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Determination of Spacing and Phosphate Fertilizer Rates for Faba Bean (*Vicia faba* L.) Production on Acidic Nitisols in the Central Highlands of Ethiopia

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Abstract: The output of faba beans is constrained in the nitisols of Western Shewa due to low soil fertility, despite the fact that they are a substantial pulse crop grown in Ethiopia's central highlands. A field experiment was conducted to determine the ideal seed and fertilizer rates for faba bean production on the acidic nitisols of West Shewa during the primary cropping seasons of 2020 and 2021. Factorial combinations of phosphate fertilizer (23, 46 and 69 kg P_2O_5/ha), intra-row spacing (7, 10 and 13 cm) and inter-row spacing (30, 40 and 50 cm) were set up in a randomized complete block design with three replications. Nitrogen (N) fertilizer at a rate of 19 kg/ha was applied uniformly to all treatments. According to the ANOVA results, most interactions did not change grain yield. However, it responded considerably ($P \leq 0.05$) to each of the main effects of the treatment. On the other hand, most of the other measured characters were significantly ($P \leq 0.05$) affected by both the main effects and the interaction effects. For almost all characteristics taken into consideration, the year effect was likewise significant ($P \leq 0.05$). There was a substantial ($P \leq 0.05$) association between the number of seeds per pod, the volume of straw generated and grain yield. The maximum net benefit in Ethiopian Birr 60,789.00 and MRR 176.21% was attained at a P_2O_5 rate of 69 kg/ha when grain production and straw yield were both considered. Based on the results of the ANOVA and economic analyses, it was determined that the maximal fertilizer rate (69 kg P_2O_5/ha), along with 10 cm intra-row spacing and 40 cm inter-row spacing, was best for faba bean production in West Shewa nitisols and related agro-ecologies.

Key words: Faba Bean · Intra-Row · Inter-Row · Phosphorus · Seed Rate · Acidic Nitisol

INTRODUCTION

Faba bean (*Vicia faba* L.) is one of the major pulse crops grown in the highlands (1800-3000 m.asl) of Ethiopia, including the Central-Western part, where the need for a chilling temperature is satisfied [1, 2]. It takes the largest share (30.12%) of the area under pulse production [3]. It is well adapted to the diverse soil types of Ethiopia, where legumes are prominently used as traditional soil fertility restoration crops in mixed cropping systems [4]. In addition, it is noted that among the major cool-season grain legumes, faba bean has the highest average reliance on N_2 fixation for growth [5]. Hence, the use of faba bean in crop rotation had a significant effect by reducing the amount of chemical nitrogen applied to soil for crop production [4]. However, the production and productivity of faba beans is constrained by several biotic and abiotic stresses. Among which, optimum plant density and lack of optimum fertilizer recommendation are two of the most important cultural practices determining grain yield, as well as other agronomic attributes of the crop [6]. It is noted that seed rate is influenced by row width, crop species, soil and climatic variables and crop use. Hence, maximizing economic returns within the constraints of a specific environment is a major research objective [7]. The more favorable the environment, the higher the optimum population will be [8] and as the level of available soil nutrients increases, the need for fertilizer decreases.

According to Agegnehu *et al*. [9] reported in central highlands of Ethiopia, faba bean is often produced on acidic nitisols where its productivity is constrained by low soil pH (less than 5.5) and associated low P availability, resulting in low yields. Furthermore, the low yields in such soils could mainly be due to the deficiency of nutrients, such as P, Ca and Mg, or the toxicity of Al, Fe and Mn. In addition, the proportion of phosphorus fertilizer that could immediately be available to a crop becomes

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inadequate [10]. As a result, P deficiency is one of the most widespread soil constraints in these soils. Moreover, acid soils could expose faba bean to greater chocolate spot infection, thereby reducing yield [11]. Vigorous plant growth, as well as increased assimilate formation and translocation to plant fruiting parts, results in improved development of seed yield and its components when legume plants are supplied with phosphorus at optimal rates [12]. Studies indicate that the response of faba bean to phosphorus fertilizer application is dependent on the residual P fertility level of the soil [13].

Accordingly, application of di-ammonium phosphate to faba beans resulted in either a lack of response or negative effects [14] or a significantly positive response to the applied P fertilizer [15, 16]. For example, Tsigie and Woldeab [17] reported the absence of a response to phosphorous fertilizer at Holetta, while Ghizaw *et al*. [14] reported the presence of a significant quadratic response to P fertilizer at a similar location (Holeta). This study further reported a lack of significant effect on seed yield at the Burkitu and Debre Zeit sites, probably due to the buildup of phosphorus that has been the result of continuous application to the field during the past three decades. In general, the application of phosphorus fertilizer ranging from 20 kg P/ha in various locations to 40 kg P/ha in the Bore highlands and at Sekela produced higher grain yields [18-20].

For most crops, including faba bean, the choice of seeding rate is an important agronomic practice that influences plant density and crop establishment as it is a major determinant of proper plant development and growth [21]. Both high and low crop densities reduce yield and total revenue [15]. It has been reported that among a variety of improved production technologies, proper plant population with appropriate adjustment of inter- and intra-row spacing plays a key role in enhancing faba bean production [22]. As reviewed by Tamrat [16], a wide range of optimum plant densities are reported depending on the faba bean cultivar, environmental conditions (soil type, soil moisture, soil fertility and relative humidity) and the sowing date. Furthermore, a few research findings on intra-row- and inter-row spacing revealed varying results under various environmental conditions. Accordingly, intra-row spacing in the range of 5 to 15 cm and an inter-row spacing of 30 to 40 cm have been recommended at different location depending on different environmental conditions.

However, most of the above recommendations didn't consider the combined effect of spacing and fertilizer application. In addition, no recommendation has been made so far for acid-prone areas considering inter- and intra-row spacing together with phosphorus application. Hence, this experiment was conducted to determine optimum spacing in combination with optimum phosphorus fertilizer rates on acid-prone areas.

MATERIALS AND METHODS

Experimental Area Description: The experiment was carried out in West Shewa zone at Holeta, Ethiopia from 2020 - 2021 under rain-fed conditions. At an altitude of approximately 2400 m above sea level, 30 kilometers west of Addis Abeba, between 09°03' N latitude and 38°30' E longitude. The average annual precipitation is 1100 mm, with 85% of that falling between June and September and the remaining 15% falling between January and May. Minimum and maximum air temperatures are 6.2°C and 22.1°C, respectively [23]. As reported by Mosissa & Taye [24], the pH of experimental field lies in the range of 4.05 to 4.44 and was found to be very strongly acidic, as rated by Murphy [25]. The organic carbon of the experimental field lies in the range of 1.19 to 2.00%, which is classified as low to medium [26]. The total nitrogen percentage was in the range of 0.14 to 0.17% and was rated as moderate [27]. The available soil phosphorous is in the range of 6.05 to 9.72 ppm, which is classified as low to medium [28].

Experimental Design and Treatments: A randomized complete block design with three replications was used to set up factorial combinations of the phosphate fertilizer (23, 46 and 69 kg P_2O_5/ha), intra-row spacing (7, 10 and 13 cm) and inter-row spacing (30, 40 and 50 cm). From 100 kg of NPS fertilizer, 38 kg of P_2O_5/ha and 19 kg of N/ha were achieved. The remaining P_2O_5 for the second level (8 kg of P_2O_5/ha) and the third level (31 kg of P_2O_5/ha) was added from TSP. Similar to this, urea was used to supplement the

Table 1: Total rainfall (mm) and mean temperature for the growth period of faba beans at Holeta

Variable	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Rainfall 2020 (mm)	263.40	334.20	216.20	31.60	8.00	3.20
Rainfall 2021 (mm)	304.10	287.60	250.90	73.60	0.00	0.00
Mean temperature 2020 (°C)	15.60	15.16	14.91	14.44	13.08	12.55
Mean temperature 2021 (°C)	15.30	15.31	15.47	15.28	14.62	13.55

Source: Holeta meteorology station (unpublished data) leftover N for the first level (7.5 kg N/ha). Accordingly, the same amount of nitrogen (N) fertilizer, 19 kg N/ha, was applied to all treatments and/or plots. All fertilizer was applied at the time of planting. All treatments were conducted on a 4.0 m x 2.4 m (9.6 m^2) gross plot; the net plot size was created by removing one outside row from each side. Thus, the net plot size was 4 m*1.8 m (7.2 m^2), 4 m*1.6 m (6.4 m^2) and 4 m*1.5 m (6 m^2) for the respective inter-row spacings of 30, 40 and 50 cm. For the 30, 40 and 50 cm inter-row spacings, there were 8, 6 and 5 rows per plot, respectively. For the 7, 10 and 13 cm intra-row spacings, there were 57, 40 and 31 germinated plants per row, respectively. For this experiment, the "Gora' faba bean variety was used. The seed rate was calculated by applying Matthews' equation [29], considering a 100-seed weight of 93.8 g, a germination rate of 98% and a 10% field loss (0.90 establishment rate). Two hand-weeding sessions took place.

Crop Data Collection: Data on plant height, number of pods per plant and number of seeds per pod were measured from 10 randomly selected plants from the central rows of each plot. Days to flowering were recorded when 50% of the plants in a plot produced their first flower, while days to physiological maturity were recorded when 90% of the plants in a plot reached physiological maturity. Grain yield was measured from the central rows of each plot while 100 seed weight was measured in grams for randomly counted 100 seed samples from each net plot.

Analysis of Variance: The impact of treatments on crop characters was statistically evaluated using GenStat for Windows Version 16's General Analysis of Variance Procedure [30] in accordance with Gomez and Gomez's [31] three-factor factorial trial statistical approach. When the ANOVA result indicated significant differences among treatments for each parameter, the means were separated using the least significant difference (LSD) test at the 5% level of probability.

A combined analysis of the data was performed once variance homogeneity was identified and Bartlett's test was employed to confirm it [31].

Economic Analysis: The economic analysis was conducted using CIMMYT [32] approach. The total variable costs were calculated using the current pricing of 34 Birr per kilogram for P_2O_5 fertilizer, 50 Birr per kilogram for faba bean seed and 45 Birr per kilogram for faba bean grain. The official price for P_2O_5 fertilizer was utilized and the field price was calculated by simply averaging the farm gate prices close to the experimental field following harvest (January to February) over the two years.

RESULTS AND DISCUSSION

Phenological and Growth Parameters: From the combined analysis of variance over years (2020 and 2021), days to 50% flowering were significantly ($\leq$0.05%) affected by the main effects of year, intra-row, inter-row spacing and the three-way interaction effect of P_2O_5 fertilizer*intra-row-*inter-row spacing (Table 2). Significantly, the earliest days to 50% flowering (52.3 days) were recorded in the first year, which might be related to the higher amount of rainfall in the second year that encouraged vegetative growth (Table 1). Days to 50% flowering were significantly and linearly increased from 52.7 to 53.5 and from 53.0 to 53.3 days as intra-row- and inter-row spacing increased from 7 cm to 13 cm and 30 cm to 50 cm, respectively (Table 2), which was probably due to higher plant-to-plant competition for growth factors that finally enhanced early flowering at higher densities. In contrast, Hailu & Ayle [33] discussed that days to flowering for faba bean were enhanced as intra-row- and inter-row spacing increased, probably due to more nutritional area available in wider spacing, which might have caused the crop to flower earlier than the closer spacing. The three-way interaction showed no clear difference among different levels of P_2O_5 fertilizer*intra-row-*inter-row spacing combinations (Table 3). However, the combination of 23 kg P_2O_5/ha*7 cm intra-row-*30 cm inter-row spacing, 46 kg P_2O_5/ha*7 cm intra-row-*40 cm inter-row spacing, 69 kg P_2O_5/ha*7 cm intra-row-*30 cm inter-row spacing and 69 kg P_2O_5/ha*7 cm intra-row-*40 cm inter-row spacing resulted in the earliest days to flower (52.3 days). Overall, narrower intra-row spacing (7 cm) contributed more to early flowering (Table 3).

Day to 90% physiological maturity was significantly ($\leq$0.05%) affected by the two-way interaction effect of P_2O_5*intra-row spacing and the main effects of year, intra-row spacing and inter-row spacing (Table 2). Significantly, longer days to 90% physiological maturity (149.2 days) were recorded in the second year, which might be related to the higher amount of rainfall in the second year that encouraged vegetative growth (Table 1). Days to maturity significantly increased from 140 to 140.7 days as intra-row spacing increased from 7 cm to 13 cm, though similar records were obtained for intra-row spacing of 10 cm and 13 cm (Table 2). This result was closely followed the findings of Singh *et al*. [34] who reported maximum days

Table 2: Main effect of phosphorus, intra- and inter-row spacing on grain yield and some agronomic parameters of faba bean at Holeta over years (2020-2021)

Treatments	DTF	DTM	Plh (cm)	NPPP	NSPP	HSW (g)	SY (t/ha)	GY (t/ha)
Year								
2020	52.3	131.7	106.8	7.3	2.7	81.01	1.73	1.45
2021	53.8	149.2	117.6	9.4	2.4	86.70	1.44	1.09
LSD (5%)	0.002	0.458	1.996	0.467	0.083	2.140	0.105	0.075
P_2O_5 (kg/ha)								
23	53.2	140.2	109.4	7.5	2.5	83.72	1.39	1.13
46	53.1	140.4	113.3	8.7	2.5	83.16	1.67	1.32
69	52.9	140.8	113.9	8.8	2.6	84.69	1.70	1.37
LSD (5%)	ns	ns	2.445	0.572	ns	ns	0.128	0.092
Intra-row spacing (cm)								
7	52.7	140.0	114.7	7.8	2.6	85.04	1.89	1.38
10	53.0	140.7	112.4	8.3	2.5	82.72	1.55	1.29
13	53.5	140.7	109.5	8.8	2.5	83.81	1.32	1.15
LSD (5%)	0.245	0.561	2.445	0.572	ns	ns	0.128	0.092
Inter-row spacing (cm)								
30	53.0	140.6	112.1	7.7	2.6	84.35	1.72	1.32
40	53.0	140.6	112.7	8.2	2.5	85.70	1.60	1.30
50	53.3	140.3	111.8	9.1	2.5	81.53	1.44	1.20
LSD (5%)	0.245	ns	ns	0.572	ns	2.620	0.128	0.092
Mean	53.07	140.48	112.18	8.34	2.54	83.86	1.59	1.27
CV (5%)	1.21	1.05	5.71	17.96	10.50	8.19	21.19	18.84
P_2O_5*Intra-row spacing	ns	**	*	ns	**	ns	*	ns
P_2O_5*Inter-row spacing	ns	ns	ns	**	ns	ns	ns	ns
Intra-*Inter-row spacing	ns	ns	ns	*	ns	ns	ns	ns
P2O5*Intra-*Inter-row spacing	*	ns	ns	ns	ns	ns	*	ns

DH=Days to 50% heading, DPM= Days to 90% physiological maturity, Ph= Plant height, NPP= Number of pods per plant, NSP= Number of seeds per pod, HSW= Hundred seeds weight, SY= Straw yield, GY= Grain yield

Table 3: Three-way interaction effects of phosphorus fertilizer*intra-row spacing*inter-row spacing on days to flowering and straw yield of faba bean at Holeta over years (2020-2021)

P_2O_5 (kg/ha)	Intra-row spacing (cm)	Inter-row spacing (cm)	Days to 50% flowering	Straw yield (t/ha)
23	7	30	52.3^{a}	1.79^{a-e}
23	7	40	53.2^{a-d}	1.69^{a-h}
23	7	50	52.8^{abc}	1.71^{a-g}
23	10	30	52.8^{abc}	1.50^{c-i}
23	10	40	52.5^{ab}	1.18^{ghi}
23	10	50	53.8^{d}	1.13^{hi}
23	13	30	53.5^{cd}	1.20^{fi}
23	13	40	53.8^{d}	1.28^{e-i}
23	13	50	53.8^{d}	1.06^{i}
46	7	30	53.0^{a-d}	2.16^{a}
46	7	40	52.3^{a}	1.88^{ad}
46	7	50	52.8^{abc}	1.69^{a-h}
46	10	30	53.5^{cd}	1.93^{abc}
46	10	40	53.2^{ad}	2.16^{a}
46	10	50	52.8^{abc}	1.37^{d-i}
46	13	30	53.3^{bcd}	1.44^{c-i}
46	13	40	53.2^{abcd}	1.23^{fi}
46	13	50	53.8^{d}	1.17^{ghi}
69	7	30	52.3^{a}	2.18^{a}
69	7	40	52.3^{a}	2.07^{ab}
69	7	50	53.0^{ad}	1.85^{ad}
69	10	30	52.8^{abc}	1.55^{b-i}
69	10	40	52.8^{abc}	1.44^{c-i}
69	10	50	52.7^{abc}	1.66^{a-h}
69	13	30	53.2^{ad}	1.75^{a-f}
69	13	40	53.3^{bcd}	1.50^{c-i}
69	13	50	53.8^{d}	1.28^{e-i}

Table 4: Two-way interaction effects of phosphorus with intra-row spacing on the date of 90% physiological maturity of faba bean at Holeta over years (2020-2021)

	Intra-row spacing (cm)		
P_2O_5 (kg/ha)	7	10	13
23	140.2^{ab}	139.8^{a}	140.7^{abc}
46	139.9^{a}	141.3^{c}	140.0^{a}
69	139.9^{a}	141.1^{bc}	141.3^{c}

Table 5: Two-way interaction effects of phosphorus with intra-row spacing on plant height of faba bean at Holeta over years (2020-2021)

	Intra-row spacing (cm)		
P_2O_5 (kg/ha)	7	10	13
23	111.9^{bc}	109.9^{cd}	106.4^{d}
46	112.7^{bc}	115.1^{ab}	112.0^{bc}
69	119.5^{a}	112.1^{bc}	110.1^{cd}

to maturity in the case of wider planting (45 x 45 cm) and the shortest time taken by dense planting (30 x 20 cm), stating that less and less availability of energy to maintain momentum for longer periods of time under overcrowded conditions than in the case of abundant energy in wider spacing. In contrast, Hailu, Ayle [33] and Gezahegn,Tesfaye [35] reported that plants grown in wider intra-row spacing matured earlier than plants grown in narrow intra-row spacing, probably due to lower canopy temperatures in the narrow rows, which potentially reduced heat accumulation by plants and thereby prolonged the maturity period. The earliest days to 90% physiological maturity (139.8 days) were recorded at a combination of 23 kg P_2O_5/ha*10 cm intra-row spacing, which is comparable to combinations of 46 kg P_2O_5/ha*7 cm intra-row spacing and 69 kg P_2O_5/ha*7 cm intra-row spacing, while the longest days (141.3 days) were recorded at a combination of 46 kg P_2O_5/ha*10 cm intra-row spacing and 69 kg P_2O_5/ha*13 cm intra-row spacing (Table 4). Overall, narrower intra-row spacing (7 cm) contributed more to the earlier maturity of the crop.

The plant height was significantly ($\leq$0.05%) affected by the two-way interaction effect of P_2O_5*intra-row spacing and the main effects of year, P_2O_5 fertilizer, intra-row spacing and inter-row spacing (Table 2). The second year resulted in significantly taller plants (117.6 cm high) than the first year (106.8 cm high). The total rainfall and mean temperature of the second growing season were higher than those of the first growing season; this may explain the higher plant height obtained from the second growing season (Table 1). These results agree with those obtained by Al- Rifaee *et al*. [36] and Yucel [37] who reported that water stress affected the plant height. Plant height significantly ($\leq$0.05%) and linearly increased from 109.4 cm to 113.9 cm as P_2O_5 levels increased from 23 kg/ha to 69 kg/ha, which is in line with the results obtained by Ghizaw *et al*. [14] and Agegnehu and Fessehaie [38] at Holeta as P_2O_5 fertilizer increased from 0 kg/ha to 69 kg/ha. In addition, Agegnehu, Tsige [39] reported a linear increase in plant height as P_2O_5 fertilizer increased from 0 kg/ha to 120 kg/ha on acid prone areas.

Similarly, Ghizaw *et al*. [14] for different locations and Alemayehu, Shumi [19] for bore highlands reported a linear increase in plant height as P_2O_5 increased from 0 kg/ha to 92 kg/ha. On the other hand, plant height significantly and linearly decreased from 114.7 to 109.5 cm as intra-row spacing increased from 7 to 13 cm (Table 2), which is probably due to competition among plants in a denser plant population for light. Similar findings were reported by Yucel [37], Khalil *et al*. [40] and Mekkei [41] who indicated that the denser plant population increased the plant height due to competition among plants. Relatively, the tallest (119.5 cm high) plant was recorded at the combination of 69 kg P_2O_5/ha*7 cm intra-row spacing, while the shortest (106.4 cm high) plant was recorded at the combination of 23 kg P_2O_5/ha*13 cm intra-row spacing (Table 5). Overall, the higher the P rate combined with the narrower intra-row spacing promoted taller plant growth, while the lower the P rate combined with the wider intra-row spacing produced shorter plants of faba bean.

Components of Yield and Grain Yield: The main effects of year, P_2O_5 fertilizer, intra-row spacing, inter-row spacing and the two-way interaction of P_2O_5 fertilizer*inter-row spacing and intra-row spacing*inter-row spacing showed a significant ($p \leq 0.05$) effect on the number of pods per plant (Table 2). A higher number of pods per plant (9.4) were recorded in the second year, which is probably related to the rainfall and temperature effect. As seen in Table 1, the higher rainfall in the second year during the podding stage (September to October) and the constantly higher temperatures in the second year beginning from October to December might have resulted in higher pod numbers than in the first year. As described by Yucel [37], this trait is greatly influenced by environmental factors such as temperature and precipitation.

The number of pods per plant linearly increased from 7.5 to 8.8 as P_2O_5 fertilizer increased from 23 kg/ha to 69 kg/ha (Table 2). In line with this result, Ghizaw *et al*. [14] described a linear increase in the number of pods per plant as P_2O_5 fertilizer increased from 0 kg/ha to 92 kg/ha at different locations, while Agegnehu and Tsige [39] reported a linear increase in the number of pods per plant as P_2O_5 fertilizer increased from 0 kg/ha to 120 kg/ha in acid prone areas. Similarly, the number of pods per plant showed an increasing trend until phosphorus reached 69 kg P_2O_5/ha in the Bore highlands of southern Ethiopia Alemayehu,Shumi [19]. On the other hand, Negasa *et al*. [4] stated a non-significant difference in the number of pods per plant while increasing P rate from 0 kg/ha to 40 kg/ha. The number of pods per plant significantly and linearly increased from 7.8 to 8.8 and from 7.7 to 9.1 as intra-row spacing and inter-row spacing, respectively, increased from 7 cm to 13 cm and 30 cm to 50 cm (Table 2), probably due to less competition for resources in wider spacing. In agreement with this result, Mekkei [41] reported a linear increase in the number of pods per plant as intra-row spacing increased from 10 cm to 25 cm, while Bakry *et al*. [42] described a linear increase in the number of pods per plant as inter-row spacing increased from 20 cm to 60 cm, justifying that less competition for resources as row spacing increased.

From the two-way results, the highest numbers of pods (10.1 and 10.4) were obtained at the combination of 46 kg P_2O_5/ha with 50 cm inter-row spacing and at the combination of 13 cm intra-row spacing with 50 cm inter-row spacing (Tables 6 and 7), probably related to a reduction in the number of branches per plant at higher plant densities/narrower spacing. In line with this result, Mondal *et al*. [43] described that the number of pods per plant increased with increasing spacing. This might be due to the fact that having fewer plants per unit area allowed more nutrients and space for growth and development, thereby producing more branches and leaf area that has the capacity to produce more photo-assimilates and total dry matter and resulted in a higher number of pods per plant.

The number of seeds per pod was significantly ($p \leq 0.05$) affected only by the main effect of year and the two-way interaction effect of P_2O_5 fertilizer*intra-row spacing (Table 2). In contrast to the number of pods per plant, the highest number of seeds per pod (2.7) was obtained in the first year (Table 2), which might have contributed to the highest grain yield in the first year. The positive correlation of it with grain yield may describe this fact (Table 11). Though the total rainfall in the first year was lower than in the second year, its distribution throughout the growing period (July to December) may have helped to have longer pods that may accommodate many more seeds than in the second year (Table 1). In line with this result, Al- Rifaee *et al*. [36] obtained a higher number of seeds per pod for the year that had a fair distribution of rainfall throughout the growth period. From the two-way results, the highest number of seeds per pod (2.7) was obtained at the combination of 69 kg P_2O_5/ha with 7 cm intra-row spacing (Table 8). Ibrahim [12] stated the presence of significant interaction between plant spacing and phosphorus rates on the number of seeds per plant of faba bean.

Table 6: Two-way interaction effects of phosphorus with inter-row spacing on the number of pods per plant of faba bean at Holeta over years (2020-2021)

	Inter-row spacing (cm)		
P_2O_5 (kg/ha)	30	40	50
23	7.4^{de}	7.5^{de}	7.8^{cde}
46	7.1^{e}	8.8^{bc}	10.1^{a}
69	8.7b^{c}	8.3^{bcd}	9.4^{ab}

Table 7: Two-way interaction effects of intra-row spacing with inter-row spacing on the number of pods per plant of faba bean at Holeta over years (2020-2021)

	Inter-row spacing (cm)		
Intra-row spacing (cm)	30	40	50
7	7.6^{b}	7.9^{b}	8.1^{b}
10	7.9^{b}	8.4^{b}	8.7^{b}
13	7.7^{b}	8.3^{b}	10.4^{a}

Table 8: Two-way interaction effect of phosphorus with intra-row spacing on the number of seeds per pod of faba bean at Holeta over years (2020-2021)

	Intra-row spacing (cm)		
P_2O_5 (kg/ha)	7	10	13
23	2.6^{ab}	2.4^{b}	2.5^{b}
46	2.4^{b}	2.5^{b}	2.6^{ab}
69	2.7^{a}	2.6^{ab}	2.4^{b}

Only the main effects of year and inter-row spacing showed a significant effect on the hundred seed weight (Table 2). Significantly ($\leq$0.05%), the heaviest 100 seed weights (86.70 g and 85.70 g) were recorded in the second year and at 40 cm inter-row spacing, respectively (Table 2), which could be related relatively to periods of moisture stress during the podding and pod filling stages (September to October) in the first growing period. Similarly, Al- Rifaee *et al*. [36] and Yucel [37] described that periods of drought during faba bean development decreased 100-seed weight.

The main effects of year, P_2O_5 fertilizer, intra-row spacing, inter-row spacing, the two-way interaction effect of P_2O_5 fertilizer*intra-row spacing and the three-way interaction effect of P_2O_5 fertilizer*intra-row spacing*inter row spacing showed a significant ($\leq$0.05%) effect on straw yield (Table 2). Since the three-way interaction of

P_2O_5 fertilizer*intra-row spacing*inter row spacing showed a significant (≤0.05%) effect on straw yield, only the year effect and the three-way interaction results are reported in this article. Accordingly, the highest straw yield (1.73 t/ha) was recorded in the first year, showing a positive correlation with grain yield (Table 11) where higher dry matter production was favored by the fair distribution of rainfall throughout the growth period (Table 1). Similarly, significantly (≤0.05%), the highest straw yield (2.18 t/ha) was recorded at the combination of 69 kg P_2O_5 / ha*7 cm intra-row-*30 cm inter-row spacing, which was comparable to the combination of 46 kg P_2O_5/ha*7 cm intra-row-*30 cm inter-row spacing (2.16 t/ha), as well as to the combination of 46 kg P_2O_5/ha*10 cm intra-row-*40 cm inter-row spacing (2.16 t/ha), while the lowest straw yield (1.06 t/ha) was obtained at the combination of 23 kg P_2O_5/ha*13 cm intra-row-*50 cm inter-row spacing (Table 3). This was probably due to higher straw yield production at a higher P_2O_5 level and narrower spacing and less partitioning into grain yield. In agreement with this result, Al- Rifaee *et al.* [36] obtained the highest straw yield from the highest population (100 and 150 plants m^{-2}) due to greater amounts of biomass, which in turn produced a higher amount of straw yield due to less partitioning into grain yield.

The main effects of year, P_2O_5 fertilizer, intra-row spacing and inter-row spacing all had a significant ($p \leq 0.05\%$) effect on grain yield, but interaction effects had no effect (Table 2). Similar to the straw yield, the highest grain yield (1.45 t/ha) was recorded in the first year, probably due to the fair distribution of rainfall throughout the growth period (Table 1). The presence of considerable and unpredictable year-on-year variation in the seed yield of faba bean, despite adequate control of pests and diseases, is well reported by López-Bellido *et al.* [21]. The same authors find that yield shows a greater response to yearly environmental conditions such as rainfall and maximum daily temperatures.

Grain yield linearly increased by 21.24% as P_2O_5 fertilizer increased from 23 kg/ha to 69 kg/ha, which is probably attributed to the increased P availability due to P fertilizer application on acidic nitisols that had the problem of P deficiency brought about by P fixation (Table 2). In line with this result, Agegnehu, Tsige [39] reported a linear increase in grain yield as P fertilizer increased from 0 kg/ha to 52 kg/ha on acid prone areas of the central highland nitisols of Ethiopia. Similarly, Ghizaw *et al.* [14] reported a significant and linear increase in grain yield as P_2O_5 fertilizer increased from 0 kg/ha to 92 kg/ha at different locations, including Holeta. Similarly, the highest grain yield was obtained in response to P_2O_5 fertilizer application at a rate of 92 kg/ha, which was found to be economically optimum in the Bore highlands of southern Ethiopia [19]. In our experiment, since there was no significant difference between P_2O_5 fertilizer rates of 46 and 69 kg/ha, economic analysis was found to be the best option in selecting the feasible P_2O_5 rate. Accordingly, based on the economic analysis results, the feasible rate of P_2O_5 was found to be 69 kg/ha while considering grain yield alone, with a net benefit of 53,139.00 and an MRR of 158.95% (Table 9), or while considering grain yield plus straw yield, with a net benefit of 60,789.00 and an MRR of 176.21% (Table 10). This result indicates that the use of higher rates of P fertilizer on acidic nitisols could help in obtaining economically higher yields than the blanket recommendation of 46 kg P_2O_5/ha. Yet further evaluation of higher P_2O_5/ha rates than 69 kg/ha is required as higher returns are obtained from the highest level of this experiment. In line with this result, Tsige *et al.* [44] obtained higher grain yield from the highest P fertilizer rate of 92 kg P_2O_5/ha on acid soils of the Wolaita zone in southern Ethiopia. In contrast, Agegnehu & Tsige [39] reported that P fertilizer at the rate of 13 kg/ha (equivalent to 30 kg P_2O_5/ha) was found economically optimum for the production of faba beans on acidic nitisols of the central highlands of Ethiopia.

Concerning spacing, grain yield linearly decreased by 20% and 10% with increasing intra-row spacing and inter-row spacing from 7 cm to 13 cm and from 30 cm to 50 cm, respectively (Table 2). However, statistically no significant difference was observed between intra-row spacing of 7 cm and 10 cm as well as between inter-row spacing of 30 cm and 40 cm. Since there was no interaction between intra-row spacing and inter-row spacing, economic analysis could not be performed. Hence, selecting the feasible spacing by the use of ANOVA results is crucial on top of higher grain yields. Accordingly, though the higher yields were obtained from narrower spacings, the seed rates required for narrower spacings are higher than those of wider spacings. Hence, narrower spacings accompanied by higher seed rates could not be feasible. Therefore, in this experiment, an intra-row spacing of 10 cm, which is statistically on par with the intra-row spacing of 7 cm and an inter-row spacing of 40 cm, which is statistically on par with the inter-row spacing of 30 cm, was found to be optimum for faba bean production on acidic nitisols in the West Shewa central highlands of Ethiopia.

Table 9: Dominance and marginal rate of return analysis for the effect of population density and phosphate fertilizer rate on grain yield (t/ha) of faba bean at Holeta over two years (2020 and 2021)

P_2O_5 (kg/ha)	Observed Grain yield (t/ha)	Adjusted grain yield (t/ha)	GB (Birr/ha)	TVC (Birr ha^{-1})	NB (Birr ha^{-1})	MRR (%)
23	1.13	1.02	45765.00	782.00	44983.00	
46	1.32	1.19	53460.00	1564.00	51896.00	884.02
69	1.37	1.23	55485.00	2346.00	53139.00	158.95

GB= Gross benefit, TVC= Total variable cost, NB= Net benefits, MRR= Marginal rate of return

Table 10: Dominance and marginal rate of return analysis for the effect of population density and phosphate fertilizer rate on grain yield (t/ha) plus straw yield (t/ha) of faba bean at Holeta over two years (2020 and 2021)

	Observed Grain	Adjusted grain	Observed straw	Adjusted straw			TVC	NB
P_2O_5 (kg/ha)	yield (t/ha)	yield (t/ha)	yield (t/ha)	yield (t/ha)	GB (Birr/ha)	(Birr ha^{-1})	(Birr ha^{-1})	MRR (%)
23	1.13	1.02	1.39	1.25	52020.00	782.00	51238.00	
46	1.32	1.19	1.67	1.50	60975.00	1564.00	59411.00	1045.14
69	1.37	1.23	1.70	1.53	63135.00	2346.00	60789.00	176.21

GB= Gross benefit, TVC= Total variable cost, NB= Net benefits, MRR= Marginal rate of return

Table 11: Correlation coefficients between the studied faba bean characters

	DTF	DTM	PH	NPPP	NSPP	HSW	SY	GY
DTF	-							
DTM	0.695**	-						
PH	0.316**	0.584**	-					
NPPP	0.399**	0.454**	0.459**	-				
NSPP	-0.316**	-0.407**	-0.103ns	-0.276**	-			
HSW	0.161*	0.382**	0.302**	0.135ns	-0.168*	-		
SY	-0.276**	-0.249**	0.230**	-0.162ns	0.210**	-0.051ns	-	
GY	-0.362**	-0.473**	0.124ns	-0.117ns	0.264**	-0.079ns	0.726**	-

DTF=Days to 50% heading, DTM= Days to 90% physiological maturity, Plh= Plant height, NPPP= Number of pods per plant, NSPP= Number of seeds per pod, HSW= Hundred seeds weight, SY=Straw yield, GY= Grain yield

As presented in Table 11, only the number of seeds per pod and straw yield were significantly ($p \leq 0.05$) and positively correlated with grain yield, reflecting the importance of the number of seeds per pod and straw yield in determining grain yield in the study area. Similarly, plant height showed a positive but non-significant correlation with grain yield. On the other hand, a negative and significant ($p \leq 0.05$) correlation was observed between grain yield and each of the days to flowering and days to 90% physiological maturity, while the number of pods per plant and hundred seed weight showed a negative non-significant correlation with grain yield. In line with these results, Tadesse *et al*. [45] reported the presence of a positive and significant correlation between grain yield and the number of seeds per pod at Sinana, southern Ethiopia.

In general, the highest fertilizer rate of 69 kg P_2O_5/ha together with 10 cm intra-row-and 40 cm inter-row spacing (equivalent to 25 plants per square meter) was found to be optimum for the study area. In line with this result, an inter-and intra-row spacing of 40 cm x 10 cm was found optimum for row planting of faba beans in southern Ethiopia against the national blanket recommendation of 40 cm x 5 cm Ayele *et al*. [46]. Similarly, from fertilizer experiment conducted on faba beans, Tsige *et al*. [44] suggested the use of 92 kg P_2O_5/ha in combination with 23 kg N/ha and 60 kg K_2O/ha in the acidic soils of the Wolaita Zone, southern Ethiopia.

CONCLUSIONS

According to the ANOVA results of this study, the majority of interactions had little impact on grain yield. However, it showed a significant response ($P \leq 0.05$) to each of the treatment factors main effects (phosphorus fertilizer, intra-row spacing and inter-row spacing). Both the main effects and the interaction effects had a significant impact on the majority of the other assessed characters. As per the findings of the ANOVA and economic analysis, the highest fertilizer rate of 69 kg P_2O_5/ha, along with 10 cm intra-row spacing and 40 cm inter-row spacing, were discovered to be ideal for faba bean production in West Shewa nitisols and related agro-ecologies. Additionally, as the highest and most feasible grain yield was obtained from the highest P_2O_5 fertilizer level, additional research should take higher fertilizer rates than 69 kg P_2O_5/ha into consideration.

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