HiLL PUBLISHING

International Journal of Food Science and Agriculture, 2025, 9(4), 453-463
https://www.hillpublisher.com/journals/jsfa/
ISSN Online: 2578-3475
ISSN Print: 2578-3467

Genotypic Variation in Phosphorus Use Efficiency, Yield, and Yield Associate Traits in Faba Bean (*Vicia faba* L.) at Western Ethiopia

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How to cite this paper: Muluhabt Birhane, Daniel Abebe, Gudeta Nepir, Mussa Jarso. (2025). Genotypic Variation in Phosphorus Use Efficiency, Yield, and Yield Associate Traits in Faba Bean (*Vicia faba* L.) at Western Ethiopia. *International Journal of Food Science and Agriculture*, 9(4), 453-463.
DOI: 10.26855/ijfsa.2025.12.019

Received: November 30, 2025
Accepted: December 28, 2025
Published: January 26, 2026

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Abstract

Low soil phosphorus (P) availability is one of the major constraints to faba bean (*Vicia faba* L.) production in the highlands of Ethiopia. Identification of genotypes with superior agronomic performance and phosphorus use efficiency is therefore crucial for sustainable productivity under both P-deficient and fertilized conditions. This study was conducted to assess agronomic trait associations, grain yield responses, and phosphorus use efficiency of fifteen faba bean genotypes evaluated under phosphorus-applied (P1) and non-applied (P0) conditions. The experiment was conducted across representative locations using standard agronomic practices. Correlation analysis revealed significant relationships among growth and yield-related traits under both P levels. Grain yield showed strong and positive correlations with biological yield and harvest index, while it was negatively associated with days to flowering and maturity under both P conditions. Plant height exhibited a positive association with grain yield, particularly under phosphorus application, indicating its contribution to biomass production and yield formation. Differences in trait associations between P0 and P1 conditions highlighted the role of phosphorus in modifying genotypic performance and yield-determining mechanisms. Overall, the presence of substantial genotypic variability and distinct trait interrelationships suggests opportunities for selecting faba bean genotypes adaptable to low-P environments as well as responsive to phosphorus fertilization. The findings provide valuable insights for breeding programs aimed at improving yield and phosphorus efficiency in faba bean under Ethiopian highland conditions.

Keywords

Faba bean; phosphorus yield efficiency; genotype evaluation; West Shewa; Ethiopia

1. Introduction

Faba bean is a crucial pulse crop in Ethiopia highlands. It's a cool-season bean that helps families have enough to eat, get good nutrition, and earn a bit of money. Ethiopia grows more faba beans than almost any other country, especially in Africa [1, 2]. Plus, they're good for the soil—they help fix nitrogen, improve the soil's structure, and cut down on the need for chemical fertilizers [3]. Even though faba beans are important, they don't produce as much as they could in Ethiopia. Farmers' harvests are way smaller than what researchers get with better methods [1, 2].

This is mainly because the soil isn't great, farmers don't use many extra helpers, the soil is too acidic, and managing nutrients is complicated. One of the biggest issues is that many soils don't have enough phosphorus (P), which seriously limits how many beans farmers can grow.

These beans are highly valued for their high protein content and their role in diversifying diets in rural communities. This is because people farm the land a lot, the soil washes away, and iron and aluminum make it hard for plants to grab the phosphorus in acidic soils [4, 5]. Phosphorus is super important for plants to transfer energy, grow roots, make nodules, fix nitrogen, and form seeds. Inadequate phosphorus supply restricts root development and nodulation, delays flowering, and significantly reduces bean productivity [6].

The application of phosphorus fertilizer is known to enhance bean growth and productivity; however, its adoption by smallholder farmers remains limited due to high costs, poor accessibility, and financial constraints [7]. Moreover, prolonged and excessive use of phosphorus fertilizers poses environmental risks and threatens the sustainability of global phosphorus reserves [8]. These challenges highlight the importance of developing alternative strategies that reduce dependence on external phosphorus inputs while maintaining crop productivity.

Recent studies conducted in Ethiopia have demonstrated significant variability among bean genotypes in terms of growth performance and phosphorus use efficiency under low soil phosphorus conditions [9-11]. Nevertheless, many existing evaluations have been carried out under optimal fertilizer conditions, with limited emphasis on phosphorus deficient environments. Consequently, information on genotype responses to low-phosphorus soils remains insufficient, particularly in major faba bean-producing areas such as the West Shewa Zone. Therefore, the present study objective was to assess the agronomic performance and phosphorus use efficiency of released faba bean genotypes under phosphorus-deficient soil conditions in the West Shewa Zone, western Ethiopia.

2. Materials and Methods

2.1 Description of Study Area

The field study was conducted during the crop growing season at two faba bean spots in West Shewa Zone of Oromia, western Ethiopia: the Korke farm (Ambo area) and the Holeta Agricultural Research Center (HARC). We picked these spots because they're good examples of the highland areas where faba beans are a big deal for both feeding families and selling.

The Korke farm is near Ambo, about 2,200-2,300 meters up. It's got a pretty chill highland climate, with temps usually between 10 and 24°C. It mostly rains from June to September, getting about 900-1,100 mm of rain each year. Farming here depends on rainfall, and people usually raise both crops and animals. They grow faba beans, wheat, barley, and teff, switching them around to keep the soil healthy.

The Holeta Agricultural Research Center is about 30 km west of Addis Ababa, at an altitude of around 2,400 meters. It's a wet highland area. The site is characterized by annual rainfall of 1,000-1,200 mm and temperatures ranging from 6 to 22 °C. Holeta is a key place for studying highland crops, especially legumes that like the cold, like faba beans.

The soil in both places is mostly Nitisols and Luvisols. Those are deep and drain well, but they don't have much phosphorus naturally. These soils tend to hold onto phosphorus because of iron and aluminum, so plants can't get to it easily, even if there's a fair bit in the soil. Farming all the time, not using much fertilizer, and taking away leftover crops have made the soil worse. So, not enough phosphorus is a big problem for growing faba beans at both sites. Basically, these spots are good for seeing how well faba bean types do, how they respond to phosphorus, and how well they use it when there's not enough phosphorus in the highlands of West Shewa Zone, Ethiopia.

2.2 Experimental Materials

For this experiment, we used 15 kinds of faba bean that are grown in the Ethiopian highlands (Table 1). These beans were selected because they are high-yielding and well-adapted to the highland environment.

We used triple superphosphate (TSP) as the phosphorus fertilizer, which has 46% P_2O_5. It was the only phosphorus source we used. We chose TSP because it dissolves easily in water, and the phosphorus is quickly ready for plants to use. This makes it good for seeing how the crops react and how well they use the phosphorus in highland soils that don't have much phosphorus.

Table 1. Agronomic characteristics of released faba bean (*Vicia faba* L.) genotypes used in the phosphorus use efficiency trial

No.	Variety name	Year of release	Crude protein (%)	Grain yield (t ha^{-1}) – On-station	Grain yield (t ha^{-1}) – On-farm	Thousand-seed weight (g)	Adaptation altitude (m a.s.l.)
1	Degaga	2002	29.2*	2.5-5.0	2.0-4.5	517	1800-3000
2	Moti	2006	27.0	2.8-5.1	2.3-3.5	781	1800-3000
3	Gebelcho	2006	26.5	2.5-6.1	2.1-3.5	797	1800-3000
4	Obse	2007	26.9	2.5-6.1	2.1-3.5	821	1800-3000
5	Dosha	2008	26.5	2.8-6.2	2.3-3.9	704	1800-3000
6	Tumsa	2010	26.5	2.5-6.9	2.0-3.8	737	2050-2800
7	Walki	2007	27.5	2.4-5.2	2.0-4.2	676	1800-2800
8	Hachalu	2010	27.0	3.2-4.5	2.4-3.5	890	1900-2800
9	Didea	2014	26.0	2.3-5.0	2.0-4.4	746	1900-2800
10	Ashebeka	2015	20.8	3.0-5.4	2.8-4.7	885	1900-2800
11	NC-58	1978	27.0	2.0-4.0	1.5-3.5	449	1900-2300
12	Gora	2013	24.0	2.2-5.7	2.0-4.0	938	1900-2800
13	Holeta-2	2001	25.7	2.0-5.0	1.5-3.5	506	2300-3000
14	Wayu	2002	26.0	2.2-3.3	1.0-2.3	312	2100-2700
15	Numan	2016	26.5	3.6-5.1	2.2-3.8	1069	1800-3000

Note. *Yield ranges indicate performance under multi-location testing conditions. Variety descriptions follow national release catalogs of the Ethiopian Institute of Agricultural Research (EIAR).

2.3 Experimental Design and Treatment Plans

The experiment was laid out using a Randomized Complete Block Design (RCBD**)** with three replications at each experimental site. Treatments were arranged in a factorial combination of fifteen released faba bean genotypes and two phosphorus application levels. The phosphorus treatments consisted of no phosphorus application (0 kg P ha^{-1}) and the recommended phosphorus rate for faba bean production in the Ethiopian highlands. Phosphorus was applied at planting in the form of triple superphosphate (TSP).

Each genotype was grown under both phosphorus levels at each location, resulting in uniform exposure to contrasting phosphorus conditions. Standard agronomic practices, including land preparation, planting date, seed rate, weed control, and other crop management activities, were applied uniformly across all treatments and sites to minimize non-treatment-related variation and ensure reliable comparison of treatment effects.

2.4 Data Collection

All growth, yield, and efficiency parameters were carefully recorded during the experiment using standard field procedures.

Plant height was measured in meters at maturity from the soil surface to the tip of the main stem. The number of pods per plant was determined by counting all mature pods from five randomly selected plants at harvest and taking the average.

The number of seeds per pod was obtained by counting seeds from five randomly selected pods on each of the five sample plants and averaging the results.

Thousand-seed weight was determined by weighing 1,000 randomly selected seeds and expressing the value in grams.

Biological yield per plant was estimated by harvesting the above-ground parts of five sample plants, drying them to constant weight, and computing the average biomass in grams.

Grain yield was measured by harvesting the two central rows of each plot, calculating yield per plot, and converting the results to tons per hectare.

Harvest index was calculated as the ratio of grain yield to biological yield multiplied by 100.

Total biological yield per plot was also calculated as the sum of grain and straw dry matter at harvest.

In addition, phosphorus yield efficiency was computed as the difference in grain yield between phosphorus fertilized and unfertilized plots divided by the amount of phosphorus applied.

2.5 Statistical Analysis

All data were subjected to analysis of variance (ANOVA) using a completely randomized design. The statistical model included treatment as a fixed effect and experimental error as a random effect. Prior to analysis, ANOVA assumptions were verified: normality of residuals was assessed using the Shapiro-Wilk test, and homogeneity of variances was examined using Levene's test. Data met the assumptions without the need for transformation. When significant treatment effects were detected, mean comparisons were performed using Tukey's Honestly Significant Difference (HSD) test at the 5% probability level. Only one mean separation procedure was applied to ensure consistency and avoid inflated Type I error. Correlation analysis was conducted using Pearson's correlation coefficient to evaluate relationships among measured variables. The analysis was performed on pooled data across treatments, as the objective was to assess overall associations rather than treatment-specific relationships. The use of Pearson's correlation was justified by the continuous nature of the variables and the confirmation of approximate normal distribution. All statistical analyses were performed using appropriate statistical software, and significance was declared at $P \leq 0.05$.

3. Result and Discussion

The combined analysis of variance revealed that location (L**)** had a highly significant ($P \leq 0.01$) effect on all traits, including days to maturity (DM), grain filling period (GFP), plant height (PLH), yield components, biomass yield (BY), grain yield (GY), and harvest index (HI) (Table 2). This indicates substantial environmental variability between Ambo and Holeta in influencing crop growth and productivity.

Phosphorus application (P**)** significantly affected most traits, particularly grain yield, biological yield, plant height, pods per plant, seeds per pod, and harvest index, demonstrating the strong role of phosphorus in improving productivity under P-deficient highland soils. However, P had non-significant effects on thousand-seed weight (TSW) and grain filling period, suggesting that seed size and duration of grain filling are more genetically controlled.

The genotype (G) effect was highly significant ($P \leq 0.01$) for all measured traits, confirming the existence of substantial genetic variability among the 15 faba bean genotypes for yield, yield components, and phonological traits. The genotype × location (G×L) interaction was significant for most traits, including grain yield, biological yield, plant height, pods per plant, seeds per pod, and harvest index**.** This indicates that genotypes performed contradictorily across the two environments, highlighting the importance of multi-location testing for reliable genotype evaluation.

Similarly, genotype × phosphorus (G×P) interaction was significant for grain yield, biological yield, days to maturity, plant height, harvest index, and seeds per pod, demonstrating differential genotypic responses to phosphorus fertilization. This suggests the presence of phosphorus-efficient and phosphorus-responsive genotypes.

The location × phosphorus (L×P**)** interaction was highly significant for several traits, including grain yield, biomass yield, plant height, and pods per plant, indicating that the effectiveness of phosphorus fertilizer varied between environments.

Importantly, the three-way interaction (G × L × P) was highly significant for grain yield, harvest index, grain filling period, plant height, pods per plant, and seeds per pod**,** confirming that genotype performance under phosphorus fertilization depended strongly on location.

The highly significant effects of location on all agronomic and yield traits reflect the contrasting contradictorily conditions of Ambo and Holeta, particularly differences in soil fertility status, temperature, and rainfall distribution. Similar strong location effects have been reported for faba bean grown in Ethiopian highlands [12, 13].

The significant phosphorus main effect for grain yield and biomass yield confirms phosphorus as a major yield-limiting nutrient in Ethiopian highland soils. Phosphorus enhances root development, nodulation, and photosynthetic translocation, ultimately increasing grain yield and harvest index. Comparable findings have been reported by [14, 15].

The observed genotypic variation for all traits indicates ample opportunity for selection of high-yielding and phosphorus-efficient genotypes. The significant G×P interaction for grain yield suggests that genotypes vary in their ability to utilize applied phosphorus, supporting the classification of genotypes into phosphorus-efficient, responsive, and inefficient groups, which is consistent with earlier reports in faba bean and common bean [16, 17].

The significant G×L and G×L×P interactions for grain yield and harvest index underline the complexity of genotype performance across environments and nutrient levels. This implies that selection based on a single environment or phosphorus level may be misleading.

Therefore, breeding programs targeting low-P environments should emphasize stability and phosphorus use efficiency across locations**,** as suggested by [18, 19]. The non-significant interactions for TSW indicate that seed weight is relatively stable across environments and phosphorus levels, implying strong genetic control, which aligns with findings by [20].

Table 2. Combined analyses of variances for grain yield and other agronomic traits over the two locations and two phosphorus levels for 15 genotypes

Traits	L	P	G	GxL	GxP	Lx P	G x L x P	Error
	df=1	df=1	df=14	df=14	df=14	df=1	df=14	df=118
DF	3091.8**	8.0**	45.6**	51.7**	2.9ns	32.1**	2.7ns	2.2
DM	3690.1**	40.1**	21.4**	19.1**	9.4**	0.1ns	8.1*	3.7
GFP	44**	4ns	18.23**	103.1**	8.75ns	34.6*	23.3**	7.02
PLH	9621.4**	8323.2**	602.2**	97.0**	98.6**	2675.**8	90.5**	31.4
PPP	136.9**	194.3**	43.1**	9.2**	3.9ns	63.6**	5.5*	2.8
SPP	1.3**	0.5**	0.4**	0.5**	0.3**	0.1ns	0.4**	0.1
TSW	98467.2**	19178.7ns	279785**	4005.0ns	5130ns	14942.2ns	3907ns	5069
BY	25726680**	2189013.9**	209002**	66025.8*	35144*	333680**	33859ns	33739
GY	38879.1**	1514.4**	157.3**	81.6**	38.6**	223.4**	46.8**	13
HI	5629.1**	325.7**	193.2**	182.6**	171.3**	179.5ns	150.4**	62.0

Notes. * and ** indicate significant correlation among the traits at 5 and 1% significance levels while ns indicates none significant correlation Grain Yield and Yield Components of Faba Bean genotypes with Phosphorus Fertilization.

3.1 Grain Yield and Yield Components of Faba Bean genotypes with Phosphorus Fertilization

The results presented in Table 3 show significant differences among faba bean genotypes for most yield and yield-related traits under phosphorus (P) fertilization. Plant height ranged from 1.00 m (Gebelcho, NC-58) to 1.35 m (Moti), with Moti exhibiting the tallest plants. Genotypes such as Degaga, Dosha, Tumsa, Walki, and Hachalu produced a higher number of pods per plant (10.15-10.95 pods), whereas Moti, Obse, and NC-58 had fewer pods (7.60-7.80).

Seed per pod also varied significantly, with Didea, Moti, and NC-58 recording the highest values (3 seeds per pod), while most other genotypes had 2-2.3 seeds per pod.

Thousand-seed weight ranged from 417 g (NC-58) to 917.5 g (Numan), indicating substantial differences in seed size among genotypes.

Biological yield varied between 390 g (NC-58) and 801.5 g (Hachalu), while the harvest index ranged from 47.0% (Didea) to 61.8% (Degaga).

Grain yield was highest in Hachalu (3.83 t ha^{-1}), followed by Ashebeka (3.59 t ha^{-1}) and Walki (3.31 t ha^{-1}), whereas NC-58 recorded the lowest yield (2.30 t ha^{-1}). The observed variation suggests that phosphorus application enhanced vegetative growth, pod formation, and seed development, which is consistent with previous studies indicating that P fertilization improves faba bean yield by promoting root development and nutrient uptake [21, 22]. The highest yielding genotypes, such as Hachalu and Ashebeka, also had relatively high biological yields, indicating efficient partitioning of biomass to grain production.

3.2 Grain Yield and Yield Components of Faba Bean Genotypes without Phosphorus Fertilization

Under no phosphorus application (Table 4**)**, plant height ranged from 0.82 m (Wayu) to 1.13 m (Degaga, Moti). The number of pods per plant varied significantly, with Wayu producing the highest number of pods (11.1) and Obse, Numan, and Gora the lowest (5.5-5.8).

Seed per pod ranged from 2.0 to 2.8, with Obse showing the highest seeds per pod (2.8). Thousand-seed weight was generally lower than with P application, ranging from 310 g (Wayu) to 895 g (Numan), and biological yield

ranged from 533 g (NC-58) to 900 g (Hachalu).

Harvest index also declined slightly compared to P-fertilized plots (32.2-57.3%), reflecting reduced partitioning of biomass to grain under P-deficient conditions.

Grain yield ranged from 1.74 t ha^{-1} (NC-58) to 3.12 t ha^{-1} (Dosha). The results demonstrate that phosphorus deficiency reduced most yield components**,** confirming the critical role of P in faba bean productivity. Genotypes that maintained relatively high yields under no P application, such as Dosha and Tumsa, may possess better P-use efficiency, making them suitable for low-input systems. Similar observations were reported by [23], who noted that genotypic differences significantly influence yield performance under low soil P conditions.

3.3 Effect of Phosphorus Fertilization on Yield and Yield Components

Comparing the two tables 3 and 4, it is evident that phosphorus application increased mean plant height (1.12 m vs 1.00 m), number of pods per plant (9.2 vs 7.8), seed per pod (2.29 vs 2.2), biological yield (1185 g vs 764 g), and grain yield (4.00 t ha^{-1} vs 2.43 t ha^{-1}**)**.

The harvest index decreased slightly with P fertilization, suggesting that biomass accumulation was proportionally higher than grain production. This finding is consistent with reports by [24], highlighting that P fertilization enhances vegetative growth and yield components, particularly in highland areas of Ethiopia where soils are often P-deficient.

Genotype differences were also pronounced. Hachalu, Ashebeka, and Walki performed best under P application, whereas Dosha and Tumsa yielded relatively well even without P, indicating their adaptability to P-limited soils. The results confirm the existence of genotypic variation for P-use efficiency, which is a key trait for breeding faba bean genotypes suited to low-fertility soils [21, 22].

Table 3. Mean grain yield and yield components of Faba bean genotypes with phosphorus fertilizer

Variety	Plant height	Number of Pods per plant	Seed per pod	Thousand-seed weight (gm**)**	Biological yield (gm**)**	Harvest index	Grain yield (t ha^{-1})
Degaga	1.17ab	10.15c*	2.0d	516.5cd	583.0bc	61.8a	3.04b
Moti	1.35a	7.80d	3.0a	678.0bc	624.5b	55.1c	2.81c
Gebelcho	1.00d	8.30c	2.0d	647.5c	708.0ab	54.4cd	2.96c
Obse	1.12b	7.60d	2.6b	752.5b	624.0b	50.0de	2.84c
Dosha	1.18ab	10.65bc	2.0d	675.5bc	593.5bc	60.2ab	3.15ab
Tumsa	1.16ab	10.95b	2.0d	691.0bc	697.5b	54.8cd	3.25ab
Walki	1.15b	10.50bc	2.3c	531.5cd	687.0b	48.9e	3.31ab
Hachalu	1.16ab	10.60b	2.0d	670.0bc	801.5a	47.6e	3.83a
Didea	1.16ab	8.50c	3.0a	693.0bc	468.0c	47.0e	2.72c
Ashebeka	1.19ab	8.80c	2.0d	800.5ab	728.5ab	47.9e	3.59ab
NC-58	1.00d	13.15a	3.0a	417.0d	390.0d	59.4b	2.30c
Gora	1.13b	7.95d	2.0d	805.0ab	615.0b	50.0de	2.80c
Holeta-2	1.05c	10.95bc	2.3c	506.0cd	541.0bc	43.7e	2.60cd
Wayu	0.90d	14.95a	2.0d	319.5e	479.0c	56.8bc	2.33c
Numan	1.04	6.80d	2.0d	917.5a	666.0b	48.4e	3.49ab
Mean	1.12	9.2	2.29	653	1185	52.4	4.00
LSD	8.49	2.33	0.44	145.50	317.70	6.38	6.88

Note. *Values followed by the same letters within a column are not significantly different at $p \leq 0.05$ according to Duncan's Multiple Range Test (DMRT).

Table 4. Mean grain yield and yield components of Faba bean genotypes under no phosphorus application

Variety	Plant height (m)	Number of pods per plant	Seed per pod	Thousand seed weight (Gm)	Biological yield (Gm)	Harvest index	Grain yield (t/ha)
Degaga	1,13a	8.5b*	2.1cde	514c	750bc	48.7ab	2.59b
Moti	1.11a	6.8c	2.5abc	661ab	850ab	41.4bc	2.64ab
Geblcho	0.91c	6.3c	2.0de	723a	800ab	55.0a	2.44b
Obse	1.01c	5.5c	2.8a	627b	850ab	45.6abc	2.38b
Dosha	1.07ab	7.8bc	2.0de	653ab	758bc	48.2ab	3.12a
Tumsa	1.02b	7.0bc	2.0de	655ab	800ab	57.3a	3.04a
Wolki	1.03b	9.8ab	2.1cde	516c	766bc	49.4ab	2.32bc
Hachalu	1.03b	8.5b	2.0de	630ab	900a	42.1bc	2.59b
Didea	1.01b	6.5c	2.3bcd	699ab	683c	46.6abc	2.10c
Ashbeka	1.06ab	8.3b	2.0de	779a	850ab	43.8bc	2.65ab
NC58	0.92c	9.3ab	2.6ab	411d	533d	48.7ab	1.74c
Gora	1.06ab	5.8	2.0de	746a	791bc	38.5c	2.34bc
Holeta-2	0.95c	9.6ab	2.1cde	490cd	808ab	32.2c	1.95c
Wayu	0.82c	11.1a	2.0de	310e	591d	43.9bc	2.20c
Numan	0.95c	5.8c	2.0de	895a	733bc	45.7abc	2.28bc
Mean	1.00	7.8	2.2	621	764	45.8	2.43
LSD	5.83	1.45	0.30	83.40	172	8.85	3.64

Note. * Values followed by the same letters within a column are not significantly different at $p \leq 0.05$ according to Duncan's Multiple Range Test (DMRT).

3.4 Phosphorus Yield Efficiency

Phosphorus use efficiency varied significantly among genotypes (Table 5). The highest PYE values were recorded for Numan (1.34**)** and Hachalu (1.33**)**, which were statistically superior or at par with Ashebeka and Wolki**.**

Varieties such as Degaga and Dosha **e**xhibited significantly lower PYE values, indicating weaker conversion of applied phosphorus into economic yield. High PYE values recorded for Numan**,** Hachalu**,** and Ashebeka demonstrate their potential for inclusion in breeding programs targeting phosphorus-limited environments.

Genotypes with higher PYE not only ensure better productivity under low-input systems but also contribute to sustainable nutrient management by reducing fertilizer requirements. The observed genotype in PYE aligns with previous findings that phosphorus use efficiency is strongly genotype-dependent and influenced by both uptake and utilization efficiency. The observed significant differences in phosphorus yield efficiency among faba bean genotypes confirm the presence of substantial genetic variability in phosphorus uptake and utilization efficiency.

Genotypes such as Numan, Hachalu, and Ashebeka, which consistently showed higher PYE across locations, demonstrate superior ability to convert applied phosphorus into economic yield. This may be attributed to improved root system development, enhanced root-soil contact, and more efficient internal phosphorus remobilization during reproductive growth stages. Similar genotype-dependent variations in phosphorus efficiency have been reported in faba bean and other legumes under Ethiopian conditions, emphasizing the importance of selecting phosphorus-efficient genotypes for low-input farming systems [12, 20].

Table 5. Mean grain yield use efficiency (PYE) of faba bean varieties under phosphorus application (WP) and without phosphorus (WOP) across Ambo and Holeta (Combined)

Variety	WP	WOP	PYE
Degaga	30.46c	25.96b	1.06d
Moti	28.15cd	26.49b	1.15cd
Gebelcho	*29.66*cd	24.46c	1.17cd

Table 5 Continued

Variety	WP	WOP	PYE
Obse	28.47cd	23.86c	1.21c
Dosha	31.52c	31.24a	1.08d
Tumsa	32.57bc	30.47a	1.16cd
Wolki	33.06bc	23.26c	1.28b
Hachalu	38.32a	25.94b	1.33ab
Didea	27.18d	21.06c	1.24c
Ashebeka	35.91ab	26.53b	1.29b
NC58	23.02e	17.46e	1.25c
Gora	28.02cd	23.44c	1.19c
Holleta-2	26.07d	19.53d	1.22c
Wayu	23.28e	22.62c	1.16cd
Numan	34.91b	22.84c	1.34a
Mean	30.04	24.34	1.21
LSD	6.12	4.54	0.09

Notes. WP=with P fertilizer application; WOP=without P fertilizer application; RR relative reduction; LSD= Least significant differences

3.5 Grouping of the Genotypes into Phosphorus Efficiency

Based on the combined mean phosphorus yield efficiency, faba bean genotypes were grouped into three phosphorus-efficiency categories.

1. Highly Phosphorus-Efficient Genotypes (PYE ≥ 1.30); these genotypes showed superior ability to convert applied phosphorus into grain yield and maintained stable performance across environments. Numan (1.34) and Achalu (1.33) with Characteristics of high responsiveness to applied phosphorus, Suitable for phosphorus-deficient soils, and Potential donors for breeding programs targeting nutrient-use efficiency
2. Moderately Phosphorus-Efficient Genotypes (PYE = 1.20-1.29); these genotypes demonstrated acceptable phosphorus utilization efficiency and stable performance; Ashebeka (1.29), Wolki (1.28), Didea (1.24), NC58 (1.25), Holleta-2 (1.22), and Obse (1.21) with Characteristics: Perform reasonably well under both fertilized and unfertilized conditions and are suitable for environments with moderate phosphorus input
3. Low Phosphorus-Efficient Genotypes (PYE < 1.20); These genotypes exhibited poor phosphorus utilization and limited yield gains from phosphorus application; Gora (1.19), Gebelcho (1.17), Tumsa (1.16), Wayu (1.16), Moti (1.15), Dosha (1.08), and Degaga (1.06). They require higher phosphorus inputs to achieve optimal yield and are less suitable for low-input farming systems.

3.6 Correlation between Growth Traits and Yield

Plant height (PLH) exhibited a strong positive correlation with biological yield (BY) and grain yield (GY) under both P regimes. Under P0, PLH correlated with BY (r = 0.81**) and GY (r = 0.81**), while under P1, the associations remained significant though slightly reduced (BY: r = 0.67**, GY: r = 0.58**). Pods per plant (PPP) showed a positive and significant correlation with grain yield under P0 (r = 0.51**), but this relationship became non-significant under P1, indicating that phosphorus application modified yield formation pathways. Seeds per pod (SPP) and thousand-seed weight (TSW) displayed weak and non-significant correlations with grain yield under both P conditions, suggesting limited direct contribution to yield variability among the tested genotypes (Table 6).

Table 6. Correlation coefficients (r) between agronomic traits in 15 faba bean genotypes in the absence and presence of phosphorus fertilizer in Ethiopia

Trait	P level	DF	DM	PLH	PPP	SPP	TSW	BY	GY	HI
DF	P0#	1	0.73**	-0.68**	-0.33*	-0.23ns	-0.38*	-0.76**	-0.8**	-0.46*
	P1	1	0.69**	-0.26ns	0.12ns	-0.12ns	-0.21ns	-0.57**	-0.7**	-0.46*
DM	P0		1	-0.71**	-0.44*	-0.32*	-0.17ns	-0.74**	-0.81**	-0.51**
	P1		1	-0.22ns	-0.08ns	-0.15ns	-0.06ns	-0.57**	-0.71**	-0.44*
PLH	P0			1	0.32*	0.25ns	0.33*	0.81**	0.81**	0.35*
	P1			1	-0.16ns	0.27ns	0.45*	0.67**	0.58**	0.06ns
PPP	P0				1	0.03ns	-0.32*	0.46*	0.51**	0.33*
	P1				1	-0.11ns	-0.53*	-0.08ns	0.022ns	0.19ns
SPP	P0					1	-0.05ns	0.21ns	0.17ns	0.09ns
	P1					1	0.06ns	0.28ns	0.24ns	0.08ns
TSW	P0						1	0.29ns	0.27ns	0.16ns
	P1						1	0.29ns	0.24ns	-0.04ns
BY	P0							1	0.92**	0.41*
	P1							1	0.91**	0.07ns
GY	P0								1	0.57**
	P1								1	0.43*
HI	P0									1
	P1									1

Notes.
#p0 indicates that the trait is under no P application
"1" indicates the trait is under P fertilizer application.
Figures in the diagonal indicate correlation of the performances of a trait under no P and P application; * and ** indicate significant correlation among the traits at 5 and 1% significance levels, while ns indicates no significant correlation.

3.7 Associations among Biomass, Grain Yield, and Harvest Index

Biological yield (BY) was strongly and positively correlated with grain yield (GY) under both P0 (r = 0.92**) and P1 (r = 0.91**), indicating that biomass production was the major driver of grain yield across nutrient environments.

Harvest index (HI) showed a moderate positive correlation with grain yield, which was stronger under P0 (r = 0.57**) than under P1 (r = 0.43*), suggesting that efficient dry matter partitioning was particularly important under phosphorus-stress conditions.

The strong positive correlation between DF and DM reflects normal phenological synchronization in faba bean and confirms that flowering time is a reliable predictor of maturity under both phosphorus-deficient and fertilized conditions. The consistent negative association of DF and DM with grain yield suggests that early-maturing genotypes had yield advantages, likely due to better adaptation to terminal moisture stress and improved resource-use efficiency in Ethiopian highland environments [12, 13].

The significant and positive correlations of plant height with biomass and grain yield indicate that taller plants accumulated greater assimilates, contributing to higher yield. This relationship remained stable under both P levels, highlighting plant height as an important indirect selection trait for yield improvement in faba bean, which agrees with reports by [15, 20].

The loss of a significant association between pods per plant and grain yield under P application suggests that phosphorus fertilization reduces competition among yield components by improving overall plant vigor and integrate availability. Similar findings have been reported where nutrient supplementation altered yield component relationships in legumes [16].

The **c**onsistently strong correlation between biological yield and grain yield under both P0 and P1 confirms that yield improvement in faba bean is primarily associated with increased total dry matter production rather than changes in individual yield components. This finding supports earlier conclusions in Ethiopian faba bean and

common bean studies [17, 19].

The comparatively stronger association between harvest index and grain yield under P0 indicates that under phosphorus stress, genotypes with superior assimilate partitioning to grains had a clear advantage. This underscores the importance of selecting genotypes with both high biomass production and efficient partitioning for low-P environments.

4. Conclusion

The study demonstrated that the applied treatments significantly influenced plant growth, biomass accumulation, and yield-related traits. Among the treatments, T3 consistently outperformed the control, indicating that the experimental factors effectively enhanced physiological and metabolic processes essential for crop development.

Improvements in plant height and biomass suggest enhanced nutrient availability and uptake efficiency under superior treatments, which likely contributed to increased photosynthetic capacity and improved assimilate division toward reproductive structures. These responses collectively resulted in higher yield performance compared with the control treatment.

The observed positive correlations among growth, biomass, and yield parameters confirm the close interdependence of these traits and emphasize the importance of early vegetative growth in determining final productivity. Overall, the findings indicate that optimized treatment application can significantly improve crop performance through coordinated effects on growth and yield components.

5. Recommendations

Breeding and Selection

- Breeding programs should prioritize genotypes that combine high biological yield, superior harvest index, and stable grain yield under both phosphorus-applied and non-applied conditions.
- Early- to medium-maturing genotypes should be favored due to the negative association between excessive maturity duration and grain yield.

Phosphorus Efficiency Improvement

- Genotypes performing well under P-deficient conditions should be further evaluated and promoted for low-input farming systems to reduce dependency on phosphorus fertilizers.
- Phosphorus-efficient genotypes can serve as valuable parental materials in future breeding programs.

Agronomic Management

- Integrated use of phosphorus fertilizer with genotype selection is recommended to maximize yield gains and nutrient use efficiency in faba bean production.
- Farmers in phosphorus-deficient areas should adopt genotypes proven to perform well under low P conditions.

Future Research

- Further multi-location and multi-season studies are recommended to validate genotype performance and trait associations across diverse environments.
- Detailed physiological and root-trait studies should be conducted to better understand the mechanisms primary phosphorus uptake and utilization efficiency in faba.

Acknowledgements

The authors gratefully acknowledge the Ministry of Education (MoE) for financial support and Ambo University for academic facilitation. Sincere thanks are extended to the Holeta Agricultural Research Center (HARC) for providing experimental fields, facilities, and research support, and to its staff and participating farmers for their valuable cooperation during the study.

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