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Original Research Article

Influence of Environment by Spacing and Phosphorus Fertilizer Interaction on the Productivity of Faba Bean (*Vicia faba* L.) in the Major Nitisol Production Areas in Ethiopia

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Abstract: Though Faba bean is an important pulse crop grown in the highlands of Ethiopia, its productivity is far below its potential due to several constraints, such as optimum plant density and fertilizer rates meant for major faba bean growing areas. Hence, a field experiment was conducted to determine the appropriate seeding and fertilizer rates for faba bean production at Holeta, Jima, Kulumsa, and Sinana areas during the 2019 to 2021 main cropping seasons. Factorial combinations of phosphorus 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 laid out in a randomized complete block design with three replications. Due to the non-homogeneity of variances across locations, a separate combined ANOVA was done for Kulumsa and Jimma that were found homogeneous. Similarly, a separate combined ANOVA over years was done for Holeta. On the other hand, Sinana's two-year data lacked homogeneity across years and with either of the other testing sites. Hence, results of each year presented. Based on the ANOVA results, the lowest fertilizer rates of 23 kg P_2O_5/ha together with 10 cm intra-row spacing and 40 cm inter-row spacing, were found to be optimum for the study areas around Kulumsa and Jimma while, the highest fertilizer rate of 69 kg P_2O_5/ha together with 10 cm intra-row spacing and 40 cm inter-row spacing, were found to be economically optimal for faba bean production in West Shewa acidic nitisols. On the other hand, to get reliable results, the experiment should be repeated at least once in one growing season at Sinan testing sites.

Keywords: Holeta, Intra-row, Inter-row, Jimma, Kulumsa, Phosphorus, Seed rate, Sinana.

INTRODUCTION

Faba bean (*Vicia faba* L.) is one of the major pulse crops grown in the highlands (1800–3000 m asl) of Ethiopia, where the need for a chilling temperature is satisfied (Abebe and Tolera, 2014). It is grown largely by subsistence farmers during the cool season (Yirga *et al.*, 2012). Faba bean takes the largest share (30.12%) of the area under pulse production (CSA, 2021). 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 (Negasa *et al.*, 2019). Also, it is noted that among the major cool-season grain legumes, faba bean has the highest average reliance on N_2 fixation for growth (Adak and Kibritci, 2016). 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 (Negasa *et al.*, 2019). However, the production and productivity of faba bean is constrained by several biotic and abiotic stresses. Among which, optimum plant density and lack of an optimal fertilizer recommendation are two of the most important cultural practices determining grain yield, as well as other important agronomic attributes of the crop (Sangoi, 2000). It is also to be noted that plant population or 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 (Smitchger and Weeden, 2018). When the environment becomes favorable, the optimum population will

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increase (Olle, 2018), and as the level of available soil nutrients increases, the need for fertilizer decreases (Itelima *et al*., 2018).

When legume plants are supplied with phosphorus at optimal rates, vigorous plant growth as well as increased assimilate formation and translocation to plant fruiting parts result in improved development of seed yield and its components (Ibrahim, 2009). Studies indicate that the response of faba bean to phosphorus fertilizer application is dependent on the residual P fertility level of the soil (Agegnehu, 2018). Accordingly, application of diammonium phosphate to faba beans resulted in either a lack of response or negative effects (Ghizaw, 1999) or a significantly positive response to the applied P fertilizer (Dobocha and Bekele, 2021; Tamrat, 2021)**.** For example, Tsigie and Woldeab (1995) reported the absence of a response to phosphorous fertilizer at Holetta, while Ghizaw *et al*., (1999) 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 (Agegnehu *et al*., 2006; Alemayehu and Shumi, 2018; Getu *et al.*, 2020).

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 (López-Bellido *et al*., 2005). Both high and low crop densities reduce yield and total revenue (Dobocha and Bekele, 2021). It has been reported that among a variety of improved production technologies, proper plant population management with appropriate adjustment of inter- and intra-row spacing plays a key role in enhancing faba bean production (Gezahegn *et al*., 2016). 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 (Tamrat, 2021). Furthermore, a few research findings on intra- 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 localities depending on different environmental conditions (Tamrat, 2021).

However, most of the above recommendations didn't consider the combined effect of spacing and fertilizer application. In addition, no recommendations have been made so far considering specific soil and environmental conditions, such as acid-prone areas. Hence, this experiment was conducted to determine optimum spacing in combination with an optimum phosphorus application rate for major faba bean growing areas.

MATERIALS AND METHODS

Area description

The field experiment was conducted at Holeta, Jima, Kulumsa, and Sinana research centers in the period from 2019 to 2021 under rain-fed conditions during the main cropping season. At Holeta, it was conducted for two consecutive years from 2020 to 2021; at Jimma, it was conducted for three consecutive years from 2019 to 2021; at Kulumsa, it was conducted for one year in 2019; and at Sinana, it was conducted for two consecutive years from 2019 to 2020.

Holeta is 30 kilometers west of Addis Abeba, at an elevation of about 2400 meters above sea level, between latitude 09°03′ N and longitude 38°30′ E. The long-term average annual rainfall is 1100 mm, about 85% of which is received from June to September, with the remainder from January to May. The long-term average minimum and maximum air temperatures are 6.2°C and 22.1°C, respectively. The Jimma testing site (Dedo) is located at a distance of about 373 km from Addis Ababa in the south-western direction, at 7^{0}29'93" northern latitude and 36°51'47" eastern longitude, at an elevation of 2325 meters above sea level. Kulumsa Agricultural Research Center (KARC) is located in Oromia National Regional State, Arsi Administrative Zone. It is approximately 170 kilometers south-east of Addis Abeba. Its geographical extent is between 08^{0}01'10'' northern latitude and 39^{0}09'11'' eastern longitude, at an elevation of about 2200 m above sea level. The long-term average annual rainfall is 820 mm. The mean annual maximum temperature is 22.8 ^{0}C, whereas the mean annual minimum temperature is 10.5 ^{0}C. The soil of the area is dominated by clay soils (*Luvisols*) with a pH of 6.0. The Sinana testing site is located in Oromia National Regional State, West Bale Administrative Zone, at a distance of about 463 km from Addis Ababa in the south-eastern direction, at 7^{0}7'N latitude and 40^{0}10'E longitude, at an elevation of 2400 meters above sea level, and the soil of the area is dominated by *pellic-vertisols* and slightly acidic.

Treatments and experimental design

Similar experimental designs and treatment combinations were used at all locations. Accordingly, the treatments included factorial combinations of phosphorus fertilizer in the form of P_2O_5 (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) laid out in a randomized complete block design with three replications. A starter amount of nitrogen (N) fertilizer at the rate of 19 kg N/ha was applied uniformly to all treatments or plots. From 100 kg of NPS fertilizer, 38 kg of P_2O_5/ha and 19 kg of N/ha were obtained, and the remaining amounts of 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) were added from TSP. Similarly, the remaining amount of N for the first level (7.5 kg N/ha) was added from urea. All the fertilizer was applied at the time of planting. The gross plot size of 4.0 m x 2.4 m (9.6 m^2) was used for all treatments, while the net plot size was made by excluding one outer row from each side. Thus, the net plot size for the respective inter-row spacings of 30, 40, and 50 cm 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), respectively. The number of rows per plot for the 30, 40, and 50 cm inter-row spacing was 8, 6, and 5 rows, respectively, and the number of plants per row for the 7, 10, and 13 cm intra-row spacing was 57, 40, and 31 germinated plants, respectively. The faba bean variety "*Gora*" was used for this experiment. The germination percentage and seed weight were determined before planting to convert into a seed rate. The seed rate was calculated using the equation stated by Matthews (2005) as follows:

$$\text{Seed rate (kg/ha)} = \frac{\text{Target plant density (m}^{-2}\text{) X 100 seed weight (g) X 10}}{\text{Germination percentage (\%) X Establishment percentage (decimal)}}$$

Consequently, to convert plant density into a seed rate, 100 seeds (for our purpose, 93.8 g), germination rates (95%), and 10% field loss (0.90 establishment rate) were used as estimation inputs. Hand weeding was undertaken two times.

Soil characterization

A one-kg composite soil sample was collected from the whole plot (from five spots) in a zigzag fashion to a depth of 0–30 cm just before sowing for the purposes of determining soil pH, organic carbon, total nitrogen, available phosphorus, and CEC. Soil pH was tested using the potentiometric method described by Murphy (1968), organic carbon was determined using the Walkley and Black method described by Tekalign (1991), total N was determined by the modified Kjeldahl method described by Tekalign (1991), available P was determined in some sites using the Olsen method described by Cottenie (1980) and in some sites using the Bray II method described by Bray and Kurz (1945), and CEC was determined by the flame photometer described by Hazelton and Murphy (2007).

Weather conditions during the crop growth period

As depicted in Figure 1, higher rainfall was recorded at Holeta from July to September than other sites. At Jimma, there was a fair distribution throughout the growth period, followed by Sinana. Overall, the lowest amount of rainfall was recorded at Kulumsa throughout the growth period compared to other sites. In general, there was rainfall at all sites throughout the growth period, except December at Kulumsa.

The mean maximum temperature at Jimma showed a more consistent increasing trend from July to December than the other sites, where it showed an unpredictable pattern but was higher than Jimma in most months (Fig 2). Higher temperatures were recorded at Holeta in the months of October to December than other sites.

The mean minimum temperature showed huge variation between Holeta and the other sites (Jimma and Kulumsa) (Fig 2). It showed similar patterns for Kulumsa and Jimma, except for October. The records in all months were higher than 11^{0}C for Kulumsa and Jimma, while they were lower than 10^{0}C at Holeta in all months. Variation both in rainfall and temperature between Holeta and other sites might be an indication of the necessity of separate recommendations. Temperature data is not available for the Sinana site.

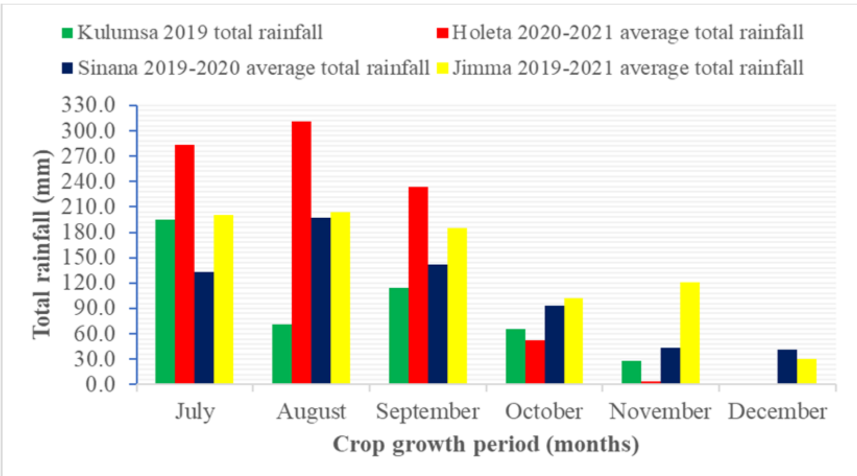

Figure 1: Total rainfall (mm) for the growth period of faba bean at Kulumsa, Holeta, Jimma and Sinana
Source: Unpublished data from each research centre

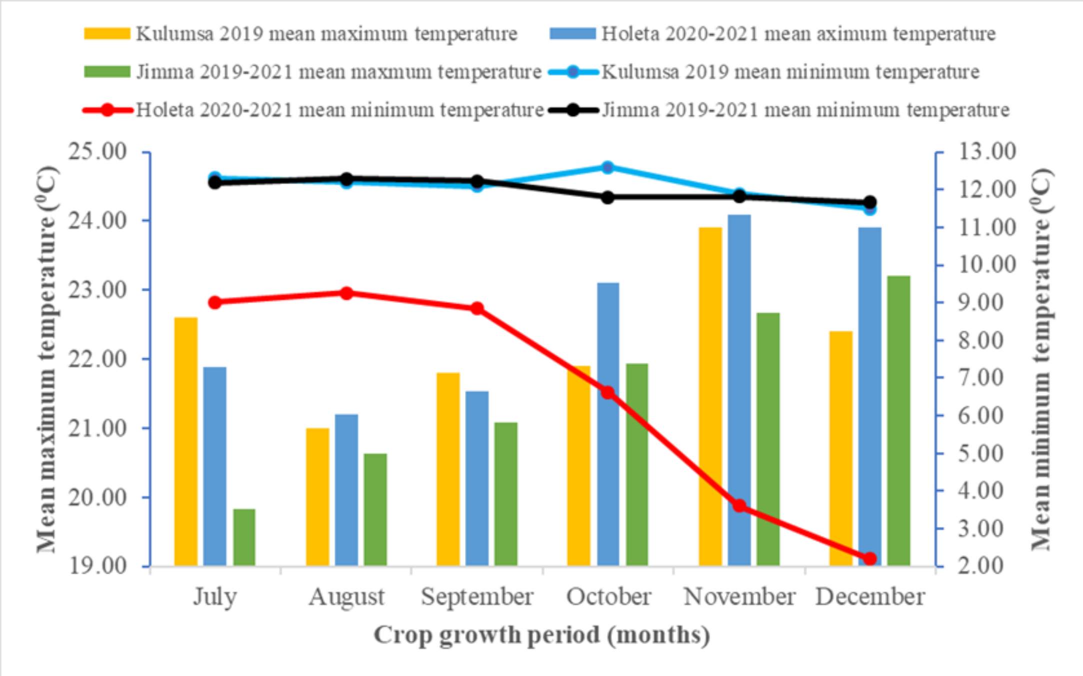

Figure 2: Mean maximum and minimum temperature (^{0}C) for the growth period of faba beans at Kulumsa, Holeta and Jimma

Source: Unpublished data from each research centre

Crop data collection and statistical analysis

The number of pods per plant was measured from 10 randomly selected plants in the central rows of each plot, while grain yield was measured from the central rows of each plot. The collected data was subjected to analysis of variance (ANOVA) using the General Analysis of Variance Procedure of GenStat for Windows Version 16 (VSN, 2013) in accordance with the statistical procedure stated by Gomez and Gomez (1984) for three-factor factorial experiments. The combined analysis of different locations' data was performed after obtaining variance homogeneity, which was tested by employing Bartlett's test (Gomez and Gomez, 1984). The mean comparison was performed using the Least Significant Difference (LSD) at a 5% level of significance upon obtaining significant F-values for the factors and interactions (Gomez and Gomez, 1984).

According to Bartlett's test for homogeneity of variance, only the three-year data from Jimma (2019, 2020, and 2021) and the one-year data (2019) from Kulumsa were found to be homogeneous. Hence, a combined analysis was performed for both localities by considering each year or site as an environment. Accordingly, for the purpose of data analysis and interpretation, environment one is denoted by the Kulumsa site in 2019, environment two is denoted by the Jimma site in 2019, environment three is denoted by the Jimma site in 2020, and environment four is denoted by the Jimma site in 2021. Similarly, the two-year data for Holeta was found to be homogeneous, and a separate combined analysis was performed. On the other hand, at Sinana, the variance from the two years (2019 and 2020) was not homogeneous with any of the other sites either and could not be combined even at similar testing sites. Hence, separate results are reported for each year.

Results and Discussion

Soil Physico-Chemical Properties of the Experimental Sites

The soil pH of the experimental fields was found to be 4.66, 5.90, 5.75, and 6.83 at the Jimma, Kulumsa, Holeta, and Sinana testing sites, respectively (Table 1). As rated by Murphy (1968), the soil at Jimma lies in the very strongly acidic soil class, while the soils at Kulumsa and Holeta are classified under the moderately acidic soil class, and at Sinana are classified under the neutral soil class. According to Rajan *et al*., (2012), soils with a pH range of 6.5–8.0 are suitable for faba bean production. As a result, the current findings indicate the need for lime application in the Jimma, Kulumsa, and Holeta areas for faba bean production.

The analysis of the soil organic carbon of the experimental fields amounted to 2.16% at Jimma, 2.87% at Kulumsa, and 1.25% at Holeta, while it was not determined at Sinana (Table 1). Tekalign (1991) classified soils having an organic carbon content of < 0.50% as very low, 0.5-1.5% as low, 1.5-3.0% as medium/moderate, and > 3.0% as high. Accordingly, the organic carbon contents of the experimental soils were found to be medium at Jimma and Kulumsa while low at Holeta, indicating the low potential of a soil to supply nitrogen to plants as it can be used as an index of nitrogen availability.

The total N percent in the experimental fields was 0.20, 0.18, 0.135, and 0.18% at Jimma, Kulumsa, Holeta, and Sinana, respectively (Table 1). According to Tekalign (1991), the total nitrogen content of all the experimental soils lies in the moderate range. The available phosphorous of the experimental soil was 4.50 ppm at Jimma, 10.84 ppm at Kulumsa, 14.79 ppm at Holeta, and 10.12 ppm at Sinana (Table 1). The Bray II method was used at the Jimma and Kulumsa sites, and the available soil phosphorus at Jimma lies in a very low range, while that at Kulumsa lies in a low range (Bray and Kurz, 1945). The soil available P at Holeta and Sinana, on the other hand, was determined using the Olsen method as described by Cottenie (1980) and is in the moderate range at both testing sites. Based on these classifications, the available P of the experimental sites was found to be below the P requirement of faba bean (over 20 ppm) (Agegnehu and Tsige, 2006).

Table 1: Pre-planting soil analysis results of the study sites

Parameter	Value				Rating/soil reaction class			
	Jimma	**Kulumsa**	**Holeta**	**Sinana**	**Jimma**	**Kulumsa**	**Holeta**	**Sinana**
pH (1:2.5 H_2O)	4.66	5.90	5.75	6.83	Very strongly acidic	Moderately acidic	Moderately acidic	Neutral
Organic carbon (%)	2.16	2.87	1.25	nd	Medium	Medium	Low	nd
Total nitrogen (%)	0.20	0.18	0.135	0.18	Moderate	Moderate	Moderate	Moderate
Available phosphorus (ppm)	4.50 (Bray II)	10.84 (Bray II)	14.79 (Olsen)	10.12 (Olsen)	Very low	Low	Medium	Medium

nd=not determined

ANOVA procedures

As described in the methodology section, only the three-year data from Jimma (2019, 2020, and 2021) and the one-year data (2019) from Kulumsa were found to be homogeneous, and a combined analysis was performed by considering each year and/or site as an environment. Accordingly, environment one is denoted by the Kulumsa site in 2019, environment two is denoted by the Jimma site in 2019, environment three is denoted by the Jimma site in 2020, and environment four is denoted by the Jimma site in 2021. Similarly, the two-year data for Holeta was found to be homogeneous, and a separate combined analysis was performed. On the other hand, at Sinana, the variance from the two years (2019 and 2020) was not homogeneous with any of the other sites either and could not be combined even at similar testing sites. Hence, separate results are reported for each year. In general, the variation among environments is probably related to the variation in climatic factors such as temperature and precipitation (Yucel, 2013).

1. Combined analysis of Jimma and Kulumsa sites

The number of pods per plant was significantly ($p<0.05$) affected by the main effects of the environment, P_2O_5 fertilizer, and inter-row spacing, as well as by the two-way interaction of the P_2O_5 fertilizer with intra-row spacing (Table 2). A higher number of pods per plant (10.6) was recorded at Jimma in 2021, which was statistically at par with Jimma 2019 (10.3), while the number of pods per plant at Kulumsa 2019 (8.9) was statistically at par with Jimma 2020 (8.5). The number of pods per plant increased linearly from 9.2 to 9.9 as P_2O_5 fertilizer increased from 23 to 69 kg/ha (Table 2). In line with this result, Ghizaw *et al.*, (1999) described a linear increase in the number of pods per plant as P_2O_5 fertilizer increased from 0 to 92 kg/ha at different locations, while Agegnehu & Tsige (2006) reported a linear increase in the number of pods per plant as P_2O_5 fertilizer increased from 0 to 120 kg/ha in acid-prone areas. On the other hand, Negasa *et al.*, (2019) stated a non-significant difference in the number of pods per plant while increasing the P rate from 0 kg/ha to 40 kg/ha. The number of pods per plant significantly and linearly increased from 9.2 to 9.8 as inter-row spacing increased from 30 to 50 cm (Table 2), probably due to less competition for resources at wider spacing. In agreement with this result, Bakry *et al.*, (2011) described a linear increase in the number of pods per plant as inter-row spacing increased from 20 to 60 cm, justifying that there was less competition for resources as row spacing increased. From the two-way results, the highest number of pods per plant (10.2) was obtained at the combination of 69 kg P_2O_5/ha with 13 cm intra-row spacing, which is statistically at par with the combination of 46 kg P_2O_5/ha with 10 cm intra-row spacing (Table 3), probably related to a reduction in the number of branches per plant at higher plant densities or narrower spacing. In line with this result, Mondal *et al.*, (2014) 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 have the capacity to produce more photoassimilates and total dry matter, resulting in a higher number of pods per plant.

Table 2: Main effects of environment, phosphorus, intra- and inter-row spacing on number of pods per plant, number of seeds per pod and grain yield of faba bean combined over environments (during 2019 at Kulumsa and during 2019-2021 at Jimma)

Factors	NPPP	NSPP	GY (t/ha)
Environment			
Kulumsa 2019	8.9[b]	2.8	6.04[a]
Jimma 2019	10.3[a]	2.8	4.68[c]
Jimma 2020	8.5[b]	2.7	5.11[b]
Jimma 2021	10.6[a]	2.8	3.60[d]
P_2O_5 (kg/ha)			
23	9.2b	2.7	4.7
46	9.6ab	2.8	4.9
69	9.9a	2.8	4.9
Intra-row spacing (cm)			
7	9.4	2.8	5.04[a]
10	9.6	2.7	4.88[a]
13	9.7	2.8	4.63[b]
Inter-row spacing (cm)			
30	9.2[b]	2.7	4.42[b]
40	9.7[a]	2.7	5.08[a]
50	9.8[a]	2.8	5.05[a]
Mean	9.6	2.8	4.85
CV (%)	18.78	7.61	16.09
P_2O_5*Intra-row spacing	*	ns	**
P_2O_5*Inter-row spacing	ns	ns	*

**, * = significant at 1% and 5% level of significance respectively, ns = not significant, na = not applicable, CV=coefficient of variation, NPPP= Number of pods per plant, NSPP= Number of seeds per pod, GY= Grain yield

Table 3: Two-way interaction effects of phosphorus with intra-row spacing on the number of pods per plant and grain yield of faba bean combined over four environments (during 2019 at Kulumsa and during 2019-2021 at Jimma)

P_2O_5 (kg/ha)	Number of pods per plant			Grain yield (t/ha)		
	Intra-row spacing (cm)					
	7	10	13	7	10	13
23	8.8[d]	8.9[cd]	9.9[ab]	4.99[ab]	4.67[bc]	4.59[bc]
46	9.6[a-d]	10.1[a]	9.1[bcd]	4.98[ab]	5.28[a]	4.37[c]
69	9.9[ab]	9.8[abc]	10.2[a]	5.15[a]	4.68[bc]	4.93[ab]

The number of seeds per pod was not significantly affected by any of the main effects or by any of their interactions, as it is mainly affected by genotypic effects rather than environmental ones (Lopez-Bellido *et al.*, 2005).

Grain yield was significantly ($p<0.05$) affected by the main effects of the environment, intra-row spacing, and inter-row spacing, as well as by the two-way interaction of the P2O5 fertilizer with intra-row spacing and inter-row spacing (Table 2). The highest grain yield (6.04 t/ha) was recorded at Kulumsa in 2019, probably due to better soil conditions at Kulumsa than at Jimma testing sites (Table 1). Grain yield decreased linearly by 8.85% with increasing intra-row spacing from 7 to 13 cm, though statistically no significant difference was observed between intra-row spacings of 7 cm and 10 cm (Table 2). On the other hand, the highest grain yield (5.08 t/ha) was obtained at an inter-row spacing of 40 cm, though statistically at par with the inter-row spacing of 50 cm (Table 2). Since there was no interaction between intra-row spacing and inter-row spacing, economic analysis could not be performed. As a result, in addition to higher grain yields, selecting the feasible spacing using ANOVA results is critical. From the results, while narrower intra-row spacing produced a higher yield, the seed rate required for narrower spacing is higher than for wider spacing. 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 50 cm, was found to be optimum for faba bean production around Kulumsa and Jimma areas and similar agro-ecologies. Though the main effect of phosphorus had no significant effect on grain yield, its interaction with intra-row and inter-row spacing showed a significant effect on grain yield (Tables 3 and 4). Accordingly, the highest grain yields (5.28 t/ha and 5.26 t/ha) were obtained at the combination of 46 kg P_2O_5/ha with 10 cm intra-row spacing (Table 3) and 46 kg P_2O_5/ha with 50 cm inter-row spacing (Table 4), which are statistically at par with a combination of 23 kg P_2O_5/ha with 40 cm inter-row spacing (Table 4), probably related to a reduction in the number of branches per plant at higher plant density or narrower spacing (Table 4). In line with this result, Ibrahim (2009) reported the presence of interaction between plant spacing and fertilizer application in faba bean.

In general, the lowest fertilizer rate of 23 kg P_2O_5/ha and N at a rate of 19 kg/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 areas. 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, compared with the national blanket recommendation of 40 cm x 5 cm (Ayele *et al.*, 2015). In contrast to the present result at Kulumsa and Jimma, Tsige *et al.*, (2022) 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.

Table 4: Two-way interaction effects of phosphorus with inter-row spacing on the grain yield of faba bean combined over four environments (during 2019 at Kulumsa and during 2019-2021 at Jimma)

P_2O_5 (kg/ha)	Inter-row spacing (cm)		
	30	40	50
23	4.21[e]	5.25[a]	4.80[bcd]
46	4.41[de]	4.96abc	5.26[a]
69	4.64[cd]	5.03[abc]	5.09[ab]

2. Holeta combined over years (As summarized from Mebrate *et al*., 2023)

From the combined analysis of variance over years (2020 and 2021), 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 with inter-row spacing and intra-row spacing with inter-row spacing showed a significant ($p \leq 0.05$) effect on the number of pods per plant (Table 5). A higher number of pods per plant (9.4) were recorded in the second year, which is probably related to the rainfall and temperature effects (the two-year separate weather data is not shown). Though the two-year separate weather data is not shown, 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 (2013), this trait is greatly influenced by environmental factors such as temperature and precipitation. The number of pods per plant increased linearly from 7.5 to 8.8 as P_2O_5 fertilizer increased from 23 kg/ha to 69 kg/ha (Table 5). In line with this result, Ghizaw *et al.*, (1999) described a linear increase in the number of pods per plant as P_2O_5 fertilizer increased from 0 to 92 kg/ha at different locations, while Agegnehu & Tsige (2006) reported a linear increase in the number of pods per plant as P_2O_5 fertilizer increased from 0 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, 2018). On the other hand, Negasa *et al.*, (2019) stated a non-significant difference in the number of pods per plant while increasing the P rate from 0 to 40 kg/ha.

Regarding spacing, 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 to 13 cm and 30 to 50 cm (Table 5), probably due to less competition for resources in wider spacing. In agreement with this result, Mekkei (2014) reported a linear increase in the number of pods per plant as intra-row spacing increased from 10 to 25 cm, while Bakry *et al.*, (2011) described a linear increase in the number of pods per plant as inter-row spacing increased from 20 to 60 cm, justifying that there was 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 or narrower spacing. In line with this result, Mondal *et al*., (2014) 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 have the capacity to produce more photo assimilates and total dry matter and resulting in a higher number of pods per plant.

Table 5: Main effect of phosphorus, intra- and inter-row spacing on number of pods per plant, number of seeds per pod and grain yield of faba bean at Holeta over years (2020-2021)

Factors	NPPP	NSPP	GY (t/ha)
Year			
2020	7.3b	2.7a	1.45a
2021	9.4a	2.4b	1.09b

Factors	NPPP	NSPP	GY (t/ha)
P_2O_5 (kg/ha)			
23	7.5^{b}	2.5	1.13^{b}
46	8.7^{a}	2.5	1.32^{a}
69	8.8^{a}	2.6	1.37^{a}
Intra-row spacing (cm)			
7	7.8^{b}	2.6	1.38^{a}
10	8.3^{ab}	2.5	1.29^{a}
13	8.8^{a}	2.5	1.15^{b}
Inter-row spacing (cm)			
30	7.7^{b}	2.6	1.32^{a}
40	8.2^{b}	2.5	1.30^{a}
50	9.1^{a}	2.5	1.20^{b}
Mean	8.3	2.5	1.27
CV (%)	17.96	10.5	18.84
P_2O_5*Intra-row spacing	ns	**	ns
P_2O_5*Inter-row spacing	**	ns	ns
Intra-row*Inter-row spacing	*	ns	ns

**, * = significant at 1% and 5% level of significance, respectively, ns = not significant, na = not applicable, CV=coefficient of variation, LSD=Least significant difference, NPPP= Number of pods per plant, NSPP= Number of seeds per pod, GY= Grain yield

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

P2O5 (kg/ha)	Inter-row spacing (cm)		
	30	**40**	**50**
23	7.4^{de}	7.5^{de}	7.8^{cde}
46	7.1^{e}	8.8^{bc}	10.1^{a}
69	8.7^{bc}	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, combined over years (2020-2021)

Intra-row spacing (cm)	Inter-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}

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 with intra-row spacing (Table 5). 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 5), which might have contributed to the highest grain yield in the first year. The positive correlation between it and grain yield may describe this fact (Table 10). Though the total rainfall in the first year was lower than in the second year (separate data is not shown), its distribution throughout the growing period (July to December) may have helped to produce longer pods that may accommodate many more seeds than in the second year. In agreement with this result, Al-Rifaee *et al.*, (2004) 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 (2009) stated the presence of a significant interaction between plant spacing and phosphorus rates on the number of seeds per plant of faba bean.

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

P_2O_5 (kg/ha)	Intra-row spacing (cm)		
	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}

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 5). 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 (separate weather data is not shown). 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*., (2005). The same authors find that yield shows a greater response to yearly environmental conditions such as rainfall and maximum daily temperatures. Grain yield increased linearly by 21.24% as P_2O_5 fertilizer increased from 23 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 1). Agegnehu & Tsige (2006) reported a linear increase in grain yield as P fertilizer increased from 0 to 52 kg/ha in acid prone areas of the central highland nitisols of Ethiopia. Similarly, Ghizaw *et al*., (1999) reported a significant and linear increase in grain yield as P_2O_5 fertilizer increased from 0 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 optimal in the Bore highlands of southern Ethiopia (Alemayehu and Shumi, 2018). 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 for 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 with a net benefit of 53,139.00 and an MRR of 158.95% (Table 9). 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 at the highest level of this experiment. Tsige *et al*., (2022) obtained a 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 (2006) 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 the acidic nitisols of the central highlands of Ethiopia.

Concerning spacing, grain yield decreased linearly by 20% and 10% with increasing intra-row spacing from 7 to 13 cm and inter-row spacing from 30 to 50 cm, respectively (Table 5). 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. As a result, selecting the feasible spacing using ANOVA results is critical in addition to higher grain yields. Accordingly, though higher yields were obtained from narrower spacing, the seed rates required for narrower spacing are higher than those of wider spacing. Hence, narrower spacing 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, were found to be optimum for faba bean production on acidic nitisols in the West Shewa central highlands of Ethiopia.

As presented in Table 10, the number of seeds per pod was significantly ($p \leq 0.05$) and positively correlated with grain yield, reflecting the importance of the number of seeds per pod in determining grain yield in the study area (Holeta). On the other hand, the number of pods per plant showed a negative, non-significant correlation with grain yield. In line with these results, Tadesse *et al*., (2011) reported the presence of a positive and significant correlation between grain yield and the number of seeds per pod at Sinana in southern Ethiopia.

In general, the highest fertilizer rates of 69 kg P_2O_5/ha and N at a rate of 19 kg/ha, together with 10 cm intra-row-and 40 cm inter-row spacing (equivalent to 25 plants per square meter), were 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, compared with the national blanket recommendation of 40 cm x 5 cm (Ayele *et al*., 2015). Similarly, from fertilizer experiments conducted on faba beans, Tsige *et al*., (2022) 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.

Table 9: Dominance and marginal rate of return analysis for the effect of population density and phosphorus 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)	NB (Birr/ha)	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: Correlation coefficients between grain yield and number of pods per plant and number of seeds per pod of faba bean at Holeta

Character	Grain yield
Number of pods per plant	-0.117ns
Number of seeds per pod	0.264**

3. Sinana 2019 and 2020

According to individual ANOVA results for each year, the number of pods per plant was not significantly affected by any of the main effects in either year (2019 or 2020) (Table 11). However, it was significantly affected by the two-way interaction of P_2O_5 fertilizer with inter-row spacing in both years (2019 and 2020) and by the two-way interaction of intra-row spacing with inter-row spacing in 2020 (Table 11). From the two-way results, in 2019, the highest (17.8) number of pods per plant was recorded while combining P_2O_5 fertilizer at the rate of 23 kg/ha with 50 cm inter-row spacing (Table 12), while in 2020, the highest (15.3) number of pods per plant was recorded when combining P_2O_5 fertilizer at the rate of 23 kg/ha with 30 cm inter-row spacing (Table 12). The results were inconsistent from year to year, though theoretically, the number of pods per plant increases with increasing spacing due to a reduction in the number of branches per plant at higher plant densities/narrower spacing (Mondal *et al.*, 2014).

Table 11: Main effects of phosphorus, intra- and inter-row spacing on number of pods per plant and grain yield of faba bean at Sinana in 2019 and 2020

Factors	NPPP		GY (t/ha)	
	2019	2020	2019	2020
P_2O_5 (kg/ha)				
23	14.9	13.3	2.84	3.29
46	15.0	12.9	2.73	3.57
69	13.7	13.7	2.70	3.54
Intra-row spacing (cm)				
7	14.0	12.9	2.73	3.79[a]
10	14.6	14.3	2.70	3.59[a]
13	15.1	12.7	2.84	3.01[b]
Inter-row spacing (cm)				
30	13.4	13.8	2.88	3.58
40	14.6	13.2	2.76	3.45
50	15.6	12.9	2.63	3.36
Mean	14.5	13.3	2.76	3.46
CV (%)	23.32	19.94	15.13	13.39
P_2O_5*Intra-row spacing	ns	ns	ns	**
P_2O_5*Inter-row spacing	**	*	ns	ns
Intra-row*Inter-row spacing	ns	*	ns	**

**, * = significant at 1% and 5% level of significance respectively, ns = not significant, na = not applicable, CV=coefficient of variation, LSD=Least significant difference, NPPP= Number of pods per plant, NSPP= Number of seeds per pod, GY= Grain yield

Table 12: Two-way interaction effects of phosphorus with inter-row spacing on the number of pods per plant of faba bean at Sinana in 2019 and 2020

P2O5 (kg/ha)	**2019**			**2020**		
	Inter-row spacing (cm)			**Inter-row spacing (cm)**		
	30	**40**	**50**	**30**	**40**	**50**
23	14.3[abc]	12.4[bc]	17.8[a]	15.3[a]	11.3[b]	13.2[ab]
46	14.1[bc]	15.8[ab]	15.1[abc]	13.4[ab]	13.2[ab]	12.0[b]
69	11.9[c]	15.4[abc]	13.9[bc]	12.7[ab]	15.0[a]	13.6[ab]

Concerning grain yield, in 2019, none of the main effects and their interactions showed any significant effect on grain yield (Table 11). On the other hand, in 2020, the main effect of intra-row spacing, the two-way interaction of the P2O5 fertilizer with intra-row spacing, and the two-way interaction of intra-row spacing with inter-row spacing showed a significant ($p \leq 0.05\%$) effect on grain yield (Table 11). Accordingly, grain yield significantly and linearly decreased by 25.91% with increasing intra-row spacing from 7 cm to 13 cm, though statistically no significant difference was observed between intra-row spacing of 7 cm and 10 cm (Table 11). The highest grain yields (4.06 t/ha and 4.11 t/ha) were obtained at the combination of 69 kg P2O5/ha with 7 cm intra-row spacing (Table 13) and at the combination of 7 cm intra-row spacing with 30 cm inter-row spacing (Table 14), respectively.

In general, as indicated in table 11, the numerical values as well as the interactions were inconsistent across years. Hence, to get reliable results, the experiment should be repeated at least once in one growing season in that locality.

Table 13: Two-way interaction effects of phosphorus with intra-row spacing on the grain yield of faba bean at Sinana in the year 2020

P2O5 (kg/ha)	Intra-row spacing (cm)		
	7	10	13
23	3.43[b]	3.62[ab]	2.80[c]
46	3.88[ab]	3.39[b]	3.43[b]
69	4.06[a]	3.76[ab]	2.79[c]

Table 14: Two-way interaction effects of intra-row spacing with inter-row spacing on the number of pods per plant and grain yield of faba bean at Sinana in the year 2020

Intra-row spacing (cm)	Number of pods per plant			Grain yield (t/ha)		
	Inter-row spacing (cm)			Inter-row spacing (cm)		
	30	40	50	30	40	50
7	12.6[bc]	11.8[bc]	14.3[ab]	4.11[a]	3.78[ab]	3.48[bc]
10	15.8[a]	13.7[abc]	13.6[abc]	3.39[bcd]	3.76[ab]	3.63[bc]
13	13.1[abc]	14.1[ab]	10.9[c]	3.24[cde]	2.82[e]	2.96[de]

CONCLUSIONS

In this study, the environments were found to be heterogeneous enough to conduct a combined analysis and recommend similar fertilizer rates and spacing across all environments. As a result, Kulumsa and Jimma were determined to be homogeneous, and similar recommendations were made. At Holeta, the two-year data were found to be homogeneous, and a specific recommendation has been made. On the other hand, the two-year data from Sinana found no homogeneity over the years and none with either of the other testing sites. Accordingly, based on the ANOVA results, the lowest fertilizer rates of 23 kg P_2O_5/ha and N at the rate of 19 kg/ha, together with 10 cm intra-row and 40 cm inter-row spacing (equivalent to 25 plants per square meter), were found to be optimum for the study areas around Kulumsa and Jimma. Similarly, based on ANOVA and economic analysis results, the highest fertilizer rates of 69 kg P_2O_5/ha and 19 kg N/ha, along with 10 cm intra-row and 40 cm inter-row spacing, were found to be optimal for faba bean production in West Shewa acidic nitisols and similar agro-ecologies. In addition, further study needs to consider using higher fertilizer rates than 69 kg P_2O_5/ha, as the highest and most feasible grain yield was obtained from the highest P_2O_5 fertilizer level. On the other hand, the numerical values as well as the interactions were inconsistent across years at Sinana testing sites. Hence, to get reliable results, the experiment should be repeated at least once in one growing season in that locality.

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