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Original Article

Effect of Inter- and Intra-Row Spacing on Seed Multiplication Ratio and Seed Quality Attributes of Faba Bean (*Vicia faba* L.) in Midland and Highland Areas of Central Ethiopia

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Abstract

Faba bean (*Vicia faba* L.) is an important pulse crop cultivated for food, feed, and soil fertility improvement in Ethiopia. However, its productivity remains below potential due to suboptimal agronomic practices, particularly improper planting spacing for quality seed production. This study was conducted to evaluate the effects of inter- and intra-row spacing on seed multiplication ratio and seed quality attributes of faba bean under midland and highland agro-ecological conditions of Central Ethiopia. A factorial experiment consisting of five inter-row spacings (30, 35, 40, 45, and 50 cm) and four intra-row spacings (5, 10, 15, and 20 cm) was arranged in a randomized complete block design with three replications. Laboratory analysis was conducted using a completely randomized design with four replications. The results revealed significant ($P < 0.05$) effects of planting spacing on growth, yield, and seed quality parameters. The highest seed multiplication ratio (52.67 and 50.47) and pure seed yield (17.43 and 20.57 qt ha^{-1}) were recorded at spacing combinations of 45 cm × 10 cm and 35 cm × 10 cm in midland and highland areas, respectively. Seed quality parameters, including germination percentage, seed vigor index, and physical purity, were improved under wider spacing. Economic analysis indicated that the highest marginal rate of return was obtained at 45 cm × 20 cm in the midland and 35 × 15 cm in the highland areas. Therefore, spacings of 45 cm × 20 cm (midland) and 35 cm × 15 cm (highland) are recommended for optimal seed production and economic return. Further multi-season validation is suggested.

Categories: Food security and sustainability, Seed technology, Field & Horticultural crops sustainable production

Keywords: faba bean, plant spacing, seed multiplication ratio, seed quality, ethiopia

Introduction

Legumes play an important role in improving food security, household income, livestock feed supply, and soil fertility through biological nitrogen fixation in Sub-Saharan Africa [1,2]. Among grain legumes, faba bean (*Vicia faba* L.) is one of the major pulse crops cultivated worldwide for human consumption, animal feed, and as an inexpensive source of protein and essential amino acids [3,4]. In Ethiopia, faba bean is widely produced in the highland areas ranging from 1,800 to 3,000 m above sea level and serves as an important cash and food crop for smallholder farmers [5-7]. Ethiopia is the second largest producer of faba bean in the world after China [8]. Despite its economic and nutritional importance, the productivity of faba bean in Ethiopia remains low compared with its potential yield due to several biotic and abiotic constraints, including poor crop management practices, diseases, low-quality seed, and inappropriate planting density [9,10]. Chocolate spot disease caused by *Botrytis fabae* is among the major diseases reducing seed yield and quality by affecting photosynthetic efficiency and plant growth [11,12]. Seed quality is one of the most important factors

influencing crop productivity and seed multiplication efficiency. High-quality seed improves germination, seedling vigor, crop establishment, and final yield [13,14]. Good seed quality is determined by several parameters such as physical purity, germination percentage, seed vigor, moisture content, and pure live seed percentage [15,16]. Previous studies reported that quality seed alone can increase crop productivity by 15%-20% under suitable management conditions [17]. Plant spacing is a major agronomic practice that significantly affects plant growth, disease development, seed quality, and yield components in faba bean production. Appropriate inter- and intra-row spacing improves light interception, nutrient utilization, aeration, and moisture availability, thereby enhancing seed yield and quality [9,18]. Narrow spacing may increase competition among plants and disease incidence, whereas excessively wide spacing may reduce land-use efficiency and total yield [19]. Although several studies have focused on grain yield optimization of faba bean, limited information is available on appropriate planting spacing for quality seed production and seed multiplication under the midland and highland agro-ecologies of Central Ethiopia. Therefore, this study aimed to determine the effects of inter- and intra-row spacing on seed multiplication ratio, seed yield, and quality attributes of faba bean under midland and highland agro-ecologies of Central Ethiopia.

Materials And Methods

Study location and design

A field experiment was conducted during the 2022-2023 growing season at the Worabe Agricultural Research Sub-station (Mirab Azernet) and on farmer fields in the Meskan woreda. The experiment utilized a factorial combination of different spacing arrangements to assess their impact on faba bean cultivation.

Treatment Combinations

The experimental design included five inter-row spacings (30, 35, 40, 45, and 50 cm) and four intra-row spacings (5, 10, 15, and 20 cm). These combinations were arranged in a randomized complete block design with three replications for the field experiments. Additionally, a completely randomized design was employed in laboratory settings, with four replications to support the research.

Plot Configuration

Each plot in the field experiment measured 3.6 m × 3 m, totaling an area of 10.8 m^2.

Experimental Material

The varietal material utilized for this study was faba bean (*Vicia faba*) variety "Gebelcho," which was released by the Holeta Agricultural Research Center. This variety is known for its adaptability and yield potential within the target agro-ecological zones.

Data collection

Agronomic Measurements

Plant Height: The vertical length of the plant was measured from the base to the highest point for five randomly selected plants per plot.

Number of Effective Tillers: The count of productive tillers that successfully produced heads contributing to yield was recorded for each plant.

Seed Multiplication Ratio: The number of seeds produced relative to the amount of seed planted was calculated by averaging five plants per plot.

Number of Pure Seeds per Pod: The average count of healthy, well-developed seeds found in each pod, excluding abnormal seeds, was recorded based on five plants.

Yield Assessments

Total Gross Yield (qt/ha): The total amount of produce harvested from the designated area was analyzed without deductions.

Total Pure and Impure Seed Yield (qt/ha): The amounts of clean, healthy, usable seeds were determined after removing impurities and accounting for factors such as moisture content and 100-seed weight. A sample area of 10.8 m^2 from each plot was harvested and threshed, and yields were converted to qt/ha for statistical analysis.

Disease Incidence and Severity of Faba Bean Chocolate Spot

Chocolate spot disease incidence (%) was calculated as the percentage of infected plants, while disease severity (%) was assessed using a 0-9 rating scale based on the proportion of leaf area affected by *B. fabae*. The total number of plants infected by chocolate spot was counted, and the percentage disease incidence was calculated using the following formula:

$$DI\% = \frac{\text{Number of infected plants}}{\text{Total number of plants assessed}} \times 100$$

Severity scores were converted to percentage disease severity before statistical analysis, as described in Table *1*.

Score	Leaf area affected (%)	Disease reaction
1	0%	No visible symptoms (highly resistant)
2	1–5%	Very slight lesions
3	6–10%	Slight infection
4	11–20%	Mild infection
5	21–35%	Moderate infection
6	36–50%	Moderately severe infection
7	51–65%	Severe infection
8	66–80%	Very severe infection
9	>80%	Extremely severe infection or plant nearly dead

TABLE 1: Disease severity rating scale (1–9) for chocolate spot (*Botrytis fabae*) in faba bean based on the percentage of leaf area affected

Percentage Severity Index (PSI)

The disease severity ratings were converted to percentage severity using the following formula:

$$\text{PSI}(\%) = \frac{\text{Sum of disease ratings}}{\text{Number of plants assessed} \times \text{Maximum disease rating}} \times 100$$

Seed Quality Evaluation

Standard Seed Germination (SGEM): One hundred seeds from each treatment were germinated under controlled conditions (24°C) in sterilized sand. Germination was assessed by counting the appearance of the radicle over 12 days. The germination percentage was calculated as:

$$\mathrm{SGEM}(\%) = \frac{\text{Number of seeds germinated}}{\text{Total number of seeds planted}} \times 100$$

Seed Vigor Index (SVI): Seed vigor was assessed using the following formula:

$$\mathrm{SVI} = \text{Standard seed germination}(\%) \times \text{Seedling length (cm)}$$

where seedling length is the sum of shoot and root lengths.

Physical Purity (PHYP): A 200 g sample from each treatment was sorted into four components: pure seeds, other crops, inert matter, and weeds. PHYP was calculated as follows:

$$\mathrm{PHYP}(\%) = \frac{\text{Weight of pure seed (g)}}{\text{Total weight of sample (g)}} \times 100$$

Pure Live Seed (PLS): The percentage of viable seeds was determined using the following formula:

$$\mathrm{PLS}(\%) = \frac{\text{Purity}(\%) \times \text{Seed germination}(\%)}{100}$$

Statistical analysis

Data on crop parameters, disease incidence, severity, PSI, growth, seed yield, and quality parameters were analyzed using analysis of variance using SAS Institute (2002) software. Treatment means were compared using the least significant difference test at a 5% significance level.

Economic analysis

Partial budget analysis was conducted using adjusted yield and the prevailing market price of faba bean seed to determine economic feasibility following standard procedures [20]. The market price of faba bean seed (C1) was recorded at 11,550 Ethiopian birr (ETB) per quintal. Seed yield varied across treatments, while other input costs were assumed to remain constant for all treatments.

Results And Discussion

Effect of planting spacing on growth parameters of faba bean

Plant height was significantly ($P < 0.05$) influenced by planting spacing at both experimental locations (Tables *2*-*3*). The tallest plants were recorded under the narrowest spacing (30 cm × 5 cm), with mean values of 174.73 cm and 171.60 cm at the midland and highland areas, respectively. Greater plant height under narrow spacing may be attributed to increased competition for light, which enhances vertical elongation [21]. Plants grown under high density tend to be taller due to the shading effect. Narrow spacing enhances stem elongation due to reduced light penetration within the canopy [22,23]. However, this finding contrasts with some studies [24,25], where plant height decreased with increasing plant population, depending on the crop species and environmental conditions. The number of productive tillers per plant increased under wider spacing treatments. Wider spacing reduces inter-plant competition for nutrients, light, and moisture, thereby enhancing branching and tiller formation [12,20]. Higher tiller numbers were recorded at lower plant densities (Tables *2*-*3*).

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Effect of planting spacing on pure seed and yield components of faba bean

The number of pods per plant was significantly ($P < 0.05$) affected by planting spacing at both experimental locations (Tables *2*-*3*). The highest number of pods per plant (15.33 and 14.07) was recorded at 45 cm × 10 cm and 35 cm × 10 cm spacing in the midland and highland areas, respectively. Optimum spacing improved light interception and nutrient utilization, thereby enhancing pod formation [20]. Optimal plant density significantly improves yield components of faba bean [21,26]. Pod number decreases with increasing plant density [21,26]. Furthermore, lower plant density results in a higher number of pods per plant [27]. Increased pod formation under wider spacing has been associated with more favorable plant growth conditions [12,28-30]. The number of seeds per pod was significantly ($P < 0.05$) influenced by planting spacing at both experimental sites (Tables *2*-*3*). The highest values (3.80 and 3.73) were recorded at wider spacing levels such as 50 cm × 20 cm and 40 cm × 20 cm in the midland and highland areas, respectively. This may be attributed to reduced competition under wider spacing, which allows plants to utilize available resources more efficiently, thereby enhancing seed development. Wider spacing increased the number of seeds per pod [31]. Similarly, the maximum number of seeds per pod was achieved under wider spacing conditions [12]. However, dense plant populations reduce seeds per pod due to increased competition [32]. Plant density did not significantly affect seeds per pod [33], with environmental conditions also affecting outcomes; by contrast, dense planting had no significant effect on seed number per pod [34,35].

The highest seed multiplication ratio was recorded at 45 cm × 10 cm and 35 cm × 10 cm spacing at the midland and highland areas, respectively (Tables *2*-*3*). Moderate planting spacing improved resource use efficiency and seed production [36]. Higher seed multiplication ratios were recorded at lower plant density. Similarly, dense plant populations reduced seed production per plant [32]; wider spacing allowed individual plants to express their full yield potential [37]. In contrast, the number of seeds per pod, pods per plant, and seeds per plant (seed multiplication ratio) was not affected by plant density [34,35]. Pure seed yield was significantly ($P < 0.05$) influenced by planting spacing at both experimental locations (Tables *4*-*5*). The highest pure seed yield was obtained at 45 cm × 10 cm and 35 cm × 10 cm spacing in the midland and highland areas, respectively. Appropriate spacing enhanced yield components while minimizing competition and lodging effects [18,38]. Narrow spacing reduced seed yield owing to lodging, reduced light penetration, and decreased photosynthetic efficiency. In contrast, excessively wide spacing may also decrease seed yield due to reduced plant population and greater weed competition [20]. Optimal plant density is essential for maximizing seed yield; however, it varies with environmental conditions and crop management practices.

Treatment No.	Treatment arra ngement	PH (cm)	NTP	NSP	NPP	SMR
1	30 cm × 5 cm	174.733a	1.4667h	2.4667j	6.733i	17.533g
2	30 cm × 10 cm	166.733bdac	2.4667f	2.7333ihj	8.000ih	21.667g
3	30 cm × 15 cm	148.400gih	2.800f	2.933gih	8.400igh	24.600fg
4	30 cm × 20 cm	145.400i	3.6667ba	2.9333gih	11.133fecd	31.400efd
5	35 cm × 5 cm	170.00bac	1.5333hg	2.4667j	9.400fgh	23.467g
6	35 cm × 10 cm	161.600ebdfc	3.1333dce	3.1333gef	12.933bc	42.733b
7	35 cm × 15 cm	153.00gifh	3.0667de	3.3333ecd	14.133ba	43.467b
8	35 cm × 20 cm	144.800i	3.2667bdc	3.400bcd	10.400fegd	3200efd

9	40 cm × 5 cm	167.067bdac	1.7333hg	2.7333ihj	9.200fgh	24.867efg
10	40 cm × 10 cm	159.933edfc	3.5333bac	3.200gefcd	10.200feg	32.667ecd
11	40 cm × 15 cm	152.533gifh	3.600ba	3.2667efcd	12.067becd	39.867bc
12	40 cm × 20 cm	146.800ih	3.6667ba	3.4667bc	12.267becd	41.600b
13	45 cm × 5 cm	170.533ba	1.9333g	2.667ij	7.800ih	20.667g
14	45 cm × 10 cm	163.667ebdc	3.2667bdc	3.3333ecd	15.333a	52.667a
15	45 cm × 15 cm	157.200egdfh	3.3333bdac	3.000gfh	12.467bcd	38.200bcd
16	45 cm × 20 cm	156.267egfh	3.600ba	3.0667gef	12.733bc	41.467b
17	50 cm × 5 cm	165.200ebdac	1.4667h	2.5333j	8.733igh	21.667g
18	50 cm × 10 cm	157.733egdf	3.0667de	3.4667bc	11.933ecd	44.267b
19	50 cm × 15 cm	146.933ih	3.5333bac	3.6667ba	12.600bc	45.200ba
20	50 cm × 20 cm	143.733i	3.7333a	3.800a	12.933bc	45.733 ba
Mean		157.6133	2.893333	3.08000	10.970	34.29000
LSD		10.417	0.4635	0.3207	2.0695	7.8017
CV%		3.998401	9.691701	6.299799	11.41322	13.76483

TABLE 2: Effect of planting spacing on plant height, number of tillers per plant, number of seeds per pod, number of pods per plant, and seed multiplication ratio of faba bean in midland areas

CV, Coefficient of Variation; LSD, Least Significant Difference; NPP, Number of Pods per Plant; NSP, Number of Seeds per Pod; NTP, Number of Tillers per Plant; PHP, Plant Height; SMR, Seed Multiplication Ratio

Treatment No.	Treatment arrangement	PHP (cm)	NTP	NSP	NPP	SMR
1	30 cm × 5 cm	171.600a	1.1333g	2. 400j	8.533egf	19..933gh
2	30 cm × 10 cm	151.467b	1.8667ef	2.8000ih	8.667egdf	29.067egfh
3	30 cm × 15 cm	122.00dc	2.1333ef	2.8667ihg	10.200edfc	29.000egfh
4	30 cm × 20 cm	85.533gf	2.1333ef	2.9333fhg	10.467ebdfc	25.200gfh
5	35 cm × 5 cm	153.467ba	1.800ef	2.800ih	8.000gf	24.733gfh

6	35 cm × 10 cm	113.600de	3.000dc	3.200fde	14.067a	50.467a
7	35 cm × 15 cm	97.467gef	3.1333bc	3.1333feg	10.933ebdfc	33.733edfc
8	35 cm × 20 cm	90.400gf	3.200bc	3.2667dec	13.000bac	25.933gfh
9	40 cm × 5 cm	144.000b	1.5333gf	2.6000ij	8.667egdf	22.467gfh
10	40 cm × 10 cm	103.400def	2.4000ed	2.8667ihg	10.533ebdfc	30.467egdf
11	40 cm × 15 cm	93.600gf	2.8667dc	3.2000fde	8.533egf	27.133gfh
12	40 cm × 20 cm	80.333g	3.000dc	3.7333a	8.533egf	31.867edfc
13	45 cm × 5 cm	136.933bc	1.800ef	2.6667ihj	6.933g	18.000h
14	45 cm × 10 cm	103.533def	3.200bc	3.4000bdec	12.933bac	41.000bdac
15	45 cm × 15 cm	92.933gf	3.1333bc	3.4667bdac	8.667egdf	29.067egdf
16	45 cm × 20 cm	91.400gf	3.2000bc	3.6000ba	11.333ebdac	39.000ebdc
17	50 cm × 5 cm	116.000de	1.9333ef	2.7333ih	8.200gf	22.333gfh
18	50 cm × 10 cm	98.467gef	3.3333bac	3.4667bdac	10.933ebdfc	45.867ba
19	50 cm × 15 cm	93.600gf	3.7333ba	3.5333bac	11.33bdac	42.200bac
20	50 cm × 20 cm	88.067gf	3.8667a	3.7333a	13.400ba	40.267ebdac
Mean		111.3900	2.6200	3.120	10.0133	31.42667
LSD		19.304	0.6201	0.2903	3.1172	11.413
CV%		10.4843	14.31867	5.628821	18.8338	21.97034

TABLE 3: Effect of planting spacing on plant height, number of tillers per plant, number of seeds per pod, number of pods per plant, and seed multiplication ratio of faba bean in highland areas

CV, Coefficient of Variation; LSD, Least Significant Difference; NPP, Number of Pods per Plant; NSP, Number of Seeds per Pod; NTP, Number of Tillers per Plant; PHP, Plant Height; SMR, Seed Multiplication Ratio

Effect of plant spacing on disease (chocolate spot) of faba bean

Planting spacing significantly ($P < 0.05$) affected chocolate spot incidence and severity at both experimental sites (Tables *4-5*), indicating a clear influence of spacing on disease development. In the midland areas, disease incidence reached 100% across all treatments, while the greatest severity occurred under narrow plant spacing at both sites. Lower plant density reduced disease pressure, whereas denser planting stands likely increased chocolate spot severity by creating favorable microclimatic conditions and restricting air circulation [39,40].

Treatment No.	Treatment arrangement	GY (qt ha^{-1})	PSY (qt ha^{-1})	IMSY (qt ha^{-1})	CHSIT	CHSST
1	30 cm × 5 cm	18.633ba	14.5997 bdac	4.0333a	100	25.00bedc
2	30 cm × 10 cm	15.033edf	11.733fg	2.3000fe	100	23.333bedc
3	30 cm × 15 cm	14.033ef	13.033fgde	2.000fe	100	23.333bedc
4	30 cm × 20 cm	13.500f	11.367g	2.1667fe	100	20.000ed
5	35 cm × 5 cm	18.300bac	14.800bdec	3.5000bac	100	25.000bedc
6	35 cm × 10 cm	19.300a	16.600ba	2.7000fbdec	100	23.333bedc
7	35 cm × 15 cm	18.833ba	16.633ba	2.2000fe	100	21.667edc
8	35 cm × 20 cm	16.133edc	14.167fbdec	1.9667f	100	21.667edc
9	40 cm × 5 cm	15.200edf	11,533g	3.6000ba	100	30.000ba
10	40 cm × 10 cm	19.067a	16.067bac	2.9667bdec	100	28.333bac
11	40 cm × 15 cm	14.967edf	12.367fge	2.600fdec	100	25.000bedc
12	40 cm × 20 cm	16.533bdc	14.100fbdec	2.4667fde	100	23.333bedc
13	45 cm × 5 cm	15.100edf	11.700fg	3.4333bdac	100	26.667bdc
14	45 cm × 10 cm	19.267a	17.433a	1.7667f	100	25.000bedc
15	45 cm × 15 cm	18.367bac	13.767fgdec	2.2667fe	100	18.333e
16	45 cm × 20 cm	16.033edc	16.200bac	2.1333fe	100	18.333e
17	50 cm × 5 cm	16.000edc	12.70fg	3.3000bdac	100	35.000a
18	50 cm × 10 cm	15.500edf	12.833fgde	2.6667fbdec	100	28.3333bac
19	50 cm × 15 cm	13.767ef	11.800fg	2.1667fe	100	23.333bedc
20	50 cm × 20 cm	13.767ef	11.500g	2.2667fe	100	21.667edc
Mean		16.37500	13.74333	22.53152	100	24.33333
LSD		2.4604	2.5512	0.9776	0	7.3718
CV%		9.090381	11.23057	2.625000	0	18.32819

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TABLE 4: Effect of planting spacing on gross yield, pure seed yield, impure seed yield, chocolate spot incidence, and chocolate spot severity of faba bean in midland areas

CHSIT, Chocolate Spot Incidence per Treatment; CHSST, Chocolate Spot Severity per Treatment; CV, Coefficient of Variation; GY, Gross Yield; IMSY, Impure Seed Yield; LSD, Least Significant Difference; PSY, Pure Seed Yield

Treatment No.	Treatment arrangement	GY (qt ha^{-1})	PSY (qt ha^{-1})	IMSY (qt ha^{-1})	CHSIT	CHSST
1	30 cm × 5 cm	21.033ba	17.533b	3.5000a	85.000bdc	20.167ebdac
2	30 cm × 10 cm	19.467bdec	16.333cbd	2.9000dc	83.333bdec	20.833bdac
3	30 cm × 15 cm	17.633feg	14.900efd	2.7333dgef	81.667fdec	20.000ebdc
4	30 cm × 20 cm	15.500ihg	13.333gefh	2.5333hgf	81.667fdec	17.500egf
5	35 cm × 5 cm	22.533a	17.567b	3.1667bc	90.000ba	22.500ba
6	35 cm × 10 cm	20.467bac	20.567a	2.0000jk	89.2167ba	18.333edf
7	35 cm × 15 cm	19.200bdec	17.300cb	1.9000k	81.667fdec	18.333edf
8	35 cm × 20 cm	16.533fhg	14.833efd	1.7333k	70.000g	15.000g
9	40 cm × 5 cm	18.833dec	15.533cebd	3.2667ba	85.833bdc	23.333a
10	40 cm × 10 cm	20.400bdac	17.567b	2.8333de	85.000bdc	23.333a
11	40 cm × 15 cm	17.533feg	15.033cefd	2.5667hgef	76.667feg	22.500ba
12	40 cm × 20 cm	15.533ihg	13.100gfh	2.4333hi	76.667feg	21.667bac
13	45 cm × 5 cm	18.300fde	15.467cebd	3.2667ba	93.333a	19.167edc
14	45 cm × 10 cm	17.467feg	14.700efd	2.7333dgef	81.667fdec	18.333edf
15	45 cm × 15 cm	14.400jih	11.933gih	2.4333hi	80.000fde	17.5egf
16	45 cm × 20 cm	16.433fihg	14.133gefd	2.3000hi	75.000fg	15.000g
17	50 cm × 5 cm	14.367ji	11.267ih	3.1333bc	89.667bdac	21.667bac
18	50 cm × 10 cm	14.633jih	11.900gih	2.7667def	88.333bac	20.000ebdc
19	50 cm × 15 cm	12.900j	10.467i	2.4667hgi	86.667bdac	19.167edc
20	50 cm × 20 cm	13.33j	11.100ih	2.2000ji	85.000bdc	15.833gf
Mean		17.32500	14.72833	2.643333	83.16667	19.50833

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LSD		2.1555	2.3208	0.2803	-'	7.3718
CV%		7.526959	9.532952	6.416029	4.937777	9.851901

TABLE 5: Effect of planting spacing on gross yield, pure seed yield, impure seed yield, chocolate spot incidence, and chocolate spot severity of faba bean in highland areas

CHSIT, Chocolate Spot Incidence per Treatment; CHSST, Chocolate Spot Severity per Treatment; CV, Coefficient of Variation; GY, Gross Yield; IMSY, Impure Seed Yield; LSD, Least Significant Difference; PSY, Pure Seed Yield

Effect of plant spacing on seed quality attributes of faba bean

Wider and moderate spacing improved germination, seed vigor index-I, seed purity, and pure live seed percentage compared with narrow spacing. Higher seed vigor and purity (>90%) were recorded under moderate spacing treatments (45 cm × 10 cm and 35 cm × 20 cm) at the midland and highland areas, respectively, while narrow spacing resulted in lower values due to increased competition (Tables *6*-*7*). Adequate spacing enhances seed development and overall crop performance by reducing inter-plant competition [9,15,16,41,42]. These results are consistent with improved germination and seed quality under wider spacing and optimal plant density conditions.

Treatment No.	Treatment arrangement	MCT	100 SW g^{-1}	SLT (cm)	RLT (cm)	SGEMT%	SVI-IT	PHYPT%	PLST%
1	30 cm × 5 cm	10.5000f	79.267d	14.467bdac	13.233bdc	70.833g	1962.074fg	78.3539bdec	55.500i
2	30 cm × 10 cm	10.5667fe	78.833d	15.933bac	13.767bdac	86.367fe	2565.099bdec	83.700bdc	72.28gfd
3	30 cm × 15 cm	11.0333fedc	82.133bdc	16.033bac	14.967bac	87.867dec	2723.877bdac	84.067bdac	73.867gfd
4	30 cm × 20 cm	11.800ba	88.367a	17.767ba	15.700ba	93.600ba	3132.51ba	86.733bac	83.874bac
5	35 cm × 5 cm	11.3333bdc	81.367bdc	12.733bec	12.500dc	81.533f	2060.094feg	80.533fdec	65.660h
6	35 cm × 10 cm	11.0667fedc	82.033bdc	13.967bdc	13.567bdac	93.133bac	2564.32bdec	85.833bac	79.938bdc
7	35 cm × 15 cm	11.1000fedc	78.800d	18.200a	14.967bac	95.300ba	3160.81ba	87.767ba	83.641bac
8	35 cm × 20 cm	10.7000fed	84.467ba	18.300a	16.376a	97.367a	3376.29a	90.367a	87.987a

9	40 cm × 5 cm	10.9333fedc	79.833dc	10.600fde	11.900d	83.267fe	1873.50fg	76.100fe	63.366h
10	40 cm × 10 cm	11.3000bdc	82.267bdc	13.667bdc	12.300dc	91.867bdc	2384.86fde	84.200bac	77.352dc
11	40 cm × 15 cm	11.3333bdc	84.333bac	14.400bdac	12.633dc	92.800bdac	2508.66bdec	82.300bdec	76.37gfdec
12	40 cm × 20 cm	12.0333a	88.667a	16.033bac	12.800dc	93.367ba	2691.56bdac	85.267bac	79.611bdc
13	45 cm × 5 cm	10.8667fed	79.800dc	8.067f	11.900d	84.633fe	1689.867g	77.333fde	65.449h
14	45 cm × 10 cm	11.1333fbedc	81.200bdc	14.833bac	13.367bdac	96.767ba	2728.82bdac	90.800a	87.864a
15	45 cm × 15 cm	11,1667fbedc	81.600bdc	15.633bac	14.233bdac	91.867dc	2743.69bdac	85.867bac	78.883bdc
16	45 cm × 20 cm	11.6000bac	82.633bdc	15.733bac	14.400bdac	96.767ba	2915.88bacfg	88.500ba	85.638ba
17	50 cm × 5 cm	11.2000bedc	82.933bdc	9.133fe	12.933bdc	87.633de	1933.70fg	79.375bdec	69.558gfh
18	50 cm × 10 cm	11.2667bdc	79.233d	9.467fe	13.033bdc	93.033bac	2093.24feg	82.600bdec	76.845fdec
19	50 cm × 15 cm	10.7667fed	80.033bdc	10.500fde	14.233bdac	91.933bdc	2273.77fde	84.300bac	77.499dec
20	50 cm × 20 cm	10.5667fe	82.433bdc	11.967fdec	14.967bac	93.300ba	2512.94bdec	83.533bdc	77.936dc
Mean	-	11.11333	82.01167	13.87167	13.68833	90.13667	2494.63	83.70167	75.444
LSD	-	0.6669	4.5672	4.1271	2.8667	5.3463	1686.43	6.7629	75.804
CV%	-	3.630618	3.369172	17.99967	12.67036	3.588411	13.05105	4.091531	6.066890

TABLE 6: Effect of planting spacing on moisture content, 100-seed weight, shoot length, root length, germination percentage, seed vigour index, physical purity, and pure live seed of faba bean in midland areas

100 SW, 100 Seed Weight; CV, Coefficient of Variation; LSD, Least Significant Difference; MCT, Moisture Content per Treatment; PHYPT%, Physical Purity per Treatment (%); PLST%, Pure Live Seed per Treatment (%); RLT, Root Length per Treatment; SGEMT%, Germination Percentage per Treatment (%); SLT, Shoot Length per Treatment; SVI-IT, Seed Vigor Index per Treatment

Treatment No.	Treatment arrangement	MCT	100 SW g^{-1}	SLT (cm)	RLT (cm)	SGEMT%	SVI-IT	PHYPT%	PLST%
1	30 cm × 5 cm	10.3000c	72.800fg	10.133edf	13.133bdec	70.833e	1648.000i	83.300dfce	59.00j
2	30 cm × 10 cm	11.1333ba	77.400efd	11.667ebdfc	11.833de	83.267c	1956.774gih	83.900dfce	69.861fhig
3	30 cm × 15 cm	10.9000bac	75.933efdg	16.033a	13.767bdec	85.300bc	2541.94bdec	84.533dce	72.106fheg
4	30 cm × 20 cm	10.9667bac	76.533efdg	16.033a	15.800ba	91.233ba	2904.220bacfg	85.833dc	78.3080bdec
5	35 cm × 5 cm	10.6667bac	79.733edc	9.533ef	12.233dec	78.867dc	1716.619ih	85.800dc	67.667hi
6	35 cm × 10 cm	10.9000bac	82.667bac	17.500a	18.233a	97.200a	3473.2476a	91.100a	88.549a
7	35 cm × 15 cm	10.5667bac	76.967efd	17.800a	17.900a	97.200a	3470.04a	90.067a	87.545a
8	35 cm × 20 cm	10.5000bc	80.633bdc	16.733a	15.733ba	95.200a	3090.763ba	89.433ba	85.140ba
9	40 cm × 5 cm	11.1333ba	77.600efdc	14.400bdac	12.633bdec	76.267dc	2061.725fgih	82.333dfe	62.792i
10	40 cm × 10 cm	10.600bac	74.833efg	16.033a	12.800bdec	91.200ba	2629.569fbdec	86.100bc	78.523bdec
11	40 cm × 15 cm	10.8667bac	76.300efdg	10.600edfc	11.900de	93.600a	2106fgih	85.433dc	79.965bdec
12	40 cm × 20 cm	10.5667bac	73.533fg	13.667ebdac	11.400e	92.367ba	2315.363fgde	84.400dfce	78.154dec
13	45 cm × 5 cm	10.7333bac	71.633g	15.633ba	13.367bdec	92.533ba	2683.457fbdec	84.367dfce	78.067dec
14	45 cm × 10 cm	10.9333bac	82.733bac	10.767edfc	12.500bdec	91.367ba	2125.835fgih	84.233dfce	76.961fdec
15	45 cm × 15 cm	11.1667ba	75.700efdg	13.600ebdac	13.900bdec	95.433a	2624.407fbdec	82.867dfce	82.867bac

16	45 cm × 20 cm	10.8000bac	74.000fg	9.067f	12.000de	95.267a	2095.874fgih	85.967bc	81.898bdac
17	50 cm × 5 cm	10.8333bac	85.00ba	11.133edfc	12.933bdec	81.367dc	1958.178gih	78.033g	63.493i
18	50 cm × 10 cm	10.7333bac	75.933efdg	10.500edf	14.967bdac	92.433ba	2353.99fgde	81.267fge	75.117fdeg
19	50 cm × 15 cm	11.1000ba	74.100fg	14.867bac	15.567bac	94.933a	2889.190bdac	80.967fg	76.864fdec
20	50 cm × 20 cm	11.3000a	85.933a	13.933bdac	15.767ba	93.300a	2728.894bdec	83.467dfce	77.874dec
Mean	-	10.83500	77.49833	13.48167	13.91833	89.3333	2447.634	84.67	75.378
LSD	-	0.7547	5.1401	4.2913	3.4328	7.3439	619.04	3.5643	6.9548
CV%	-	4.214287	4.012628	19.25724	14.92155	4.973550	15.21539	2.546786	5.559829

TABLE 7: Effect of planting spacing on moisture content, 100-seed weight, shoot length, root length, germination percentage, seed vigour index, physical purity, and pure live seed of faba bean in highland areas

100 SW, 100 Seed Weight; CV, Coefficient of Variation; LSD, Least Significant Difference; MCT, Moisture Content per Treatment; PHYPT%, Physical Purity per Treatment (%); PLST%, Pure Live Seed per Treatment (%); RLT, Root Length per Treatment; SGEMT%, Germination Percentage per Treatment (%); SLT, Shoot Length per Treatment; SVI-IT, Seed Vigor Index per Treatment

Economic analysis

Economic analysis revealed that the highest net benefit (182,393.1 ETB and 212,673.75 ETB) was obtained at 45 × 10 cm and 35 × 10 cm spacing in the midland and highland areas, respectively. However, the highest marginal rate of return was recorded at 45 × 20 cm (midland) and 35 × 15 cm (highland), indicating better economic efficiency. Lower seed rates and optimal spacing increase economic returns for farmers [20].

Conclusions

Plant spacing significantly influenced growth, yield, seed multiplication ratio, and seed quality of faba bean under both midland and highland conditions. The highest pure seed yield and seed multiplication ratio were obtained at 45 cm × 10 cm in the midland and 35 cm × 10 cm in the highland areas. However, the highest economic return was achieved at 45 cm × 20 cm (midland) and 35 cm × 15 cm (highland). Therefore, for practical seed production, the recommended spacing is 45 cm × 20 cm for the midland and 35 cm × 15 cm for the highland. These spacing combinations are recommended for optimal economic and agronomic performance. However, further multi-season and multi-location studies are required to validate these findings.

This study provides location-specific recommendations for optimizing faba bean seed production in Central Ethiopia. The findings demonstrate that appropriate plant spacing significantly improves seed yield, quality, and economic return. The results are useful for farmers, seed producers, and agricultural extension services aiming to enhance faba bean productivity under different agro-ecological conditions.

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Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Asgelesh Fesseha, Muluken Getahun

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Supervision: Asgelesh Fesseha, Muluken Getahun

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Plant subjects: All authors have confirmed that this study did not involve any herbarium specimen.

Human subjects: All authors have confirmed that this study did not involve human participants or tissue.

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Data Availability Statements

The datasets (and/or code) supporting this study are available from the corresponding author upon reasonable request.

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