion

The data from this study carried out in a P-deficient farmer's field showed considerable differences in grain and biomass yield and P utilization efficiency among the six faba bean varieties. It was moreover found that the difference in P use efficiency was largely due to differences in P utilization efficiency. The variety Moti showed highest P utilization efficiency and produced the largest amount of biomass and provided highest grain yield. It could therefore be an ideal variety for low-P soils in the cool humid highland agro-ecosystems. However, it is also important to evaluate its effect on soil P status and the carryover effect of residue derived P nutrition of subsequent cereal crops.

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